Contents

Contents

Contents

TABLE INDEX

FIGURE INDEX

Abstract

In a panorama of the electromagnetic field applications the range of radio frequencies (RF) met success in food processing, especially in grain cereal disinfection and drying. Electromagnetic RF energy penetrating a grain volume result in dielectric heating that causes its drying and pest (insects, microscopic fungi) mortality when the temperature is critical for them. This work proposes a new theoretical mathematical model of electromagnetic interaction with a small homogeneous dielectric ellipsoid of rotation which represents an individual kernel. Through the solution of the general problem of macroscopic electrodynamics and the boundary condition application for the system “air – kernel” the model permits to calculate precisely the energy expenses by absorption and dissipation in an individual kernel when electromagnetic energy converts into heat (dielectric heating). The calculation result depends on the characteristics of both the electromagnetic field (electric field intensity, frequency) and the dielectric individual objects (geometry, volume, dielectric parameters). Knowledge of dielectric parameters is considered to be a principal part of the model development. The dielectric properties depend on temperature, moisture content, the object volumetric density and field frequency that are proved with the experimental part of this work. The method of dielectric parameters measurement is proposed and experimentally tested that forms the base for the technology of the agricultural product disinfection and drying. The experiments on the dielectric parameters measurement were conducted for wheat grain *Triticum aestivum L.* and granary weevil *Sitophilus granarius L.* The grain processing is presented for two different types of chambers, the coaxial irradiation chamber and the irradiation chamber with plane capacitor. The experimental part was done for wheat grain *Triticum aestivum L.*, granary weevil *Sitophilus granarius L.* and the species of microscopic fungi *Aspergillus fumigatus, Cladosporium cladosporioides* and *Aspergillus candidus* for the frequencies 47.5, 900 and 2,450 MHz at different processing regimes. The granary weevil (*Sitophilus granarius L.*) control achieved till 100% of insect mortality. The microscopic fungi control was about 21-97% that requires more investigation. Creation of the present mathematical model contributes not only to the development of food processing technology (particularly grain crops processing), but also forms the solid basis as a perspective to create models of electromagnetic interaction with much more complicated systems such as the human body cells for electric stimulation methods and consequent disease cure at the cellular level.

Resumen

Resumen

En el panorama de las aplicaciones del campo electromagnético el rango de radiofrecuencias encontró el éxito en el procesamiento de alimentos, específicamente en desinfección y secado de los granos de cereales. La energía electromagnética de radiofrecuencia que penetra el volumen del grano resulta en el calentamiento dieléctrico que causa el secado del mismo y morbilidad de las pestes (insectos, hongos microscópicos) alcanzando el nivel de las temperaturas críticas para ellas. Este trabajo propone el modelo matemático teórico nuevo de la interacción electromagnética con un pequeño homogéneo dieléctrico elipsoide de rotación que representa un grano individual. Mediante la solución del problema general de electrodinámica macroscópica y aplicación de las condiciones de frontera del sistema “aire-grano” el modelo nos permite calcular con precisión los gastos energéticos por absorción y disipación en un grano individual en la conversión de la energía electromagnética al calor. El resultado de los cálculos depende tanto de las características del campo electromagnético (intensidad del campo eléctrico, frecuencia) como de los objetos dieléctricos individuales (geometría, volumen, parámetros dieléctricos). El conocimiento de los parámetros dieléctricos se considera como la parte principal del desarrollo del modelo y están en función de la temperatura, humedad, densidad volumétrica del objeto y la frecuencia del campo esencialmente, lo que se comprueba en la parte experimental del trabajo. Se propone el método de medición de los parámetros dieléctricos probado experimentalmente que forma la base de la tecnología de desinfección y secado de productos agrícolas. Los experimentos de la medición de los parámetros dieléctricos se realizaron con los granos de trigo *Triticum aestivum L.* y los escarabajos del grano *Sitophilus granarius L.* Se diseñaron dos tipos de las cámaras de desinfección: la cámara de la irradiación coaxial y la cámara con el capacitor plano. Se realizó la parte experimental con el trigo *Triticum aestivum L.*, los escarabajos del grano *Sitophilus granarius L.* y los especies de los hongos microscópicos *Aspergillus fumigatus, Cladosporium cladosporioides* y *Aspergillus candidus* a las frecuencias 47.5, 900 y 2,450 MHz a diferentes regímenes del procesamiento. Se logró el control del *Sitophilus granarius L.* hasta 100% de morbilidad y de los hongos microscópicos de 21-97% lo que requiere la investigación más profunda. La creación del modelo matemático presente contribuye no solo al desarrollo de la tecnología del procesamiento de los alimentos como los productos agrícolas en particular, sino también forma la base solida como la perspectiva para la creación de los modelos de interacción electromagnética con los sistemas mucho más complicados como las células del cuerpo humano para los efectos de estimulación eléctrica y consecuente superación de las enfermedades a nivel celular.

Chapter I

Chapter I

Chapter I

1. Introduction

Protection of the agricultural product from harmful insects, mites and microscopic fungi is a worldwide problem of great importance of all mankind. As a result of the vital activity of pests, grain products can lose up to 30% of their initial weight during storage. Grain and mixed feed contaminated with insects and microorganisms can contain a large amount of toxic substances: contaridine, micotoxins, urates and oxalates. These toxic substances can be a source of serious chronic diseases and even death for men and domestic animals.

For a long time it has been known that a high-frequency electromagnetic field penetrating a volume of grain results in the two positive effects. On the one hand, the heat developed in the grain causes drying. On the other hand, heating of pests living in the grain to a temperature exceeding some critical level causes their mass mortality. This effect was suggested for use of microwave energy in protection of grain from pests. *But the problem is physically very much complicated.*

Investigations of high-frequency and microwave action on insects and microorganisms have been carried out for the last 50 years in different countries. Several theoretical conditions were suggested for the action of electromagnetic HF radiation on biological organisms. The nature of work was mainly experimental because the problem was physically complicated. The success in solving electromagnetic boundary problems makes theoretical research on electromagnetic wave interaction with granular agricultural products possible as has been realized in the present work.

Interest in the possibility of controlling insects with high-frequency electric energy dates back nearly 90 years. Reported results of initial experiments determining lethal exposures for several insect species subjected to 12-MHz electric fields and the determination of body temperatures produced in honey bees by the consequent dielectric heating. These and later studies have been summarized in numerous reviews. A patent was issued in 1934 on the high-frequency method and equipment for exterminating insect life in seed, grain, or other materials. Concern about the health hazards of chemical pesticides in the 1950s through the 1970s stimulated further studies on the possible use of radio-frequency (RF) and microwave energy for controlling stored-grain and other stored-product insects. Still today, even though the concerns about the use of chemical pesticides are still with us, the techniques have not found their way into practical use. It is important to examine the reasons for lack of acceptance and to access the potential for possible future use of RF and microwave methods for stored-grain insect control.

The biological effects of RF and microwave energy are generally believed to be mainly thermal in nature. At least nonthermal phenomena that might be useful for stored-grain insect control have never been demonstrated convincingly. Consequently, RF and microwave dielectric heating was examined for their potential use in controlling stored-grain insects.

For understanding the granular agricultural product and insects interactions with electromagnetic fields it is important to investigate its radio-frequency and microwave dielectric properties. Dielectric properties are the electrical characteristics of materials that are classed as poor conductors of electricity, or dielectrics. The dielectric properties of usual interest are the dielectric constant ε' and the dielectric loss factor ε'', the real and imaginary parts, respectively, of the relative complex permittivity, $\varepsilon = \varepsilon' - j\varepsilon'' = |\varepsilon| \cdot e^{-j\delta}$,where δ is the loss angle of the dielectric. Often, the loss tangent, $tg\delta = \varepsilon'' / \varepsilon'$, or dissipation factor, is used also as a descriptive dielectric parameter. The dielectric constant is associated with electric energy storage capability through polarization of the dielectric material, whereas the loss factor is associated with electric field energy dissipation in the material in the form of heat. These properties are important in dielectric and microwave heating applications, where the power dissipated per unit volume, ***P***, is absorbed from the alternating electric field and converted into heat in the material and is given as

$$P = E^2\sigma = kfE^2\varepsilon^{''} \tag{1.1}$$

where E is the electric field intensity in the material and k is a constant that depends on the units used for the calculation. The dielectric constant $\varepsilon^{'}$ of the material influences the electric field intensity E in the material.

The dielectric properties are also important in determining the reflection of electromagnetic waves by materials, as in radar applications.

Studies, considering all of these factors for rice weevils in wheat, have shown that selective heating of the insects can be expected, *that the loss factor is the dominant factor, and that the best frequencies for selectively heating the insects are in the range from about **10 to 100 MHz** .*

The dielectric properties of materials, although dependent upon the chemical and physical makeup of the material, depend also upon the frequency of the applied electric field and the temperature of the material. *If it is hygroscopic material, these dielectric properties also depend highly upon the amount of water in the material and upon the chemical binding of the water that is present. Molecules with significant dipole moments orient with applied electric fields and contribute to the polarization of the material that influences the magnitude of the dielectric constant. Once such molecules are polarized and the electric field is removed or altered, there is a finite time associated with the reorientation of these molecules. Thus, the dielectric relaxation characteristics of materials also influence the dielectric properties and their frequency dependence, because there is a time period associated with the frequency of the electromagnetic waves. In general, the dielectric constant of materials remains constant or decreases with increasing frequency!*

The dielectric loss factor, however, may increase or decrease with increasing frequency, depending on the dielectric relaxation characteristics of the material.

The temperature dependence of the dielectric properties of materials is rather complex in that the dielectric relaxation mechanisms can have a major influence. Outside a region of dispersion, where any dielectric relaxation is not of significant consequence, the dielectric constant tends to decrease with increasing temperature, but because the relaxations are not well documented for most substances, measurements of the dielectric properties are usually necessary to characterize their behavior with respect to frequency, temperature and other parameters.

Finally, we can note that the dielectric properties of insects are important in explaining the interaction of insects with electromagnetic fields and are of interest in considering radar tracking of insects or radio-frequency and microwave dielectric heating for treating infested products for control purposes.

The bulk density of grain crops is an important factor, second only to moisture content, affecting the dielectric properties of grain at a given frequency. It has been shown that certain functions of the dielectric properties of particulate materials are essentially linear functions of the bulk density of the air-particle mixtures. Those linear relationships are useful for predicting the dielectric constants of such granular material at any density from measurements on the materials at any known bulk density. Although the accuracy of predictions decreased as particle size increased, the relationships were still useful with particle sizes as large as those of wheat kernels.

1.1. MOTIVATION OF THE WORK

Knowledge of the dielectric properties both grain crops and insects permits to create modeling of its interaction with electromagnetic field. The thermodynamical approach is important as far as we consider the energy needed to heat the grain product for drying purposes and also disinfestation till some appropriate level of temperature. The temperature is one of the four main parameters determining the dielectric properties of the biological objects such as grain and insects. Also the dielectric properties depend considerably on moisture content of grain, granular product density and the frequency of electromagnetic radiation. Better understanding of the dielectric properties helps to develop and create the model of interaction of electromagnetic waves with grain and insects. One of the objectives of this work is a new electrodynamical approach that was never proposed before. By considering each individual grain kernel (not as a grain mass) the task was to define the field $\vec{E}$ inside the material body of ellipsoidal geometry and to develop the mathematical model of electromagnetic field interaction with each individual kernel, to resolve the problem taking into consideration the boundary conditions. For all these reasons there is a strong motivation to create and describe a new mathematical model between the electromagnetic field and granular crops and insects.

Another important objective is pursued in this work: to develop a method of the dielectric parameters measurement of both grain crops and insects on the base of the experiments successfully realized on the facility made in the frames of the project 447 with STCU support, Ukraine. Solution of the problem of electromagnetic radiation interaction with grain crops and insects requires the designing of electromagnetic models of both grain and insects with strong relation of their electrodynamics qualities with density, layer width, average seed dimension and other parameters.

The permittivity measurement of the real mixture of grain with beetles is needed to be compared with the static and the quasi-static models. In this work an attempt was made within the framework of the suggested model to describe the behavior of electromagnetic energy absorption in both grain and pests and the behavior of their main electrophysical characteristics ε' and ε'' in dependence on the electromagnetic frequency and the moisture content. To solve the problem of evaluating the efficiency of microwave grain processing at various levels of grain radiation and in different frequency ranges is essential. Important is that dielectric parameters values ε' and ε'' depend considerably on the grain and pest parameters: density, moisture content, average radius and frequency of incident electromagnetic radiation.

Another problem aroused in the frames of this work is insect control by radio-frequency and microwave energy. Insects are responsible for tremendous losses of cereal grains after harvest throughout the tropical and temperate regions of the world. Chemical insecticides have been very helpful in saving grain from insect destruction, but they are not always completely effective, and there are some hazards to personnel associated with their application. Also chemical residues on the treated grain must be held certain levels for safe consumption as human food. For these reasons, dielectric heating has been explored for possible use in controlling insects in infested grain.

The experimental part of this complex grain processing is successfully realized. The pulse method facility is constructed and put into operation for the purpose of the contaminated grain processing. A series of biological and physics-biological experiments are made with different pest species in different processing regimes. The most perspective and newly advanced achievement is made by the combined action of vacuum, high-frequency and plasma on the pests that causes their 100% mortality. This combined method of insect treatment gives an opportunity to consider it as a significant contribution into the worldwide experience on pest control by electromagnetic radiation.

Through revising all these observations and the problems mentioned above there is a strong foundation for the detailed description of grain treatment, insect control, purpose of the dielectric properties study, the experimental method of dielectric properties measuring of both grain and insects, mathematical model of interaction of electromagnetic radiation with pests and the perspective of creation of the advanced complex combined technology of grain processing.

1.2. OBJECTIVES.

The main objective of this work is

- to create a mathematical model of electromagnetic wave interaction with each individual particle of biological nature that is represented by a small dielectric homogeneous ellipsoid of rotation.
- to propose an experimental method for dielectric properties measurement of both grain crops and insects. Consider the main electrical characteristic such as a relative complex permittivity (ε′ - dielectric constant, ε′′ - dielectric loss factor) in dependence on the granular product and insect temperature, granular product moisture content and electromagnetic field frequency.
- to relate the theoretical model with the experimental part of the work, compare the results and estimate the theoretical model efficiency.

Chapter II

Chapter II

2. Previous experience.

2.1 A Study of Fiber Excitation Thresholds Using Monopolar and Bipolar Stimulating Electrodes

A.E. Grumet´s work “Electric Stimulation Parameters for an Epi-Retinal Prosthesis”, the thesis for the obtainment of the PhD degree (Massachusetts Institute of Technology, 1999), gives the understanding of a cellular tissue response under a variety of stimulating conditions through the use of monopolar and bipolar stimulating electrodes.

The human body is composed of cells. Our sensory and motor capabilities arise from the properties of various types of nerve and muscle cells, from the complex networks which they form, and from additional supporting cells which maintain a suitable operating environment. Disruption of these cells and networks, caused by disease or injury, can result in paralysis or sensory loss. This work was undertaken to contribute to the development of a retinal prosthesis which may someday provide useful artificial vision to patients blinded by diseases like retinitis pigmentosa. The prosthesis will function by electrically stimulating healthy inner retinal neurons through a micro-electrode array residing on the retina’s exposed surface. The design of such a prosthesis entails many lines of inquiry, including selection of electric stimulation parameters, selection of biocompatible device materials, development of surgical methods for implantation and fixation of the device, electronic design of intra- and extra-ocular components, and design of schemes for transmission of power and signal to the intra-ocular electronics. This thesis is concerned with selection of electric stimulation parameters for the prosthesis.

This work takes an experimental look at the problem of how to raise thresholds for stimulating axons. The experiments were motivated by reports that the excitability of elongated structures, such as axons or muscle cells, depended strongly on the orientation of the imposed electric field relative to the long axis of the structure. Thresholds were low with the stimulating field oriented along a structure and were high with the field oriented across the structure. Analytical models employing infinite parallel plate stimulating electrodes and linear passive fibers predict transmembrane potential changes in accordance with this trend. In the steady state, longitudinal fields produce larger depolarizations than transverse fields provided that the plate separation is larger than a fiber diameter. These trends led my research group to hypothesize that axon thresholds could be raised with electrodes that minimize the longitudinal component of the stimulating field.

Models

Activating function

A number of simplifying assumptions are made to model threshold variations with electrode position and orientation. The first is that axons satisfy the assumptions of the core conductor model. This general model underlies the cable and Hodgkin-Huxley models, but makes no assumptions regarding the electrical properties of the membrane. We will make use of the following core conductor equations,

$$\partial I_i(z, t)/\partial z = -K_m(z, t),$$

$$\partial V_i(z, t)/\partial z = -r_i I_i(z, t),$$

$$V_m(z, t) = V_i(z, t) - V_o(z, t),$$

where z measures distance along the fiber, t is time, I_i is the axial current flowing in the fiber, K_m is the membrane current per unit length, V_i is the intracellular potential, r_i is the intracellular resistance per unit length, V_m is the membrane potential, and V_o is the potential on the outer surface of the membrane. These equations can be manipulated to yield

$$-\partial^2 V_m(z, t)/\partial z^2 + r_i K_m(z, t) = \partial^2 V_o(z, t)/\partial z^2 \tag{2.1}$$

which relates the membrane potential and current to the extracellular potential. The relation shows that the effective drive term for the membrane current and potential is the second spatial derivative of the extracellular potential in the longitudinal direction,

$$f_a = \partial^2 V_o(z, t)/\partial z^2 \, .$$

This "activating function" f_a provides a useful tool for predicting fiber responses under a variety of stimulation conditions. From equation 2.1, a positive activating function results in either an outward membrane current, a concavedownward membrane potential versus position, or both. The net result is to locally raise or depolarize the membrane potential. By a similar argument, a negative activating function tends to hyperpolarize the membrane. Thus the activating function may be taken as a rough picture of the membrane potential changes induced in a fiber by an extracellular stimulus. Activating functions for stimuli used here may be derived if the following additional assumptions are made: 1) the tissue may be modeled as a uniform, linear conductor; 2) the presence of the fiber may be ignored when calculating the potential distribution during stimulation; 3) the planar, ten micron diameter electrodes may be modeled as point sources.

To calculate the activating function for a point source, we begin by finding the voltage it generates along a fiber. Consider a fiber oriented in the z-direction and a point source in the $z = 0$ plane. The potential at points along the fiber is given by

$$Vo = i(z^2 + D^2)^{-1/2}/4\pi\sigma,$$

where i is the stimulating current, σ is the conductivity of the medium, D is the minimum distance between the point source and fiber. Carrying out the derivatives yields the activating function,

$$f_a = i(z^2 + D^2)^{-5/2}(2z^2 - D^2)/4\pi\sigma.$$

Cathodal stimuli ($i < 0$) located at $D = 1$, 1.5 and 3 indicates that the activating function is maximal, or most strongly depolarizing, at the point along the fiber which is closest to the cathode ($z = 0$). The maximal value decreases with increasing distance between electrode and fiber.

Thresholds for monopolar stimulation

These observations suggest a simple way to model the threshold increase accompanying electrode movement away from the fiber. Consider the activating function's maximum, at $z = 0$, for a threshold stimulus $i = -I_{thr}$ with the point source at a specific distance Do,

$$f_a|_{\mathrm{max,thr}} = I_{thr}(Do)\, D_o^{-3}/4\pi\sigma.$$

Now, if it can be assumed that the threshold value of f_a is independent of distance, we have

$$I_{thr}(D) = kD^3, \tag{2.2}$$

where

$$k = (4\pi\sigma)\, f_a|_{\max,\text{thr}}\,.$$

Equation 3.2 predicts the shape of the threshold versus position curve for a monopolar point source electrode. This equation can be viewed as the product of two factors,
one describing spatial properties of the stimulus (D^3) and one containing information
about the tissue and fiber (k).

Bipolar thresholds: along orientation

The approach which yielded equation 3.2 is readily applied to the bipolar stimulation case. For simplicity we will assume that the fibers are oriented exactly parallel or perpendicular to the bipolar electrode pair.

The case when a bipolar electrode pair is oriented along a fiber is when the cathode c is located at $z = 0$ and the anode a is located at $z = d$. The fiber is at a lateral displacement x_o from the electrodes and at a height h. The activating function for the bipolar pair is

$$f_a = |i|\{\, [x_o^2 + h^2 + (z - d)^2]^{-5/2}[2(z - d)^2 - x_o^2 - h^2] - (x_o^2 + h^2 + z^2)^{-5/2}(2z^2 - x_o^2 - h^2)\, \}/4\pi\sigma$$

To a good approximation, the maximum value aligns with the cathode at $z = 0$, as before. Hence the threshold is given approximately by

$$I_{thr} = k/[(x_o^2 + h^2 + d^2)^{-5/2}(2d^2 - x_o^2 - h^2) + (x_o^2 + h^2)^{-3/2}\,]. \tag{2.3}$$

Bipolar thresholds: across orientation

The case when a bipolar electrode is oriented across the fiber.

Both anode and cathode are located at $z = 0$. The fiber is at a height h above the point sources, and is laterally situated between cathode and anode. The lateral distance to the cathode is x_o, and the lateral distance to the anode is $d - x_o$. The activating function for the bipolar pair is

$$f_a = |i|\{\, [(d - x_o)^2 + h^2 + z^2]^{-5/2}\, [2z^2 - (d - x_o)^2 - h^2] - (x_o^2 + h^2 + z^2)^{-5/2}(2z^2 - x_o^2 - h^2)\, \}/\, 4\pi\sigma.$$

If we assume the cathode is closer to the fiber than the anode (consistent with the experiments described in the sections to follow) the maximum value aligns with the cathode at $z = 0$ and the threshold is given by

$$I_{thr}(x, h) = k/\{\, (x_o^2 + h^2)^{-3/2} - [(d - x_o)^2 + h^2]^{-3/2}\, \}. \tag{2.4}$$

Empirical model

In numerous experiments reported in the literature, the relationship between threshold and distance was well-described by

$$I_{thr} = \hat{k}D^2 + I_{min} \tag{2.5}$$

where I_{thr} is the excitation threshold, $\hat{k}$ is a constant having different units than k above, D is the distance between the electrode and target, and I_{min} is the minimum threshold. Note that I_{min} is effectively zero for the first principles model since the activating function for a point source becomes infinite at zero distance.

Extension of this model to the bipolar case is less straightforward than for the first principles model. One plausible approach is suggested by the fact that in an unbounded, uniform linear medium the electric field magnitude for a point source of current is

$$|\mathbf{E}| = |i| \,/\, 4\pi\sigma r^2$$

where $\mathbf{E}$ is the electric field and r is the distance from the source. If D is defined as the minimum distance between the point source and a fiber, the maximum electric field magnitude experienced by the fiber is

$$|\mathbf{E}|_{max} = |i| \,/\, 4\pi\sigma D^2$$

assuming that the field at the fiber is not modified by the presence of the fiber. Consider this maximum for a threshold stimulus $i = -I_{thr}$ with the point source at a specific distance D_o,

$$|\mathbf{E}|_{max,thr} = I_{thr} \,/\, 4\pi\sigma D_o^2.$$

If it can be assumed that the threshold value of $|\mathbf{E}|$ is independent of distance, then

$$I_{thr} = \hat{k} D^2 \tag{2.6}$$

where

$$\hat{k} = (4\pi\sigma)|\mathbf{E}|_{max,thr}.$$

This result is equivalent to equation 3.5 provided that I_{min} is zero.

Bipolar thresholds: along orientation

If the cathode is located at the origin, the normalized electric field components generated by the bipolar electrode pair at points ($x = x_o$, $y = h$, z) along the fiber are given by

$$\bar{E}_x = x_o \{(x_o^2 + h^2 + z^2)^{-3/2} - [x_o^2 + h^2 + (z-d)^2]^{-3/2}\},$$

$$\bar{E}_y = h \{(x_o^2 + h^2 + z^2)^{-3/2} - [x_o^2 + h^2 + (z-d)^2]^{-3/2}\},$$

$$\bar{E}_z = z\,(x_o^2 + h^2 + z^2)^{-3/2} - (z-d)\,[x_o^2 + h^2 + (z-d)^2]^{-3/2}$$

where normalization was accomplished by dividing each field component by $i/4\pi\sigma$.
The magnitude of the normalized field is computed from

$$|\bar{E}| = [\,(\bar{E}_x)^2 + (\bar{E}_y)^2 + (\bar{E}_z)^2\,]^{1/2}.$$

The maximum magnitude, which occurs at $z = 0$ (and also at $z = d$), can be readily calculated for specified x_o, h, and d. As in the monopolar case, the predicted threshold is proportional to the reciprocal of this maximum value,

$$I_{thr} = \hat{k} / |\bar{E}|_{max}(xo, h, d). \tag{2.7}$$

Bipolar thresholds: across orientation

If the cathode is located at the origin and the anode is located at ($x = d, y = 0, z = 0$), the normalized electric field components generated at points ($x = x_o, y = h, z$) along the fiber are given by

$$\bar{E}_x = \{x_o(x_o^2 + h^2 + z^2)^{-3/2} - (x_o - d)\,[(x_o - d)^2 + h^2 + z^2]^{-3/2}\},$$

$$\bar{E}_y = h\,\{(x_o^2 + h^2 + z^2)^{-3/2} - [(x_o - d)^2 + h^2 + z^2]^{-3/2}\},$$

$$\bar{E}_z = z\,\{(x_o^2 + h^2 + z^2)^{-3/2} - [(x_o - d)^2 + h^2 + z^2]^{-3/2}\}.$$

The maximum magnitude, which occurs at $z = 0$, can be readily calculated for specified xo, h, and d. The predicted threshold is proportional to the reciprocal of this maximum value.

2.2 Radio-frequency and Microwave Energy for Stored-grain Insect Control

Fundamental principles of radio-frequency and microwave heating are presented, with a basic consideration of differential or selective absorption of energy from RF and microwave fields that might be applicable for stored-grain insect control.

In considering the interaction of electromagnetic energy with matter, the dielectric permittivities or dielectric properties of the materials involved are of utmost importance. The permittivity of the material can be expressed as a complex quantity, *the real part of which is associated with the capability of the material for storing energy in the electric field in the material, and the imaginary parties associated with the dissipation of electric energy in the material by conversion of electric energy to heat.* This is the phenomenon commonly referred to as *dielectric heating*, or *microwave heating* if microwave frequencies are used. The complex permittivity, relative to free space, will be represented here as $\varepsilon^* = \varepsilon' - j\varepsilon''$, where ε' is called the dielectric constant, j denotes the complex operator, $\sqrt{-1}$, and ε'' is the dielectric loss factor. The loss tangent, $\tan\delta$, also often used as an index of energy dissipation or loss in a material exposed to RF or microwave electric fields, is defined as $\tan\delta = \varepsilon''/\varepsilon'$. The ac electrical conductivity associated with the dielectric loss in the material is $\sigma = \omega\varepsilon_0\varepsilon''$ siemens/m (S/m), where ω is the angular frequency, $2\pi f$, where f is the frequency of the applied electric field, and ε_0 is the permittivity of free space, 8.854×10^{-12} farads/m (F/m). Here, ε'' represents all losses including those due to dielectric relaxation and ionic condition.

Dielectric Heating

The power dissipated per a unit volume in a nonmagnetic, uniform material exposed to RF or microwave fields can be expressed as:

$$P = E^2\sigma = 55.63\times10^{-12}\ fE^2\varepsilon'' \tag{2.8}$$

where P – watts per cubic meter (W/m^3); *f* – hertz (Hz); E – rms electric field intensity in volts/m (V/m).

Power dissipated over a period of time provides energy to raise the temperature of the material, and this time rate of temperature increase (°C/s) is given by:

$$dT/dt = P/c\rho \tag{2.9}$$

Where *c* is the specific heat of the material in kJ/(kg·°C), and ρ is its density (kg/m^3). If water is evaporated in the heating process, the energy required for the vaporization and release of the water must also be taken into account, and the temperature rise of the material would be reduced accordingly.

At dielectric heating frequencies, between about 1 and 100 MHz, where materials are often exposed between conducting parallel-plate electrodes, the electric field intensity E between the electrodes is determined by the RF voltage across the electrodes, V, and their separation, d, as $E = V/d$, V/m. If two parallel layers of different material fill the space between the electrodes with surfaces parallel to the electrodes, the electric field intensity in one material, E_1, can be calculated as:

$$E_1 = \frac{V}{d_1 + d_2(\varepsilon_1^* / \varepsilon_2^*)} \tag{2.10}$$

where d_1 and d_2 are the thicknesses of the two material layers and ε_1^* *and* ε_2^* are the respective permittivities of the two materials. This equation is frequently useful when layers of material are treated with the air gap between the material and the top electrode, in which case $\varepsilon_2^* = 1$. Equations 1 and 2 can then be used to estimate the power absorption and heating rate.

Microwave Heating

When microwave radiation is directed at a material layer, the absorption of microwave energy propagating through the material also depends upon the variables of the equation 1, but the absorption of energy as the wave travels into the material must be taken into account. Thus, the dielectric loss factor of the material is important. The frequency of the wave is also a factor, and the power absorption also depends on the square of the electric field intensity. For the plane wave, the electric field intensity E, which has $e^{j\omega t}$ dependence, can be given as:

$$E(z) = E_0 e^{j\omega t - \gamma z} \tag{2.11}$$

where E_0 – rms electric field intensity at a point of reference; t – time; γ - propagation constant for the medium in which the wave is traveling; z – distance in the direction of travel.
The propagation constant is a complex quantity:

$$g = \alpha + j\beta = j\frac{2\pi}{\lambda_0}\sqrt{\varepsilon^*} \tag{2.12}$$

where α - attenuation constant; β - phase constant; λ_0 - free-space wavelength.

The attenuation constant α and the phase constant β are related to the dielectric properties of the medium as follows:

$$\alpha = \frac{2\pi}{\lambda_0}\sqrt{\frac{\varepsilon'}{2}(\sqrt{1+\tan^2\delta}-1)} \quad \text{, nepers/m} \tag{2.13}$$

$$\beta = \frac{2\pi}{\lambda_0}\sqrt{\frac{\varepsilon'}{2}(\sqrt{1+\tan^2\delta}+1)} \quad \text{, radians/m} \tag{2.14}$$

As the wave travels through a material that has a significant dielectric loss, its energy will be attenuated. For a plane wave traversing a dielectric material, the electric field intensity at the site of interest can be obtained by combining equations 4 and 5 as follows:

$$E(z) = E_0 e^{-\alpha z} e^{j(\omega t-\beta z)} \tag{2.15}$$

where the first exponential term controls the magnitude of the electric field intensity at the point of interest, and it should be noted that this magnitude decreases as the wave advances into the material. Since the power dissipated is proportional to E^2, $P \propto e^{-2\alpha z}$. The penetration depth, D_p, is defined as the distance at which the power drops to $e^{-1} = 1/2.718$ of its value at the surface of the material. Thus, $D_p = 1/(2\alpha)$. If attenuation is high in the material, the dielectric heating will taper off quickly as the wave penetrates the material. In terms of power densities and electric field intensity values, this can be expressed as:

$$10\log_{10}\left[\frac{P_0}{P(z)}\right] = 20\log_{10}\left[\frac{E_0}{E(z)}\right] = 8.686\alpha z \tag{2.16}$$

The attenuation in decibels, combining equations 6 and 9, can be expressed in terms of the dielectric properties, when $(\varepsilon'')^2 \langle\langle (\varepsilon')^2$, as follows:

$$\alpha \cong \frac{8.686\pi\varepsilon''}{\lambda_0\sqrt{\varepsilon'}}\, dB/m \tag{2.17}$$

A plane wave incident upon a material surface will have some of the power reflected, and the rest, P_t, will be transmitted into the material. The relationship is given by the expression:

$$P_t = P_0\left(1-|\Gamma|^2\right) \tag{2.18}$$

Where P_0 is the incident power and Γ is the reflection coefficient. For an air-material interface, the reflection coefficient can be expressed in terms of the complex relative permittivity of the material as:

$$\Gamma = \frac{1-\sqrt{\varepsilon *}}{1+\sqrt{\varepsilon *}} \tag{2.19}$$

The power density diminishes as an exponential function of the attenuation and distance traveled (eq.8) as the wave propagates through the material:

$$P = P_t e^{-2\alpha z} \tag{2.20}$$

with α expressed in nepers/m. For attenuation in decibels, dB/cm = 0.08686× (nepers/m).

Basic Differences

The term RF dielectric heating is generally understood to involve frequencies between about 1 and 100 MHz, and this field of applications was developed earlier than microwave heating. Commonly used frequencies have been about 13.5, 27, and 40 MHz, although other allocations exist. Microwave heating, which is also dielectric heating, evolved after World War II, as magnetrons and other microwave sources became available. Microwave heating generally involves frequencies above 500 MHz, and principle frequencies used for application have been 869, 915, and 2,450 MHz.

RF dielectric heating is often accomplished with the load between parallel electrodes although many other configurations are available. In this case, rapid heating is produced by using very high RF electrode voltages to achieve high field intensities in the material. The maximum field intensities are usually limited by dielectric breakdown and consequent damage to the product. For cereal grains such as wheat, field intensities of1.4 to 1.5 kV/cm were used with little arcing difficulty. With the parallel-plate geometry, the field intensity is quite uniform if the load is relatively homogeneous in character, and then equations 2.8, 2.9 and 2.10 are sufficient for general description.

With microwave heating, equations 2.8 and 2.9 still apply but attenuation and consequently penetration depth becomes important. Because frequency is much greater than for RF heating, rapid heating can be achieved with much lower field intensities (eq. 2.8), and the problems of arcing in the product are diminished. However, it becomes much more complicated to estimate electric field intensities because of attenuation and the need to irradiate materials from more than one direction to obtain required interior heating. Often, the product is moved through the microwave fields or rotated during exposure to achieve better uniformity of heating.

With RF dielectric heating, penetration is not so much the problem, but the dimensions of the material to be heated are limited by high-voltage RF insulation problems in producing desired high field intensities in the material. However, all material between the parallel plate electrodes will be subjected to high field intensities; whereas, the field intensity decreases with penetration in microwave heating.

Selective Heating

The selective heating of insects in relation to the grain they infest were possible, dielectric heating would offer an advantage over conventional heating for stored-grain insect control. Therefore, consider the variables in equations 2.8 and 2.9 with respect to the relative heating effects on insects and grain. The frequency for the two materials will be the same.

However, the dielectric loss factor for the insects and the grain may be different, and in that instance, the electric field intensities in the insects and the grain might also differ.

To examine the relative electric field intensities in the insect, E_i, and that of the host-grain medium, E_m, we can consider that *for a plane wave interacting with a spherical insect, infinite medium, the electric field in the insect is*:

$$E_i = E_m \left(\frac{3\varepsilon^*_m}{2\varepsilon^*_m + \varepsilon^*_i} \right) \tag{2.21}$$

where ε^*_i and ε^*_m represent the complex relative permittivities of the insect and the host medium respectively. If the necessary permittivity values are available, $(E_i/E_m)^2$ can be calculated, which gives us the ratio of the E-fields contribution to the power dissipation per unit volume in the insect relative to that in the host medium. The product of $(E_i/E_m)^2$ and the $\varepsilon''_i / \varepsilon''_m$ ratios gives the estimated power absorption ratio for the insect in relation to the host medium.

For selective dielectric heating of the insects, one must also consider the other two variables that, along with power absorbed, affect the heating rate in the two different materials (eq. 2.9). The specific heat and the density have an inverse influence since ***c*** and ρ appear in the denominator of the right-hand side of equation 2.9. Therefore, the reciprocal of the $c_i/c_m \times \rho_i / \rho_m$ value should be multiplied by the power absorption ratio above to determine the differential heating factor for the insects in relation to the host grain medium.

Experimental Findings

The findings of many early experiments in which insects were exposed to RF electric fields can be explained by considering the physical principles already outlined. *The heating rate* of the materials exposed to RF electric fields *increases with increasing field intensity and with increasing frequency*. Since the loss factor of hygroscopic materials such as grain generally increases with increasing moisture content, their heating rates also are higher when moisture content is greater.

Experiments have shown that many insect species that infest grain and cereal products can be controlled by short exposures to RF fields that do not damage the host material. Generally, for successful RF insect-control treatments, resulting temperatures in the host materials of this kind range between 40 and 90°C, depending upon the characteristics of the host material, the insect species, and the nature of the RF or microwave treatment. Radio-frequency treatments at 13.6 and 39 MHz necessary for insect control have not been damaging to wheat germination or milling and baking qualities. So far, however, RF and microwave methods have not come into practice, because they have been considered too costly compared to conventional chemical control methods.

Differences among various stored-grain insect species in their susceptibility to control by RF dielectric heating exposures have been noted when they were treated in common host grains under similar conditions. Some differences are attributive to interspecific characteristics of a biological or physiological nature, but some can be explained by variations in size and in geometric relationships. In general, the adult stages were more susceptible to control by RF treatment than the immature stages. Physical factors such as size and geometric relationships may well account for the difference noted in susceptibility to RF treatments.

Physical Factors

The influences of various physical factors on the control of stored-grain insects by exposures to RF and microwave energy have been studied. The importance of some of these factors, such as frequency, electric field intensity, and permittivity of the materials involved, is evident from considering the consequences of equations 2.8 through 2.20. Others include heating rate, modulation of the applied energy, and other characteristics of the insects and the host media. High-heating rates are to be preferred, generally, to minimize thermal energy loss from the insects to the host material. Therefore, *high power dissipation rates are desired, and power dissipation depends on frequency, electric field intensity and the dielectric loss factor of the material* (eq.2.8). The possibilities for the selective heating of the insects, as discussed earlier in connection with equation 2.20, are important here. Thomas concluded that selective heating of insects in grain should be possible with high-frequency dielectric heating. As already mentioned, immature forms of the rice weevil, granary weevil, and lesser grain borer, which all develop inside the grain kernels, are less susceptible to control than the adults which are outside the kernel. Experiments with rice weevil adults and with adults of the lesser grain borer, treated inside and outside wheat kernels, indicated that insects treated outside the kernels suffered somewhat higher mortalities than insects of the same age that were exposed while inside the kernels. In treating adult rice weevils at 2.45GHz in wheat ranging from 12.3 to 16.0% moisture observed no significant differences in insect mortality attributable to wheat moisture level.

Experiments conducted over the past 60 years have shown that exposures of grain infested by stored-grain insects to radio-frequency and microwave energy can control the insect infestations by dielectric heating of the insects and the grain. Differences have been noted in the susceptibility to control by RF and microwave treatments among different stored-grain insect species and among the developmental stages of those species, depending also on the ages of the insects and on the characteristics of the host medium. In general the immature stages of the insect are less susceptible to control by dielectric heating than the adults of the species, however, there are exceptions.

Experimentally, RF treatments at frequencies between 10 and 90 MHz have achieved control of the insects treated in grain and grain products by exposures that raised grain temperatures to about 60 to 65°C. Microwave treatments at 2,450 MHz have required exposures that raised temperatures of the host medium to much higher temperatures, often 80 to 90°C for complete control. Measurements of the RF and microwave dielectric properties of insects and grain, and consideration of the theoretical basis for differential dielectric heating of the insects and grain, and consideration of the theoretical basis for differential dielectric heating of the insects and grain show that the range from 10 to 100 MHz should be expected to provide selective heating of the insects; whereas, little differential heating can be expected at microwave frequencies. Thus the theoretical predictions explain the experimental findings with respect to host medium temperatures resulting from treatments that produce complete control.

Costs of electric energy and RF and microwave equipment of sufficient power capability to treat grain at practical rates are much too high to justify dielectric heating as a practical means of stored-grain insect control, based on demonstrated performance. Currently, there appears to be no convincing evidence of nonthermal biological effects that can be utilized for stored-grain insect control applications of RF and microwave electromagnetic energy. Without new discoveries of lethal mechanisms of a nonthermal nature, it is highly unlikely that RF and microwave treatments can be considered as a practical alternative for other stored-grain insect control methods currently in use.

2.3 Basic Principles of Electromagnetic RF and Microwave Field Interaction with a Dielectric Material

For understanding the granular agricultural product and insects interactions with electromagnetic fields it is important to investigate its radio-frequency and microwave dielectric properties. Dielectric properties are the electrical characteristics of materials that are classed as poor conductors of electricity, or dielectrics. The dielectric properties of usual interest are the dielectric constant ε' and the dielectric loss factor ε'', the real and imaginary parts, respectively, of the relative complex permittivity,

$\varepsilon = \varepsilon' - j\varepsilon'' = |\varepsilon| \cdot e^{-j\delta}$,

where $j = \sqrt{-1}$ is the imaginary unit customarily used with complex numbers, and δ is the loss angle of the dielectric. Hereafter, “permittivity” is understood to represent the relative complex permittivity, i.e., the permittivity of the material relative to free space, or vacuum. Often, the loss tangent, $tg\delta = \varepsilon'' / \varepsilon'$, or dissipation factor, is used also as a descriptive dielectric parameter. For those more familiar with conductivity as an electrical parameter, the ac conductivity of the dielectric in S/m is $\sigma = \omega\varepsilon_0\varepsilon''$, where $\omega = 2\pi f$ is the angular frequency, with frequency f in Hz. Here, ε'' is interpreted to include the energy losses in the dielectric due to all operating dielectric relaxation mechanisms and ionic conduction. The dielectric constant is associated with electric energy storage capability through polarization of the dielectric material, whereas the loss factor is associated with electric field energy dissipation in the material in the form of heat. These properties are important in dielectric and microwave heating applications, where the power dissipated per unit volume, ***P***, is absorbed from the alternating electric field and converted into heat in the material and is given as

$$P = E^2\sigma = kfE^2\varepsilon^{"} \tag{2.22}$$

where E is the electric field intensity in the material and k is a constant that depends on the units used for the calculation. The dielectric constant $\varepsilon^{'}$ of the material influences the electric field intensity E in the material. *The dielectric properties are also important in determining the reflection of electromagnetic waves by materials, as in radar applications.* Equation 15 is basic in considering the selective heating of insects with respect to their host medium by radio-frequency or microwave dielectric heating. Such techniques have often been considered for possible insect control methods. If the insects can be heated to lethal temperatures without adversely affecting the host medium because of differential heating rates, dielectric heating can offer an advantageous treatment. In examining equation 15, it is clear that there are three factors affecting the absorption of power from the high-frequency electric fields. For an insect and host system, the frequency is the same for both the insect and its host. Thus, if the insect has a much higher dielectric loss factor than the host material, it tends to heat more rapidly. However, a higher dielectric constant for the insect than that of its host material tends to reduce the electric field intensity in the insect. In addition, differences in the specific heat, c, and the specific gravity or density, ρ, must be taken into account in calculating the heating rates, because the time rate of temperature increase is given by

$$\frac{dT}{dt} = \frac{P}{c\rho} \tag{2.23}$$

where T represents temperature and t represents time. Studies, considering all of these factors for rice weevils in wheat, have shown that selective heating of the insects can be expected, *that the loss factor is the dominant factor, and that the best frequencies for selectively heating the insects are in the range from about 10 to 100 MHz* .

The dielectric properties of materials, although dependent upon the chemical and physical makeup of the material, depend also upon the frequency of the applied electric field and the temperature of the material. *If it is hygroscopic material, these dielectric properties also depend highly upon the amount of water in the material and upon the chemical binding of the water that is present. Molecules with significant dipole moments orient with applied electric fields and contribute to the polarization of the material that influences the magnitude of the dielectric constant. Once such molecules are polarized and the electric field is removed or altered, there is a finite time associated with the reorientation of these molecules. Thus, the dielectric relaxation characteristics of materials also influence the dielectric properties and their frequency dependence, because there is a time period associated with the frequency of the electromagnetic waves. In general, the dielectric constant of materials remains constant or decreases with increasing frequency!*

The dielectric loss factor, however, may increase or decrease with increasing frequency, depending on the dielectric relaxation characteristics of the material.

The temperature dependence of the dielectric properties of materials is rather complex in that the dielectric relaxation mechanisms can have a major influence. Outside a region of dispersion, where any dielectric relaxation is not of significant consequence, the dielectric constant tends to decrease with increasing temperature, but because the relaxations are not well documented for most substances, measurements of the dielectric properties are usually necessary to characterize their behavior with respect to frequency, temperature and other parameters.

Finally, we can note that the dielectric properties of insects are important in explaining the interaction of insects with electromagnetic fields and are of interest in considering radar tracking of insects or radio-frequency and microwave dielectric heating for treating infested products for control purposes.

The bulk density of grain crops is an important factor, second only to moisture content, affecting the dielectric properties of grain at a given frequency. It has been shown that certain functions of the dielectric properties of particulate materials are essentially linear functions of the bulk density of the air-particle mixtures. Those linear relationships are useful for predicting the dielectric constants of such granular material at any density from measurements on the materials at any known bulk density. Although the accuracy of predictions decreased as particle size increased, the relationships were still useful with particle sizes as large as those of wheat kernels.

Knowledge of the dielectric properties both grain crops and insects permits to create modeling of its interaction with electromagnetic field.

2.4 Some Experimental Data

Investigations of high-frequency and microwave action on insects and microorganisms have been carried out for the last 50 years in different countries [1-12]. Several theoretical conditions were suggested for the action of electromagnetic HF radiation on biological organisms [7, 14]. The nature of work was mainly experimental because the problem was physically complicated.

The first known reported measurements of insect dielectric properties were for bulk samples (insect and air space) of rice weevil and confused flour beetle adult insects at 40 MHz {18}. Measurements with the same system used for measuring dielectric properties of grain {19} ,at T=297K, provided values of 6.6 and 7.8 for the dielectric constant of the rice weevils and confused flour beetles, respectively. The loss factor for these bulk samples of both species was 2.2 at 40 MHz. Similar measurements were reported for rice weevils, at frequencies from 1 to 50 MHz (20). For these bulk samples, which consisted of CO_2-anesthetized insects and the air and CO_2-surrounding the insects, the dielectric constant ranged from 11.5 to 6.0 as the frequency increased from 1 MHz to 50 MHz. The loss factor varied irregularly from 1.8 to 2.4. For selectively heating insects in wheat Nelson (21) realized the measurements at 297 K over a wide frequency range, 250Hz to 12.2 GHz, at known bulk densities and insect moisture contents. Results clearly identified the frequency range in which selective dielectric heating of the insects might be expected (22). This was later confirmed experimentally with treatment of infested grain at 39 and 2450 MHz (22). The dielectric constant of the bulk rice weevils, at 0.49 g/cm^3 density, varied from 15 at 250 Hz to 4 at 12 GHz. The loss factor had a value of 0.4 at 100 kHz and at frequencies of 1 GHz and higher, with a prominent peak above 2.0 between 5 and 100 MHz.

In Ref.(23) reported some measurements on the confused flour beetle, at 10 GHz, giving a dielectric constant of 14.3 to 18.4 and a loss factor of 2.1 to 4.0 for bulk samples of adult insects. Similar measurements on larvae of the same species were reported as giving 2.8 for the dielectric constant and 0.46 for the loss factor (23), which seems too much different from the values reported for the adult insects at the same frequency.

Permittivities of bulk adult rice weevil samples were measured at various degrees of compression and resultant bulk densities, and the permittivity data were extrapolated to obtain values at the density of the insect body as determined by air-comparison pycnometer measurements (24). These studies yielded a value of 35.9-j11.4 for the permittivity of the insect body at 10.2 GHz. The moisture content of the adult insects was determined by oven drying at 378 K for 16 h as 49%, based on the weight of the live insects. Permittivity measurement at 9.0 GHz at 294K by the same short-circuited waveguide technique on diced and slurried pupae of the yellow mealworm, *Tenebrio molitor* L., where reported by Lindauer (25) as 30-j18.

In another series of measurements at 9.4 GHz on bulk samples of rice weevil adults, 2 to 3 weeks after emergence from wheat kernels, at 10 different bulk densities between 0.5 and 0.9 g/cm^3, the data for the dielectric constant and loss factor, plotted against bulk density, were fitted with second-order polynomial curves. These curves were than extrapolated to the density of the insect body, determined by air-comparison pycnometer measurements, to estimate the dielectric properties of the insects without any surrounding air space (26). The resulting permittivity estimated for the body of the adult rice weevil in these studies was 31.5-j12.7 at 9.4 GHz at 297K.

Permittivities of adult rice weevils, 3 to 5 weeks old, were determined over the frequency range from 200 MHz to 20 GHz at temperatures from 288K to 338K with an open-ended 3-mm diameter coaxial-line probe, network analyzer and a temperature-controlled sample holder (27). The permittivity of the insect body was then determined for measurements across the whole frequency range by complex computations based on the Landau and Lifshitz, Looyenda dielectric mixture equation and the known density of the insect body (27). Permittivities at 288K ranged from 41-j23 at 200 MHz to 16-j14 at 20 GHz. Those at 338K ranged from 60-j52 at 200 MHz to 32-j16 at 20 GHz.

A similar series of measurements was performed, with some modification in procedures, to determine the dielectric properties of adults of known ages of tour stored-grain insect species, rice weevil, red flour beetle, *Tribolium castaneum* (Herbst.), sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.) and lesser grain borer, *Rhyzopertha dominica* (F.) (28)1998. The same frequency range, 200 MHz to 20 GHz, and a wider temperature range, 283K to 343K, were covered in these measurements. In efforts to reduce the no homogeneity of the insect samples, they were ground into a paste with a mortar and pestle just prior to the beginning of the measurement sequence, thus permitting the open-ended coaxial probe measurement to be taken at higher sample bulk densities. Air-comparison pycometer measurements were taken for insect body density determination o0n live, CO_2-anesthetized insects of each of the four species, and moisture content determinations were made by oven drying in a forced-air oven at 378K for 16h. Dielectric properties measurements on anesthetized samples from the same insect cultures were taken at room temperature by the short-circuited waveguide technique at 11.7 GHz over about 14 different densities to establish the required relationship between dielectric constant and bulk density at which the open-ended probe measurements were taken. Permittivity values for the bodies of the insects were again estimated for the 200 MHz to 20 GHz frequency range by computation with the Landau&Lifshitz, Looyenga equation and were presented in Ref. 29.

For a two-component mixture, such as air and insects as particles, this equation can be expressed as follows:

$$(\varepsilon)^{\frac{1}{3}} = \nu_1(\varepsilon_1)^{\frac{1}{3}} + \nu_2(\varepsilon_2)^{\frac{1}{3}}, \qquad (2.24)$$

where ε represents the complex permittivity of the mixture components, air and insects, $\varepsilon = \varepsilon' + j\varepsilon''$,already defined, and ε_1 and ε_2 are the complex permittivities of the two mixture components, air and insects. The volume fraction of the mixture occupied by each component is represented, respectively, by ν_1 and ν_2.

Solving equation above for the complex permittivity of the solid material and substituting $1 - j0$ for ε_1, permittivity of air, the permittivity of the solid material (insects) can be calculated as

$$\varepsilon_2 = \left[\frac{\varepsilon^{\frac{1}{3}} + \nu_2 - 1}{\nu_2}\right]^3 \qquad (2.25)$$

Dielectric properties of the bodies of live adults of the rice weevil and the confused flour beetle were calculated from the bulk sample dielectric properties is given in Ref.30.

Large differences are noted in the fat and muscle tissue of yellow mealworn larvae reported in Ref.31, and differences in other tissues also were noted in their measurements. No satisfactory explanation has been found for the differences between the rice weevil data calculated from bulk insect measurements (Ref.8) and those determined from averages of seven open-ended coaxial-line measurements on the same species Ref.27. Smaller differences were noted also between data for the rice weevil obtained by open ended coaxial-line measurements on compressed live insects (ref.27) and similar measurements on samples ground by mortar and pestle just prior to measurements (Ref.28). *For this reason the necessity of additional methods for measuring dielectric properties of both insects and grain arouse for comparison of obtained data with published work results.*

2.5 Density dependence of the dielectric properties of wheat and whole-wheat flour

An equation is provided for calculating the dielectric constant of pulverized or granular materials at any density if the dielectric constant is known at any given density.

The bulk density of grain is an important factor, second only to moisture content, affecting the dielectric properties of grain at a given frequency. It has been shown recently that certain functions of the dielectric properties of particulate materials are essentially linear functions of the bulk density of the air-particle mixtures. Those linear relationships are useful for predicting the dielectric constants of such pulverized or granular materials at any density from measurements on the materials at any known bulk density. Although the accuracy of predictions decreased as particle size increased, the relationships were still useful with particle sizes as large as those of wheat kernels.

The linear relationships were identified as follows:

$$(\varepsilon'_r)^{1/2} = m_1\rho + 1 \tag{2.26}$$

$$(\varepsilon''_r + e)^{1/2} = m_2\rho + (e)^{1/2} \tag{2.27}$$

$$(\varepsilon'_r)^{1/3} = m_3\rho + 1 \tag{2.28}$$

where ε'_r and ε''_r are the dielectric constant and the loss factor, the real and the imaginary parts, respectively, of the complex dielectric permittivity $\varepsilon_r = \varepsilon'_r - j\,\varepsilon''_r$, ρ is the bulk density of the air-particle mixture, m_1, m_2, and m_3 are constants defining the slopes of the straight lines, and e is a constant that depends upon the nature of the particulate material. Equations 2.26 and 2.27 are consistent with the quadratic behavior, with respect to density

$$\varepsilon'_r = a\rho^2 + b\rho + 1 \tag{2.29}$$

$$\varepsilon''_r = c\rho^2 + d\rho \tag{2.30}$$

where a,b,c and d are constants, and $a= m_1^2$, $b=2m_1$, $c=m_2^2$, $d=2m_2(e)^{1/2}$. Equations 2.26 and 2.29 are also consistent with the mixture formula reported by Kraszewski for calculating the dielectric constant of a two-phase mixture from the dielectric constants and volume fractions of the constituents. Equation 2.28 is consistent with the Landau and Lifshitz or Looyenda mixture formula which specifies the additivity of the cube roots of the dielectric constants of the constituents of a mixture when taken in proportion to their volume fractions.

Equation 2.28 provided more accurate estimates than did equation 2.26 for dielectric constants of pulverized coal, whole-wheat, and whole-kernel wheat measured across a wide range of densities; however, the quadratic relationships of equations 2.26 and 2.27 provided results sufficiently accurate for most practical purposes for both ε'_r and ε''_r. Equation 2.28 can be used to predict quite accurately the dielectric constant of a pulverized or granular material at any desired density if the dielectric constant is known at any given density. It follows directly from the equation 2.28 that the dielectric constant, ε'_{r2} , of a material at density ρ_2, can be calculated with the equation:

$$\varepsilon'_{r2} = [((\varepsilon'_{r1})^{1/3} - 1)\rho_2/\rho_1 + 1]^3 \qquad (2.31)$$

where ε'_{r1} is the known dielectric constant of the material at density ρ_1.

2.6 Basic Electrodynamics Equations

The methods based on integral equations of macroscopic electrodynamics is used to avoid complications at consideration of proper boundary problems. The equations, which define a state of the body put into external electromagnetic field, are known as the constitutive equations. In a substance electromagnetic field is described by four vectors $H(\vec r), E(\vec r), B(\vec r), D(\vec r)$. For majority of substances the constitutive equation may be expressed by the generalized Ohm's law

$$\vec j(\vec r) = \sigma\vec E(\vec r) + \frac{\chi}{\mu} rot\vec B(\vec r), \qquad (2.32)$$

where $\vec E(\vec r)$ is the electric field intensity vector, $\vec B(\vec r)$ is the medium magnetic induction vector, σ is the medium conductance, χ is the medium magnetic susceptibility, μ is the medium magnetic permeability, $\vec j(\vec r)$ is the electric current density induced with the external electric field $\vec E_0, \vec H_0$ in a medium.

The Maxwell equations for any medium are the following:

$$\begin{aligned}
rot\vec E &= -\frac{\partial \vec B}{\partial t} & \qquad \oint_l \vec E\cdot d\vec l &= -\frac{\partial}{\partial t}\int_S \vec B\cdot d\vec S \\
rot\vec H &= \frac{\partial \vec D}{\partial t} + \vec j & \qquad \oint_l \vec H\cdot d\vec l &= \int_S \vec j d\vec S + \frac{\partial}{\partial t}\int_S \vec D\cdot d\vec S \\
div\vec D &= \rho & \qquad \oint_S \vec D\cdot d\vec S &= \int_w \rho\, dw \\
div\vec B &= 0 & \qquad \oint_S \vec B\cdot d\vec S &= 0
\end{aligned} \qquad (2.33)$$

which are always completed with the constitutive equations

$$\begin{aligned}
\vec D &= \varepsilon_0\varepsilon\vec E \\
\vec B &= \mu_0\mu\vec H
\end{aligned} \qquad (2.34)$$

The boundary conditions for four principle electromagnetic field vectors $H(\vec r), E(\vec r), B(\vec r), D(\vec r)$ for their normal and tangential components are expressed as follows:

$$B_{2n} = B_{1n} \qquad \frac{B_{2\tau}}{B_{1\tau}} = \frac{\mu_2}{\mu_1}$$

$$D_{2n} - D_{1n} = \sigma_{\sup} \qquad \frac{D_{2\tau}}{D_{1\tau}} = \frac{\varepsilon_2}{\varepsilon_1}$$

$$\varepsilon_2 E_{2n} - \varepsilon_1 E_{1n} = \sigma_{\sup} \qquad E_{2\tau} = E_{1\tau} \tag{2.35}$$

$$\frac{H_{2n}}{H_{1n}} = \frac{\mu_1}{\mu_2} \qquad H_{2\tau} = H_{1\tau} \text{ in absence of the superficial currents } j_\sigma = 0$$

$$H_{2\tau} - H_{1\tau} = |\vec{i}| \text{ in presence of the superficial currents } j_\sigma \neq 0$$

If to introduce the electromagnetic field potentials $\vec{A}$ and φ, therefore

$$\vec{B} = rot\vec{A}$$

$$\vec{E} = -grad\varphi - \frac{\partial \vec{A}}{\partial t} \; . \tag{2.36}$$

While executing the Lorenz calibration

$$\frac{1}{V_f^2}\frac{\partial \varphi}{\partial t} + div\vec{A} = 0 \tag{2.37}$$

wave equations have the form:

$$\Delta\varphi - \frac{1}{V_f^2}\frac{\partial^2 \varphi}{\partial t^2} = -\frac{\rho}{\varepsilon_0 \varepsilon} \; ,$$

$$\Delta\vec{A} - \frac{1}{V_f^2}\frac{\partial^2 \vec{A}}{\partial t^2} = -\mu_0 \mu \vec{j} \; , \tag{2.38}$$

where $V_f = c/\sqrt{\varepsilon\mu}$ is the wave phase velocity.

Solution of wave equations with Fourier-components of electromagnetic field potentials are written in the form:

$$\vec{E}(\vec{r}) = \left(graddiv + k^2 \varepsilon\mu\right) \cdot \Pi(\vec{r}),$$

$$\vec{H}(\vec{r}) = \frac{jk}{w} rot\Pi(\vec{r}), \tag{2.39}$$

$$\Pi(\vec{r}) = \frac{1}{4\pi j \omega \varepsilon_0} \int \frac{\vec{j}(\vec{r})}{|\vec{r} - \vec{r}'|} e^{-jk|\vec{r} - \vec{r}'|} d\vec{r}$$

where $k = \omega\sqrt{\varepsilon_0 \; \mu_0}$ is a wave vector, $w = \sqrt{\mu_0 / \varepsilon_0}$ - wave resistance of free space.

More generally the electrical and magnetic induction vectors are determined by relations

$$\vec{D} = \vec{E} + 4\pi\vec{P} , \quad \vec{B} = \vec{H} + 4\pi\vec{M} ,$$

where vector $\vec{P}$ defines the electric polarization of a unit volume, and vector $\vec{M}$ defines its magnetic polarization. In a linear medium these dependences are: $\vec{D} = \varepsilon(\omega)\vec{E}$, $\vec{B} = \mu(\omega)\vec{H}$. For anisotropic bodies these dependences are tensor

$$\vec{D} = \varepsilon_{ik}\vec{E}\,, \quad \vec{B} = \mu_{ik}\vec{H}\,, \tag{2.40}$$

where ε_{ik} and μ_{ik} are dielectric and magnetic permittivity tensors.

Each neutral body is characterized by its geometry, volume, dielectric permittivity, magnetic permeability and conductivity in macroscopic electrodynamics. These parameters are sufficient to solve the general problem of electrodynamics. Suppose, the fields are given $E_0(r)$ and $H_0(\vec{r})$ in a free space. The neutral body of the prescribed geometry and electromagnetic characteristics ε and μ is put into the given electromagnetic field in a free space. What is the electric field intensity in the vicinity of the body? What is the electric field intensity within the body? Through answering these questions we solve the general problem of macroscopic electrodynamics.

Chapter III

Chapter III

Chapter III

3. Mathematical Model of Electromagnetic Field Interaction with a Dielectric Body of Ellipsoidal Shape

The objective of this investigation is to create a theoretical model and to conduct the detail research of the electromagnetic radiation interaction with granular product and insects. The models developed in the past concern granular product and as a bulk material, the two-componential mixture “air-grain”, penetrated by the external electromagnetic field. The new model presented here is completely different by its methodological approach that permits more precise consideration and calculation of the main physics parameters such as the electric field intensity, energy loss, liberated heat, etc. In the following description the basic correlation is defined which characterizes an influence of electromagnetic radiation on a system of individual particles of ellipsoidal geometry dispersed into some volume (chaotic arrangement) of another medium. The field intensity inside one isolated particle is determined depending on the parameters of the external (relative to the volume) electromagnetic field. Energy loss in an isolated particle is calculated. The shielding effect of a field in an isolated particle by other surrounding particles is taken into account.

The theoretical research on the electromagnetic wave interaction with each individual dielectric particle is done in the present work through the solving of electromagnetic boundary problem [1]**.** It is well-known that boundary problems of electrodynamics are the most complicated ones in the mathematical physics and are urgent in the theory of wave processes. We use the methods based on integral equations of macroscopic electrodynamics to avoid complications at consideration of proper boundary problems.

3.1 Basic Electrodynamics Equations

The equations, which define a state of the body put into external electromagnetic field, are known as the constitutive equations. In a substance electromagnetic field is described by four vectors $H(\vec{r}), E(\vec{r}), B(\vec{r}), D(\vec{r})$. For majority of substances the constitutive equation may be expressed by the generalized Ohm’s law

$$\vec{j}(\vec{r}) = \sigma\vec{E}(\vec{r}) + \frac{\chi}{\mu} rot\vec{B}(\vec{r}), \tag{3.1}$$

where $\vec{E}(\vec{r})$ is the electric field intensity vector, $\vec{B}(\vec{r})$is the medium magnetic induction vector, σ is the medium conductance, χ is the medium magnetic susceptibility, μ is the medium magnetic permeability, $\vec{j}(\vec{r})$is the electric current density induced with the external electric field $\vec{E}_0, \vec{H}_0$ in a medium.

The Maxwell equations for any medium are the following:

$$rot\vec{E} = -\frac{\partial \vec{B}}{\partial t},$$

$$rot\vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{j}\,, \tag{3.2}$$

$$div\vec{D} = \rho\,,$$
$$div\vec{B} = 0\,,$$

which are always completed with the constitutive equations

$$\vec{D} = \varepsilon_0 \varepsilon \vec{E}$$
$$\vec{B} = \mu_0 \mu \vec{H} \tag{3.3}$$

If to introduce the electromagnetic field potentials $\vec{A}$ and φ, therefore

$$\vec{B} = rot\vec{A}$$
$$\vec{E} = -grad\varphi - \frac{\partial \vec{A}}{\partial t}\,. \tag{3.4}$$

While executing the Lorenz calibration

$$\frac{1}{V_f^2}\frac{\partial \varphi}{\partial t} + div\vec{A} = 0 \tag{3.5}$$

wave equations have the form:

$$\Delta\varphi - \frac{1}{V_f^2}\frac{\partial^2 \varphi}{\partial t^2} = -\frac{\rho}{\varepsilon_0 \varepsilon}\,,$$
$$\Delta\vec{A} - \frac{1}{V_f^2}\frac{\partial^2 \vec{A}}{\partial t^2} = -\mu_0 \mu \vec{j}\,, \tag{3.6}$$

where $V_f = c/\sqrt{\varepsilon\mu}$ is the wave phase velocity.

Solution of wave equations with Fourier-components of electromagnetic field potentials are written in the form:

$$\vec{E}(\vec{r}) = \left(graddiv + k^2 \varepsilon\mu\right)\cdot \Pi(\vec{r}),$$
$$\vec{H}(\vec{r}) = \frac{jk}{w} rot\Pi(\vec{r}), \tag{3.7}$$
$$\Pi(\vec{r}) = \frac{1}{4\pi j\omega\varepsilon_0}\int \frac{\vec{j}(\vec{r})}{|\vec{r} - \vec{r}\,'|} e^{-jk|\vec{r} - \vec{r}\,'|} d\vec{r}$$

where $k = \omega\sqrt{\varepsilon_0\ \mu_0}$ is a wave vector, $w = \sqrt{\mu_0/\varepsilon_0}$ - wave resistance of free space.

More generally the electrical and magnetic induction vectors are determined by relations

$$\vec{D} = \vec{E} + 4\pi\vec{P}\,, \quad \vec{B} = \vec{H} + 4\pi\vec{M}\,,$$

where vector $\vec{P}$ defines the electric polarization of a unit volume, and vector $\vec{M}$ defines its magnetic polarization. In a linear medium these dependences are: $\vec{D} = \varepsilon(\omega)\vec{E}$, $\vec{B} = \mu(\omega)\vec{H}$.
For anisotropic bodies these dependences are tensor

$$\vec{D} = \varepsilon_{ik}\vec{E}\,, \quad \vec{B} = \mu_{ik}\vec{H}\,, \tag{3.8}$$

where ε_{ik} and μ_{ik} are dielectric and magnetic permittivity tensors.

3.2 Electromagnetic wave interaction with small dielectric ellipsoid.

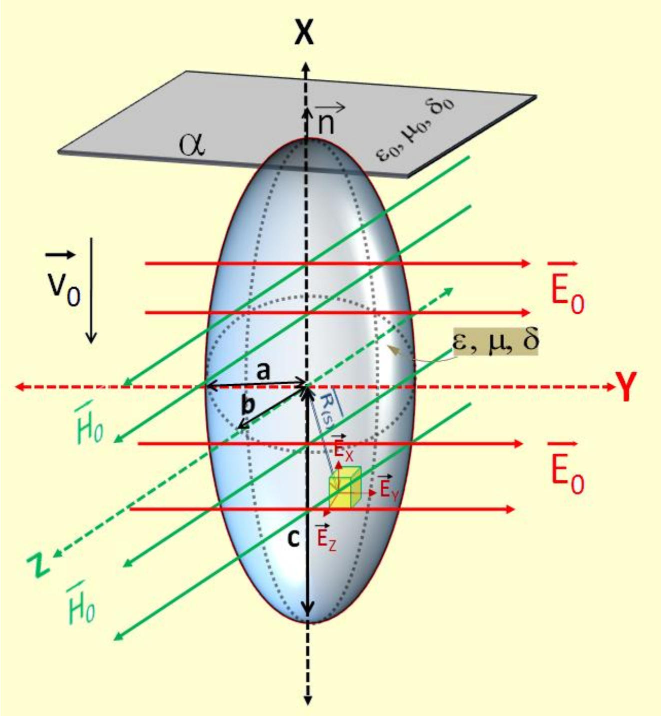


Fig. 3.1. Electromagnetic wave interaction with small homogeneous dielectric ellipsoid of rotation

An electromagnetic wave of field intensities $\vec{E}_0(r)$ and $\vec{H}_0(\vec{r})$ is incident on the dielectric ellipsoid of rotation of the volume V and the dielectric permittivity ε. We locate the ellipsoid into the origin of the Cartesian coordinate system (Fig. 3.1), so as its surface equation have the canonical form [3]

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \tag{3.9}$$

where a, b, c are the ellipsoid semi-axes. The ellipsoidal infinitesimal is prescribed with the condition $ka << 1$. To define the internal electric field it is needed to solve the integral equation

$$\vec{E}(\vec{r})=\vec{E}_0(\vec{r})+\frac{1}{4\pi}graddiv\int_V\frac{(\varepsilon-1)\vec{E}_0(\vec{r}\,')}{|\vec{r}-\vec{r}\,'|}d\vec{r}\,' \qquad (3.10)$$

Since the ellipsoid is small, the internal field of the incident wave must be considered constant at the distances comparable with the ellipsoid size. That is for $\vec{r}\in V$ the external wave field is constant $\vec{E}_0(\vec{r})=const$.

The equation (3.10) solution can be the Newton potential $W(\vec{r})$ [4] of the body of volume V with mass density $\mu(\vec{r})$, that is

$$W(\vec{r})=\int_V\frac{\mu(\vec{r})d\vec{r}}{|\vec{r}-\vec{r}\,'|}. \qquad (3.11)$$

For the case $\mu(\vec{r})=const$ and for the internal point of ellipsoid the Dirichlet formula takes place

$$W(\vec{r})=C-\pi abc\mu\left(J_1x^2+J_2y^2+J_3z^2\right), \qquad (3.12)$$

i.e. for internal points of homogeneous ellipsoid the volume potential is the uniform quadratic function of the Cartesian coordinates. For this case the integral equation (3.10) can be transformed into a system of simple linear algebraic equations of the following type

$$E_x=E_{ox}+\frac{1}{4\pi}\frac{\partial}{\partial x}\left\{(\varepsilon-1)E_x\frac{\partial W}{\partial x}+(\varepsilon-1)E_e\frac{\partial W}{\partial y}+(\varepsilon-1)E_z\frac{\partial W}{\partial z}\right\}\text{ etc.}$$

From this we can define the components of internal electric field

$$E_x=\frac{E_{0x}}{1+\frac{abc}{2}(\varepsilon-1)J_1},\quad E_y=\frac{E_{0y}}{1+\frac{abc}{2}(\varepsilon-1)J_2},\quad E_z=\frac{E_{0z}}{1+\frac{abc}{2}(\varepsilon-1)J_3} \qquad (3.13)$$

The values J_1,J_2,J_3 are called the factors of field depolarization and depend only on the ellipsoid semi-axes, i.e.

$$J_1=\int_0^\infty\frac{ds}{(a^2+s)\sqrt{R(s)}},\quad J_2=\int_0^\infty\frac{ds}{(b^2+s)\sqrt{R(s)}},\quad J_3=\int_0^\infty\frac{ds}{(c^2+s)\sqrt{R(s)}}, \qquad (3.14)$$

where $R(s)=(a^2+s)(b^2+s)(c^2+s)$. For different cases the given integrals are written through elliptic integrals $(a\neq b\neq c)$ or elementary functions.

3.3 Dependence between real and imaginary parts of the medium dielectric permittivity

A plane electromagnetic wave can be written in the form of Fourier-components of the field

$$e^{i(\omega t - k\vec{r})} \quad \text{or} \quad e^{-i(\omega t - k\vec{r})} \tag{3.15}$$

according to the dispersion equation $\vec{k} = \omega\sqrt{\varepsilon} = \omega\sqrt{|\varepsilon|}(\cos\delta \pm i\sin\delta)$, where $tg\delta = \varepsilon''/\varepsilon'$ (loss angle tangent), the plane wave can be written in the form

$$\begin{gathered} e^{i\left(\omega t - \omega\sqrt{|\varepsilon|}n\vec{r}\cos\delta\right)} e^{\omega\sqrt{|\varepsilon|}n\vec{r}\sin\delta}, \\ e^{i\left(\omega\sqrt{|\varepsilon|}nr\cos\delta - \omega t\right)} e^{\omega\sqrt{|\varepsilon|}n\vec{r}\sin\delta}. \end{gathered} \tag{3.16}$$

Thus, the wave behavior at $r \to \infty$ depends considerably on the value δ. Wave attenuation condition will be fulfilled if δ in the first case will be negative and in the second one it will be positive. Therefore the value $\varepsilon''(\omega) = -\varepsilon''(-\omega)$ is the frequency non-pair function. For the same reason $\varepsilon'(\omega) = \varepsilon'(-\omega)$ is the frequency pair function.

One can determine important dependences between real and imaginary parts of medium dielectric permittivity. Imagine, that $\varepsilon(\omega)$ is the analytical function of the complex variable ω in the upper half-plane $\operatorname{Im}\omega > 0$. If one can know $\varepsilon(\omega)$ on the contour Γ $\left(\omega = \mathrm{Re}^{i\varphi}\right)$, $R \to \infty$, value of this function in any point ω can be written as Cauchy integral

$$\varepsilon(\omega) = \frac{1}{2\pi i}\int_{\Gamma}\frac{\varepsilon(t)dt}{t-\omega} \tag{3.17}$$

The axis Γ is expanded onto two components: the axis of real values ω $(-\infty < \omega < +\infty)$ and the semicircle $0 \le \omega \le \pi$:

$$\varepsilon(\omega) = \frac{1}{\pi i}\int_{-\infty}^{+\infty}\frac{\varepsilon(t)dt}{t-\omega} + \frac{1}{\pi i}\lim_{R\to\infty}\int_{0}^{\pi}\frac{\varepsilon\left(\mathrm{Re}^{i\varphi}\right)\mathrm{Re}^{i\varphi}\,id\varphi}{\mathrm{Re}^{i\varphi}-\omega} \tag{3.18}$$

At $R \to \infty$ one can consider $\varepsilon(\omega)$ as some constant. Really, the dielectric permittivity is a substance macroscopic characteristic. It takes place, when intermolecular distances are small comparatively to the wavelength. If $\omega \to \infty$ and the wavelength is small in comparison with these distances, then $\varepsilon(\infty)$ can be considered a constant value. Therefore

$$\frac{1}{i\pi}\lim_{R\to\infty}\varepsilon(\infty)\int_{0}^{\pi}\frac{\mathrm{Re}^{i\varphi}\,id\varphi}{\mathrm{Re}^{i\varphi}-\omega} = \varepsilon(\infty) \tag{3.19}$$

Thus

$$\varepsilon(\omega)-\varepsilon(\infty)=\frac{1}{\pi i}\int_{\Gamma}\frac{\varepsilon(t)dt}{t-\omega} \tag{3.20}$$

Substituting this expression for dielectric permittivity in a form of a complex number

$$\varepsilon(\omega)=\varepsilon'(\omega)-i\varepsilon''(\omega) \tag{3.21}$$

and dividing the equation (3.20) into the real and imaginary parts, we obtain

$$\begin{gathered}\varepsilon(\omega)-\varepsilon(\infty)=\frac{1}{\pi}\int_{\Gamma}\frac{\varepsilon''(t)dt}{t-\omega}=\frac{2}{\pi}\int_{0}^{\infty}\frac{\varepsilon''(t)tdt}{t^2-\omega^2}\\ \varepsilon''(\omega)=\frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{\varepsilon'(t)dt}{t-\omega}=\frac{2}{\pi}\int_{0}^{\infty}\frac{\varepsilon'(t)\omega dt}{t^2-\omega^2}\end{gathered} \tag{3.22}$$

So the real and imaginary parts of the dielectric permittivity are the integrals of the same type.

The dielectric permittivity is related a substance conductivity. The substance conductivity can be represented as a complex value

$$\sigma=\sigma'-i\sigma'' \tag{3.23}$$

The value σ' is a real conductivity as far as the electric field intensity and the current density are the co-phase values. The value σ'' is the imaginary conductivity as far as the field vector and the current density vector are displaced in phase by $\pi/2$. Thus the dielectric permittivity can be represented as

$$\varepsilon(\omega)=1+\frac{\sigma}{i\omega}=\varepsilon'-i\varepsilon'' \tag{3.24}$$

where

$$\varepsilon'(\omega)=1+\frac{\sigma''}{\omega},\quad \varepsilon''(\omega)=\frac{\sigma'}{\omega} \tag{3.25}$$

The value $\varepsilon'(\omega)$ defines the wave phase velocity in a medium, and $\varepsilon''(\omega)$ defines the wave specific energy loss.

3.4 Basic Thermodynamics Equations

The quantity of energy W needed to heat a grain mass from the temperature T_1 to a finite temperature T_2 ($\Delta T=T_2-T_1$) may be transferred from the high-frequency field. These values are related in the equation

$$W = \rho V C_s \Delta T, \tag{3.26}$$

where ρ is the bulk density of the grain (kg/m^3),
C_s is the specific heat capacity ($kJ/kg \cdot K$),

$$C_s = L_0 C + (1 - L_0) C_0, \tag{3.27}$$

depending on moisture content L_0, where L_0 is the moisture content in percent, C is the specific heat capacity of water, C_c is the specific heat capacity of dry grain ($C_c = 1.32\, kJ/kg \cdot K$).

3.5 Model of wave interaction with a grain seed

From the standpoint of electrodynamics, each seed of grain is a material body of almost ellipsoidal shape[2] with definite macroscopic characteristics, which may be expressed as a complex dielectric permittivity

$$\varepsilon = \varepsilon' - i\varepsilon'' \tag{3.26}$$

(field dependence on time is assigned as $\exp(i\omega t)$). The grain mass is the sum of that of the individual seeds arranged one relative to another, so that an effective permittivity of the grain mass ε is defined by the equation of Clausius – Mosotti [1]:

$$\frac{\varepsilon - 1}{\varepsilon + 2} = C \frac{\varepsilon_0 - \varepsilon_1}{\varepsilon_0 + 2\varepsilon_1} \tag{3.27}$$

where C is the volumetric concentration, or volume fraction, of granular particles. As well known, the Clausius-Mosotti formula for quasistatic conditions is valid in the limiting case of particles very much smaller than the wavelength of the high frequency or microwaves. In practical cases it is valid for diameters of particles less than about 2% of the free-space wavelength .In the present work the dielectric permittivity of the grain is measured experimentally in the range 20-150 MHz. Energy losses in grain will be determined through dielectric properties of the individual seeds. They are related by equation (3.27).

The physical model of any individual seed of grain is a stretched ellipsoid of rotation with permittivity (3.26), the imaginary part of which defines the release of electromagnetic energy in the form of heat. If σ is the seed conductivity, then $\varepsilon'' = 4\pi\sigma/\omega$ and

$$\mathrm{tg}\,\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{4\pi\sigma}{\omega\varepsilon'} \tag{3.28}$$

The power released as heat in any individual seed is defined by the equation

$$W = \int_V \left[\vec{j}\vec{E}\right] dV \tag{3.29}$$

where $\vec{j} = \sigma\vec{E}$ is an electric current density in the seed, V is volume of the seed, σ is conductivity, which may be defined through $\operatorname{tg}\delta$ by equation (3.28).

The task leads to the definition of the field $\vec{E}$ inside the material body of ellipsoidal geometry in the approximation, when the wavelength considerably exceeds the linear dimensions of the ellipsoid. It is well-known that in this case [1] is presented as

$$\vec{E} = \begin{bmatrix} \dfrac{1}{1+\dfrac{a^2c}{2}(\varepsilon-1).l_1} & 0 & 0 \\ 0 & \dfrac{1}{1+\dfrac{a^2c}{2}(\varepsilon-1).l_2} & 0 \\ 0 & 0 & \dfrac{1}{1+\dfrac{a^2c}{2}(\varepsilon-1).l_3} \end{bmatrix} \cdot \begin{bmatrix} E_{ox} \\ E_{oy} \\ E_{oz} \end{bmatrix} \tag{3.30}$$

where

$$l_1 = l_2 = \frac{1}{\left(c^2-a^2\right)^{3/1}}\left(\frac{c}{a^2}\sqrt{c^2-a^2} - \ln\frac{c+\sqrt{c^2-a^2}}{a}\right),$$

$$l_3 = \frac{1}{\left(c^2-a^2\right)^{3/1}}\left(\ln\frac{c+\sqrt{c^2-a^2}}{a} - \frac{1}{c}\sqrt{c^2-a^2}\right) \tag{3.31}$$

are depolarization parameters of the ellipsoid with semi-axis a, a and c, E_{0x}, E_{0y} and E_{0z} are the values of external electric field intensity. For spherical particles $l_1 = l_2 = l_3 = \frac{2}{3}a^3$, where a is the radius, and therefore

$$\vec{E} = 3\vec{E}_0^2 \cdot (\varepsilon+2)^{-1} \tag{3.32}$$

If the deviation from the sphericity is not considerable, then

$$l_1 = l_2 = \frac{2}{3a^2\sqrt{1-e^2}}\left\{1 - \frac{2e^2}{5} + 0\left(e^4\right)\right\},$$

$$l_3 = \frac{2}{3a^2\sqrt{1-e^2}}\left\{1 - \frac{13}{5}e^2 + 0\left(e^4\right)\right\}, \tag{3.33}$$

where $e = \sqrt{1-(a/c)^2}$ is an eccentricity of the particle.
Finally one can define that

$$W = \sigma \cdot V \sum_{s=1}^{3} \frac{E_{0s}^2}{\left[1 + \frac{3V}{8\pi}\left(\frac{\varepsilon'}{\varepsilon_1} - 1\right) \cdot l_s\right]^2 + \left(\frac{3V\sigma}{2\omega} l_s\right)^2}$$

for a stretched ellipsoid of rotation, and

$$W = \frac{9V\varepsilon_1 E_{00}^2}{(\varepsilon + 2\varepsilon_1)^2 + (4\pi\sigma/\omega)^2} \tag{3.34}$$

for a sphere. Double reflection of electromagnetic field from individual particles of the granular body is taken into consideration through ε_1. Further the equations for spherical particles will be used, because, while ellipsoidal eccentricity varies over a rather wide range $0.1 \le \varepsilon \le 1.0$ the value of the released energy is the same as for spherical particles as follows.
It is convenient to transform W

$$W = W_1 \cdot W_2 - W_1 \cdot \frac{9}{4\pi} \omega V \cdot \mathrm{tg}\,\delta \cdot E_0^2 \ , \tag{3.35}$$

where W_1 is only a function of geometry of a dissipating body.
For the ellipsoid

$$W = \frac{1}{9} \sum_{s=1}^{3} \frac{\varepsilon_1 \left(E_{0s}/E_{0,on}\right)^2}{\left[1 + \frac{3V}{8\pi}\left(\frac{\varepsilon'}{\varepsilon_1} - 1\right).l_s\right]^2 + \left(\frac{3V\sigma}{2\omega}.l_s\right)^2}. \tag{3.36}$$

For the sphere (in the condition of $4\pi\sigma/\omega << (\varepsilon + 2\varepsilon_1)$)

$$W_1 = \frac{\varepsilon_1}{(\varepsilon + 2\varepsilon_1)^2} \tag{3.37}$$

One can evaluate the function W_2 by the formula:

$$W_2 = \frac{9}{4\pi} \omega_0 V_{0n} tg\delta \cdot E_{0,on}^2 \left(\frac{V}{V_{on}}\right)\left(\frac{E}{E_{0,on}}\right)^2 \left(\frac{\omega}{\omega_0}\right). \tag{3.38}$$

This is an operating formula, which may be used for calculations, where V, E and ω are in fixed units and are not connected with an available system of units.

An individual seed of grain is considered as a stretched ellipsoid of rotation with semi-axes $a = 0.15cm, c = 0.3cm, V = (0.025 - 0.028)cm^3$. This means that a granular density covers a range 0.5-0.85, i.e. $1\,cm^3$ contains about 30-35 seeds. The dielectric permittivity of grain at the frequency 150 MHz is established as $\varepsilon = 2$ and $tg\delta = 0.04$.

Evaluating the multiplier W_1 one can note that its magnitude does not depend upon the shape of the seed but on its dielectric permittivity. If $\varepsilon \approx 2.5$ and the spherical form of an individual seed is selected,

$$W_1 \approx 0.05 \tag{3.39}$$

and therefore the energy released in an individual seed per second at continuous operation of a generator will be:

$$W_2 = 0.35\left(\frac{V}{V_{on}}\right)\left(\frac{E}{E_{0,on}}\right)^2\left(\frac{\omega}{\omega_0}\right), J/s \tag{3.40}$$

In the case of pulsed operation of the high-frequency generator with pulse period to pulse duration ratio γ, the energy released in an individual seed will be defined by the equation:

$$W = \frac{0.35}{\gamma}\left(\frac{V}{V_{on}}\right)\left(\frac{E}{E_{0,on}}\right)^2\left(\frac{\omega}{\omega_0}\right), J/s \tag{3.41}$$

One can note that for heating of a seed to a temperature $T = T_0 + \Delta T$ (where T_0 is an initial temperature) the amount of heat required is

$$\Delta Q_1 = \rho \cdot V \cdot C_\rho \cdot \Delta T, kJ, \tag{3.42}$$

where C_P is specific heat capacity of grain.

Since both energy release in the region of grain W and the amount of heat necessary for its heating ΔQ have been proportional to seed volume, the value ΔT finally does not depend upon the volume of an individual seed and is defined by the equation:

$$\Delta T = \frac{0.35}{m_{0\rho}\gamma C_\rho}\left(\frac{E}{E_{=,on}}\right)^2\left(\frac{\omega}{\omega_{on}}\right), \tag{3.43}$$

where $m_{0\rho} = \rho \cdot V_{on}$ is the mass (kg) of an individual seed with a volume equal to the fixed one. To withdraw moisture of grain more energy expense is need for moisture evaporation Q_2. Therefore, total energy expense to withdraw moisture of grain is equal to

$$\Delta Q = \Delta Q_1 + \Delta Q_2, \tag{3.44}$$

where $\Delta Q_2 = \frac{m_{0\rho}}{100}(L_F - L_I)q_n$, $L_{F,I}$ are final and initial moisture content of grain in %, q_n is specific heat of evaporation (kJ/kg). Taking into consideration heat losses for evaporation, one can define a temperature increase

$$\Delta T = \left[\frac{0.35}{m_{0\rho}\cdot\gamma C_\rho}\left(\frac{E}{E_{=,on}}\right)^2\left(\frac{\omega}{\omega_{on}}\right) - \frac{L_F - L_I}{100}\left(\frac{q_n}{C_\rho}\right)\right]. \qquad (3.45)$$

From the standpoint of electromagnetic influence on pests, a beetle differs from grain by its size first of all, but also in its shape (discussed above as an ellipsoid). For the granary weevil, one can accept $a = 0.1cm, c = 0.175cm, V = 7.3\cdot 10^{-3}cm^3$. Beside that, the beetle differs from the grain in its electrophysical characteristics. According to measurements at 150 MHz one can use $\varepsilon \approx 5$ and $tg\delta \approx 0.3$ for the beetle dielectric properties. Therefore, using the same formulas as for grain, one can define as a result of direct calculations:

$$W_2 = 14.6\left(\frac{V}{V_{on}}\right)\left(\frac{E}{E_{on}}\right)^2\left(\frac{\omega}{\omega_{on}}\right), (j/s.) \qquad (3.46)$$

While impulse heating with pulse period-to-period duration ratio γ, energy release is decreases by a factor of γ. Than, $W_1 = 0.022$, therefore

$$W = \frac{0.32}{\gamma}\left(\frac{V}{V_{on}}\right)\left(\frac{E}{E_{0,on}}\right)^2\left(\frac{\omega}{\omega_{on}}\right) \qquad (3.47)$$

Comparing (3.47) and (3.41) one can see that assuming all the factors, energy release in a volume of an individual beetle is practically the same as in a volume of an individual seed. Therefore, the formula (3.41) can be applied to the beetles too. Under high-frequency radiation influence on the grain product, infested with insects, both grain and beetles are heated. Heating the beetles to the necessary temperature causes their death. Energy from the high-frequency generator is consumed for both processes simultaneously. Total high-frequency energy consumed per unit volume of the infested grain will be defined by the equation:

$$W = N_1 W_g + N_2 W_b = \frac{0.32}{\gamma}\left(\frac{E}{E_{0,on}}\right)^2\left(\frac{\omega}{\omega_{on}}\right)\left\{N_1\left(\frac{V}{V_{on}}\right)_g + N_2\left(\frac{V}{V_{on}}\right)_b\right\} \qquad (3.48)$$

So, the portion of high-frequency energy spent to annihilate beetles is approximately proportional to a volumetric concentration of beetles in infested grain (both grain and insects can lose moisture also).

From the mentioned above statements we can make the conclusions:

1. If a small homogeneous ellipsoid is put into the uniform external field, then the internal ellipsoid field will also be uniform.
2. Ellipsoid is the only convex figure, the Newton potential of which is the uniform quadratic function of Cartesian coordinates by the body homogeneous density. It means that the dielectric ellipsoid is the only figure, which has the uniform internal field in the external uniform electric field.

This mathematical model is characterized by its flexibility. It permits varying the parameters of both the external field and the dielectric particles as the initial data to realize the calculations. The model is sufficiently precise that is confirmed with the experimental part presented here in the Chapter V. It helps to predict the physics parameters such as the energy transmitted to each individual seed, energy loss, heat transmitted to each individual seed, its temperature increase and evaluate the model efficiency in the comparison with the experimental data. Due to the model one can also predict the processing regime parameters for the external field and the dielectric. The model contributes to the development of the technology of grain processing that is ecological efficient and with minimal energetic loss. It is important to note that the theoretical model presented in this work is essential only in the case of its immediate correlation with the experimental part of the material dielectric properties measurement that are grain crops and insects. The next chapter describes the proposed method of dielectric properties measurement.

Chapter IV

Chapter IV

Chapter IV

4. Measurement of Dielectric Parameters of Grain Crops and Insects.

The electromagnetic radiation power for heat which describes the absorption per body volume is written as

$$P = 2\pi f\varepsilon \cdot tg\delta \cdot E^2 \quad . \qquad (4.1)$$

f – is the electromagnetic radiation frequency, ε – is the substance dielectric permittivity, *tgδ* – is the substance relative loss tangent, E – is the electromagnetic field intensity.

To solve the problem it is necessary to measure the grain and insects complex dielectric constants. In the case grain we consider the dielectric properties measurement at different humidity levels.

The measurement of dielectric parameters of both wheat and weevils was conducted with the use of the Q-meter (Fig.4.1.)

Main parts of the Q-meter are:

I. generator unit;
II. measuring unit;
III. voltmeter;
IV. power supply unit.

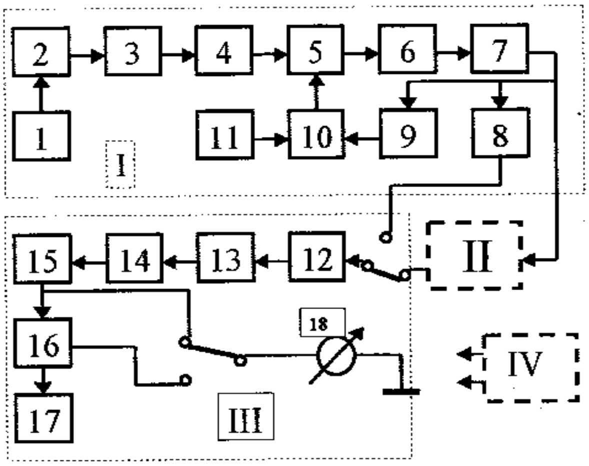


Fig.4.1. Structural scheme of a typical Q-meter

The generator unit consists of the following parts of the structural scheme:

1. reconfigurable driving oscillator ;
2. amplifier of triggering voltage;
3. scaler;
4. low frequency filter;

5. variable electronic attenuator ;
6. wide band amplifier;
7. emitter follower;
8. calibration divisor;
9. detector;
10. differential amplifier of direct current;
11. source of reference voltage.

The generator unit is used for creation of harmonic oscillations in the range of frequencies from 50 kHz to 35 MHz. The measuring unit is used for tuning of measuring contour for the resonant frequency, the counting out of resonance capacity, the introduction of voltage in the measuring unit and the metering of voltage on the capacity element of the contour. The voltmeter of the Q-meter consists of the following elements:

12. source-follower amplifier;
13. variable attenuator;
14. wide band amplifier;
15. detector;
16. differential amplifier;
17. variable source of reference voltage;
18. measuring instrument.

For measuring of dielectric parameters in the range 1-30 MHz a plane measuring capacitor (Fig.4.2) was used; and in the range from 30-150 MHz the cylindrical measuring capacitor was applied.

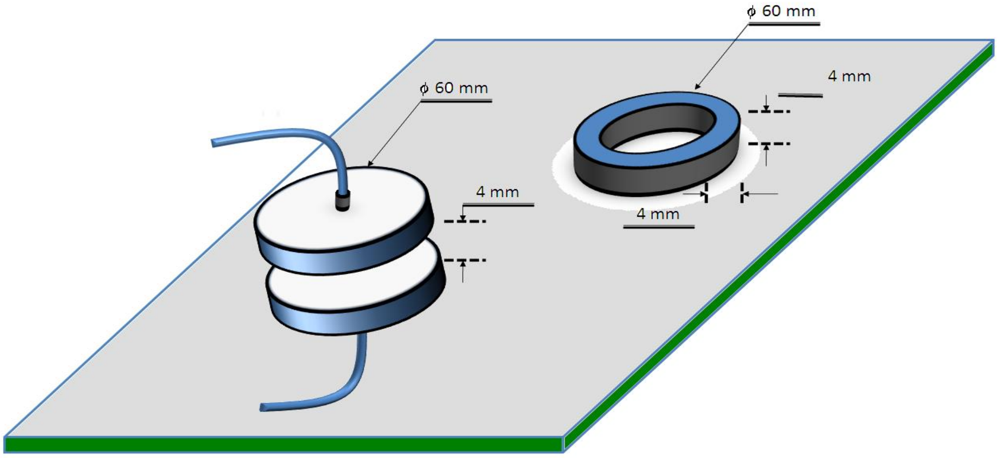


Fig. 4.2. Measuring capacitor and dielectric ring

The dielectric ring of boundary effects limiting with $\varepsilon = 3.3$ was put inside the measuring capacitor. The method of the measuring is represented in the Ref. [17]. The accuracy of measurement is 33-37%.

The capacity and durability of the measuring capacitor are calculated:

$$C_x = C_1 - C_2, \qquad Q_c = \frac{(C_1 - C_2)\cdot Q_1 Q_2}{(Q_1 - Q_2)(C_1 - C_0)} \tag{4.2}$$

Where C_0 is the coil capacity. The probe permittivity is determined as:

$$\varepsilon = (C_0 / C_x)\cdot \varepsilon_{air} \tag{4.3}$$

Hear ε_{air}=1,00058 is the air permittivity at 22 °C .
The relative loss tangent is:

$$tg\delta = \left[\frac{1}{Q_0} - \frac{1}{Q_c}\right]\frac{C_0}{C_0 + C_c} \tag{4.4}$$

Therefore one can determine the real and the imaginary parts of the relative complex permittivity according to the relation:

$$\varepsilon'' = \varepsilon' \cdot tg\delta \tag{4.5}$$

4.1 Moisture content measurement

Grain moisture content was measured with the moisture content measurer. If the initial and desirable moisture content levels are determined, the necessary quantity of water can be calculated
La humedad del grano fue determinada con el medidor de humedad. Sabiendo los niveles de humedad inicial y deseable, la cantidad necesaria de agua se calcula

$$X = m\left(\frac{100 - a}{100 - b} - 1\right), \tag{4.6}$$

where X is the quantity of water to be added to grain to reach the final moisture content level b;

m - the mass of a grain probe;
a- initial moisture content;
b- final moisture content.

Steps to prepare the grain probe of certain moisture content are the following:
1) The grain probe is put into the ceramic glass; 2) the water quantity is calculated per 0.1 cm^3 according to the probe weight and is added to the ceramic glass with the probe; 3) move the grain carefully, put it into the glass container and close it; 4) preserve the glass container with the probe for 3-4 days in a thermostat at 18-20°C; 5) make the measurement.

The proposed method of dielectric properties measurement proved to be practical and rather precise. Chapter V gives the experimental data on measurement of a dielectric constant and dielectric loss factor of wheat grain *Triticum aestivum L.* as a function of its moisture content (Table 1, Fig. 5.1-5.3) and as a function of frequency (Table 3, Table 5) that helps to calculate the energy liberated as heat (Table 2). Also the dielectric constant, dielectric loss factor and loss tangent of granary weevil *Sitophilus Granarius L.* were successfully measured (Table 4).

Chapter V

Chapter V

Chapter V

5. INTERACTION OF ELECTROMAGNETIC WAVES WITH GRANULAR AGRICULTURAL PRODUCTS AND INSECTS

5.1 Basic Thermodynamics Equations

The quantity of energy W needed to heat a grain mass from the temperature T_1 to a finite temperature T_2 $(\Delta T = T_2 - T_1)$ may be transferred from the high-frequency field. These values are related in the equation

$$W = \rho V C_s \Delta T, \tag{5.1}$$

where ρ is the bulk density of the grain (kg/m^3),
C_s is the specific heat capacity ($kJ/kg \cdot K$),

$$C_s = L_0 C + (1 - L_0) C_0, \tag{5.2}$$

depending on moisture content L_0, where L_0 is moisture content in percent, C is specific heat capacity of water, C_c is the specific heat capacity of dry grain ($C_c = 1.32\, kJ/kg \cdot K[1]$).

According to all these notes one can define:

$C_{5\%} = 1.54,.kJ/kg \cdot K$
$C_{10\%} = 1.604,.--"--"-$
$C_{15\%} = 1.750,.--"--"-$
$C_{20\%} = 1.894,--"--"-$
$C_{25\%} = 2.035,--"--"-$

Granular density of grain depends on both the size and shape of the grain kernel and varies over a rather wide range. As increasing moisture content leads to grain swelling, this parameter influences the parameter ρ, the bulk density of the grain. The electromagnetic properties of a grain mass ε' and ε'', linked with the density, are presented in a form $[10]$ for wheat in the Table 1.

TABLE 1: The real part ε' and imaginary part ε'' of dielectric permittivity at 11.67 GHz of grain in relation to moisture content

The moisture content L_0 (%)	8.5%	10%	10.9%	12.2%	14.7%
$\rho, (kg/m^3)$	730-1070	700-1050	680-1090	680-1120	640-1150
$\varepsilon' =$	2.27-3.11	2.29-3.20	2.28-3.46	2.36-3.81	2.40-4.33
$\varepsilon'' =$	0.15-0.27	0.18-0.38	0.15-0.42	0.23-0.57	0.29-0.91

Table 1 serves for the determination of intervals, in which the appropriate physical parameters may change. The more precise dependence for wheat is shown in [10].

The given data permit estimation of heat expenditure for heating of a grain mass of different moisture contents through temperatures of both $1^o C$ and $40^o C$ (Table 2).

TABLE 2: The energy W needed to heat the grain mass of different moisture contents at temperatures of 1°C and 40°C (densities of mass are 700 and 1000 kg/m^3).

Heat for		$1^o C$	$40^o C$
Density , 700	$L_0 = 5\%$	$W = 1.02 kJ/kg$	$W = 43.2 kJ/kg$
	$L_0 = 10\%$	1.12	44.8
	$L_0 = 15\%$	1.23	49.3
	$L_0 = 20\%$	1.32	52.8
	$L_0 = 25\%$	1.40	56.0
Density 1000	$L_0 = 5\%$	$W = 1.54 kJ/kg$	$W = 61.0 kJ/kg$
	$L_0 = 10\%$	1.604	64.2
	$L_0 = 15\%$	1.750	70.0
	$L_0 = 20\%$	1.894	75.6
	$L_0 = 25\%$	2.085	83.4

Water evaporation is also a physical process requiring energy expense. This amount of energy varies at different values of temperature and pressure.

At $0^o C$ $W_c = 2480 kJ/kg$
At $30^o C$ $W_c = 2421 kJ/kg$
At $99.96^0 C$ $W_c = 2255 kJ/kg$

Total energy losses are equal to an integral energy consumed for grain heating and evaporation of water. It is then necessary to provide sufficiently intensive vapor removal to prevent the moisture from condensing on the nearly cool surfaces of the grain. Under these conditions, if, for example, grain drying occurs from a moisture content of 15% to 10% (evaporation of 5% moisture) as a result of heat influence, the required energy is equal to:

124 kJ per 1 kg of grain at $0^o C$,
121 kJ per 1 kg of grain at $30^o C$.

Thus, the way to diminish energy expense for water evaporation is to dry the grain in a chamber under decreased atmospheric pressure.

It is well known [13] that decreasing atmospheric pressure leads to a reduction of the water boiling temperature at equilibrium but increases the specific heat of vaporization.

5.2 The Influence of Electromagnetic Radiation on Grain Pests

As mentioned before, grain spoilage in storage begins with formation of zones of increased moisture content, where fungous diseases are prevailing. On this basis, as a consequence, the intensive propagation of granary pests begins. The best known among the pests is the granary weevil, which will be considered below as a typical representative of a granary pest fauna. Electromagnetic radiation influences the pest fauna in a complicated way. At moderate intensities of electromagnetic radiation a release of heat occurs in a beetle body. If heat release is sufficiently intensive, the beetle is heated to the lethal temperature. At high intensities of a high-frequency electric field, at distances of a beetle -size order, a high-frequency potential difference is formed, which is sufficient for an electrical strike of an insect. So, one can consider three main characteristic spheres of influence on pests in grain crops depending on the radiation intensity.

I. The sphere of moderate influence:
  a) grain is heated and its drying occurs;
  b) beetles are heated but do not die.
II. The sphere of optimal influence:
  a) grain is heated and its drying occurs;
  b) beetles are considerably heated and die.
III. The sphere of intensive influence:
  a) grain is heated a bit;
  b) beetles die from an electric shock.

The boundaries of each sphere in a theoretical approach will be discussed taking into account disinfestation of grain produce.

The results of the dielectric properties measurements for both grain and insects and the relations with frequency of the electromagnetic field in the range 20-150 MHz are presented in *Tables 3, 4.*

Examination of Tables 3, 4 shows that:

- The relative dielectric constant of insects is greater than that of grain.
- The loss tangent reflected the intensity of RF-energy sorption to be 3-4 times greater for insects than for grain in the frequency band 20-150 MHz .
- The intensity of RF-energy sorption tends to increase in connection with frequency rise.

For comparison: Measurements with the same system used for measuring dielectric properties of grain [18] at $\approx 24^0 C$, provided values of 6.6 and 7.8 for the dielectric constant of the rice weevils and confused flour beetles, respectively. The loss factor for these bulk samples of both species was 2.2 at 40 MHz.

TABLE 3: The real ε' and imaginary ε'' part of the dielectric permittivity and the loss tangent $tg\delta$ of grain in relation to frequency.

Frequency, MHz	ε'	ε''	$tg\delta$
20	2.05-3.01	0.08-0.17	0.04-0.05
40	2.05-3.02	0.08-0.16	0.04-0.05
60	2.05-3.02	0.10-0.18	0.05-0.06
80	2.07-3.03	0.11-0.22	0.05-0.07
100	2.06-3.00	0.11-0.23	0.05-0.08
130	2.05-3.01	0.13-0.23	0.06-0.08
150	2.04-3.02	0.14-0.24	0.06-0.08

TABLE 4: The real ε' and imaginary ε'' part of the dielectric permittivity and the loss tangent $tg\delta$ of insects in relation to frequency.

Frequency, MHz	ε'	ε''	$tg\delta$
20	4.99	1.38	0.27
40	4.98	1.37	0.28
60	4.96	1.44	0.29
80	4.95	1.49	0.30
100	4.60	1.47	0.32
130	4.53	1.51	0.33
150	4.45	1.50	0.34

The results of measurement of dielectric parameters of grain at different moisture contents at the frequency 80 MHz are presented in Figures 5.1-5.3.

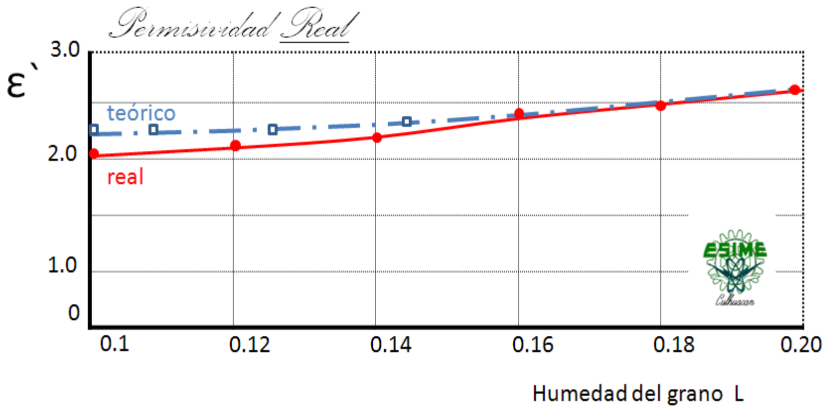


Fig. 5.1: Relation of the real part of permittivity to the grain Triticum aestivum L. moisture content (data for $\rho \approx 700\,kg/m^3$, f=80MHz)

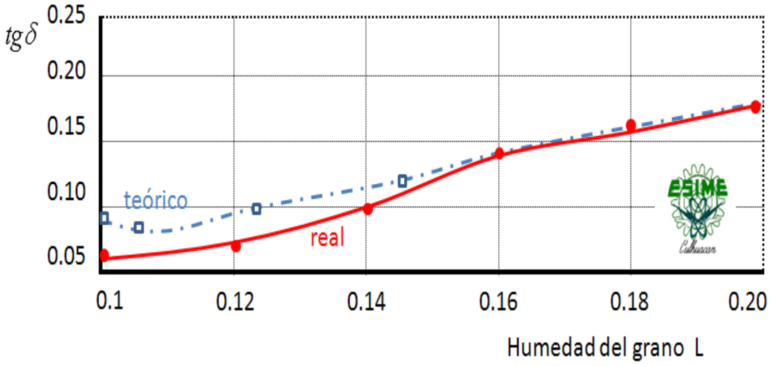


*Fig. 5.2***:** *Relation of the loss tangent to the grain Triticum aestivum L. moisture content (data for* $\rho \approx 700\,kg/m^3$ *, f=80MHz).*

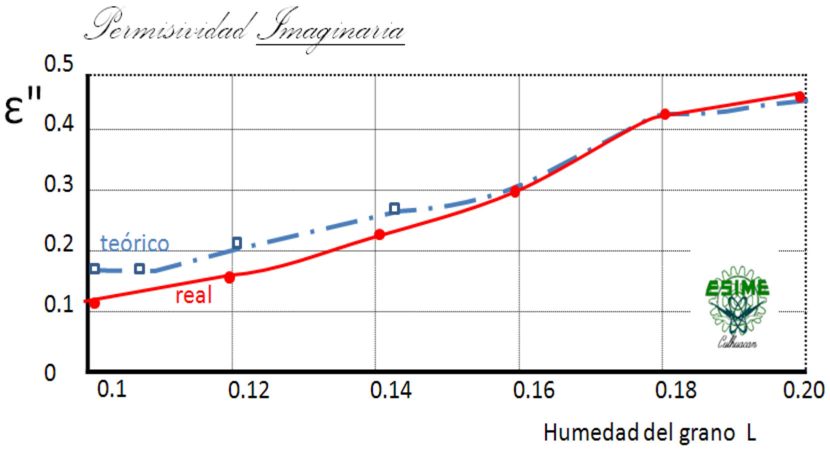


Fig.5.3: Relation of the imaginary part of permittivity to the grain Triticum aestivum L. moisture content.(*data for* $\rho \approx 700\,kg/m^3$ *, f=80MHz*).

One can see a monotonic increase of the relative dielectric constant as the grain moisture content increases (Fig.5.1). Both the imaginary part of the permittivity and the loss tangent also increase as the grain moisture content increases (see Fig. 5.2, 5.3). These results are compared with Ref.10 data for density of wheat $\rho \approx 700\,kg/m^3$.

The results of experimental measurements of temperature variation of grain and beetles as a function of exposure at $9000MHz$ and flow density of $5W/cm^2$ are presented in Figure 5.4.

One can see that the increase of the insect’s temperature exceeds that of the grain. Thus, if the insect has a much dielectric loss factor than the grain, it tends to heat more rapidly [18].

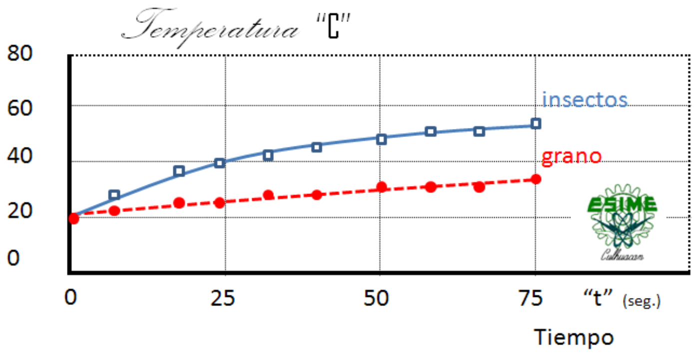


Fig.5.4: Increasing of both insects (Sitophilus Granarius L.) and grain (Triticum aestivum L.) temperature as a function of time variation, f=9GHz, j=5W/sm^3.

5.3 Discussion of Initial Data of Experimental Facilities Design

Equation (3.37) provides the electromagnetic energy conversion to heat in each individual seed. One can cite the equations needed for calculation and design of real drying and disinfestation facilities.

The main electrophysical characteristics of grain ε' and ε'' given from equation (3.28) are defined experimentally not for an individual seed but for some bulk grain mass [9,10]. Therefore, while defining $tg\delta = (\varepsilon''/\varepsilon')$, its value will be really the same for both an individual seed and the bulk grain mass. The parameters ε_1 and ε_0 are connected by equation (3.29). Therefore, the real part ε' of the permittivity inside a seed differs from the magnitude ε_1' being defined for the bulk grain mass.

To obtain useful data one can use the values ε' and ε'' given in this paper and in the literature [9], where the appropriate information is given for the hard winter wheat over a wide range of frequencies and moisture content. According to the plots given in [9] one can graph the plots for the frequency values 80 MHz, 150 MHz, 900 MHz and 3000 MHz).

While calculating these characteristics it was supposed that a volumetric concentration of grain in a bulk grain mass is C=0.75. It contains 30 seeds at an individual seed volume of $0.025\,cm^3$. The parameters W_1 and W_2 were calculated separately. The results of calculating the parameter W_2 ($E = E_{on} = 300\,kV/m$) are presented in Table 6. According to the defined values of the parameter ε_0 the calculations of the shielding factor W_1 and, therefore, energy release in $1\,m^3$ of grain (at a volumetric concentration of grain C=0.75 in a granular mass of wheat) were done.

The results of calculations are given in Table 7. According to the equations mentioned before, if an intensity of high-frequency electric field differs from 300 kV/m, the parameter $\tilde{W}$ will multiply by $(33E, kV/m)^2$.

TABLE 5: Values of W_2 as functions of grain moisture content at different frequencies: 80, 150, 900, 3000 MHz.

Frequency f=80 MHz	
Moisture content	$W_2\ j/s$
5%	3.6
10%	4.5
15%	4.5
20%	4.95
25%	4.95
Frequency f=150 MHz	
Moisture content	$W_2\ j/s$
5%	10.1
10%	16.9
15%	20.3
20%	27.0
25%	33.7
Frequency f=900 MHz	
Moisture content	$W_2, j/s$
5%	77
10%	92
15%	123
20%	128
25%	128
Frequency f=3000 MHz	
Moisture content	$W_2, j/s$
5%	153
10%	266
15%	419
20%	540
25%	640

If the source of the high-frequency field operates in a pulse mode with pulse duration ratio γ, the heat release per unit volume of product will be equal to $10^3\left(\tilde{W}/\gamma\right)kj/m^3 \cdot s$.

The mentioned equations entirely solve the problem of evaluating the efficiency of microwave grain processing at various levels of grain radiation and in different frequency ranges. Naturally, a continuous-wave (CW) mode is preferable for simultaneous grain drying and disinfestation. The electric field intensity produced in CW operation is lower than that which can be used in pulse-type equipment, although the CW mode provides a constant temperature increase up to the required values. The design of CW equipment is simpler and the efficiency is higher than that of pulsed mode generators. Therefore, the consideration will concern first of all a drying facility on the basis of a CW generator with operational frequency $f = 3 \cdot 10^3\, MHz$.

Finally, at the power of the high frequency generator, 5-10 kW, the resulting electric field at different points in a chamber is $30\,kV/m$, i.e. at the moisture content of the initial product $\approx 25\%$ the energy release is $430\,kW/m^3$. During the drying process the moisture content will diminish and the energy release will increase a little and at 10% of moisture content it will be $1620\,kW/m^3$.

TABLE 6: Values W_1 *and* W *as a function of moisture content at frequencies: 80, 150, 900, 3000 MHz*

Frequency 80 MHz		
Moisture content	W_1	$\tilde{W}\ kj/m^3s$
5%	$3.26\cdot10^2$	3520
10%	$2.45\cdot10^2$	3320
15%	$1.64\cdot10^2$	2220
20%	$1.44\cdot10^2$	2140
25%	$1.12\cdot10^2$	1670
Frequency 150 MHz		
Moisture content	W_1	$\tilde{W}, kj/m^3s$
5%	$3.45\cdot10^2$	10500
10%	$2.78\cdot10^2$	14100
15%	$2.05\cdot10^2$	12500
20%	$1.47\cdot10^2$	11800
25%		
Frequency 900 MHz		
Moisture content	W_1	$\tilde{W}, kj/m^3s$
5%	$3.70\cdot10^2$	85000
10%	$3.04\cdot10^2$	84000
15%	$2.65\cdot10^2$	98500
20%	$2.26\cdot10^2$	87000
25%	$1.79\cdot10^2$	69000
Frequency 3000 MHz		
Moisture content	W_1	$\tilde{W}, kj/m^3\ s$
5%	$4.20\cdot10^2$	192000
10%	$3.35\cdot10^2$	162000
15%	$3.14\cdot10^2$	44600
20%	$2.81\cdot10^2$	45500
25%	$2.24\cdot10^2$	43000

On the average one can suppose energy release to be on the level $10^3\ kW/m^3$. Energy of 83 kj/kg is required to heat damaged wheat by 40°C to provide total pest destruction. This takes 52 second at granular density $10^3\ kg/m^3$. To evaporate $1.5\cdot10^{-4}$ kg of moisture, 200 second of heating is required. Therefore, the wheat exposure in a high-frequency field at intensity 30 kV/m at a frequency of 3000 MHz requires 4min to render wheat totally free of pests and dry it to the moisture level of 10%. The spent high-frequency energy is 250 J. Consequently, 1 kWh of electric energy provides both drying and disinfestation of 7 kg of wheat at a costs 0.004 $/kg. So, the cost of such processing does not exceed that of other drying methods [17], and ecologically acceptable wheat is obtained.

The equipment for pulse-modulated operation is characterized by a lower efficiency, because it is sufficiently more complicated and requires more highly qualified personnel. Although, if we orient ourselves only for pest disinfestation and create facilities generating powerful short pulses of electromagnetic radiation, the cost of wheat disinfestation should not exceed the calculated costs for a CW-mode generator.

Solution of the problem of electromagnetic radiation interaction with grain crops and insects requires the designing of electromagnetic models of both grain and insects with strong relation of their electrodynamics qualities with density, layer width, average seed dimension and other parameters.

The permittivity measurement of the real mixture of grain with beetles at frequencies higher than 100 MHz does not entirely agree with the static and the quasi-static models [17]. In the present transaction an attempt was made within the framework of the suggested model to describe the behavior of electromagnetic energy absorption in both grain and pests and the behavior of their main electrophysical characteristics ε' and ε'' in dependence on the electromagnetic frequency and the moisture content. The mentioned equations entirely solve the problem of evaluating the efficiency of microwave grain processing at various levels of grain radiation and in different frequency ranges. The results of the experimental definition of the dielectric parameters ε' and ε'' reveal that their values depend considerably on the grain and pest parameters: density, moisture content, average radius and frequency of incident electromagnetic radiation.

Estimating the economical profit of microwave protection of the grain harvest is necessary to be guided by the following considerations [12]:

- To conduct simultaneous microwave drying and grain disinfestation is economically profitable.
- If grain drying is not required, microwave radiation to control pests should be applied in a short pulse mode with high intensity electric fields.
- Caution should be taken not to use low level power applications that may realize grain drying, but at the same time will create favorable conditions for intensive pest propagation.

5.I. INTERACTION OF RADIO-FREQUENCY, HIGH-STRENGTH ELECTRIC FIELDS WITH HARMFUL INSECTS

The objective of the research reported here is to investigate the influence of radio-frequency electric fields of high strength on insect mortality. The experiments were accomplished at the frequencies 47.5, 900 and 2450 MHz for the pulse modulated radiation treatment and the continuous wave RF radiation. Two types of systems, which are the coaxial irradiation chamber and the irradiation chamber with plane capacitor, are presented in this work. The experiments in the coaxial type radiation chamber on granary weevil (*Sitophilus granarius L.*) at voltages U = 5.5-10.5 kV, frequency 47.5 MHz, electric field intensity 180-350 kV/m and exposures 5-60 seconds give 40-90 % of insect mortality that mainly depends on voltage increase. The experiments in the irradiation chamber with plane capacitor are presented for the pulse modulated regime at different the frequency 47.5 MHz and field intensities 350-2000 kV/m. 100% of insect mortality is reached at the exposures 1-30 seconds, field intensity 2000 kV/m. The RF radiation of granary weevil (*Sitophilus granarius L.)* in the coaxial irradiation chamber in stationary mode reaches 100% insect mortality at major exposure times for the frequencies 900 and 2450 MHz. Stationary generator mode also permits 21-97% fungi (Cladosporium cladosporioides, Aspergillus candidus) control at voltage U = 10.5 kV, frequencies 900 and 2450 MHz and exposures 120-180 seconds. Further investigation is needed for microscopic fungi control to understand the fungi reproduction mechanism during the RF-radiation treatment for *Aspergillus fumigatus*.

Investigations of radio-frequency (RF) and microwave energy action on insects and microorganisms have been carried out for the last 50 years in different countries (Whitney et al., 1961; Nelson and Kantack 1966; Nelson, 1973; Borodin et al, 1993; Schastnaya, 1958, Mishenko et al., 2000). The action of electromagnetic RF-irradiation on biological organisms depends on the dielectric parameters of the biological structures, the electric field intensity and frequency, temperature and moisture content of the dielectric biological objects (Kudryashov, 1980; Akimov, 1984; Rashkovan et al., 2003). The insects, with a higher organismic structure, are more sensitive to RF fields. Nelson (1996) showed that the preferable wavelengths for insect treatment are of a few meters in the radio-frequency spectrum. Lethal outcome for insects, usually connected with heating of tissues or damage of their nervous system, depends considerably on the frequencies, field strength and their complex dielectric permittivity, with final temperature being the dominant factor (Nelson and Charity, 1972, Nelson 1981, 2001; Rashkovan et al. 2003). Sterilization of male insects was observed at relatively low RF-field levels (Nelson and Kantack, 1966, Nelson, 1973, Rai, 1970, Rai et al. 1974, Whitney et al. 1961). This destroys the reproductivity of the population (Zakladnoi and Rabanova, 1973). Some investigations showed bactericidal effects of RF radiation (Anonymous, 1999). Some scientists claimed that microwaves in the centimeter range (0.01-0.30 m) have a higher bactericidal activity than in the meter range (6-10 m) (Anonymous, 1999). The bactericidal effect can be obtained at lower temperatures and with shorter exposure time than with ordinary heat disinfestation. When the RF-field power is considerable, 0.8-4.5 kW, the process observed in microorganisms (*Paramecia*) exhibited a so-called “electric shock” when subjected to the action of microwaves while the medium is heated only one degree. Similar reactions were observed at very high temperatures when using simple overheating (Presman and Rappoport, 1965). Microwaves cause disturbances in both the structure and nerve cells, which are not always interpreted as pure temperature influence. The reaction of brain tissue cells is the most distinct in the case of pulsed HF fields in a frequency band of 150-450 MHz with pulse repetition rates of 1-50 Hz with a radiating power of $0.1\text{-}1\times10^{10}\ W/m^2$ (Ismailov, 1987; Kudryashov, 1980). Examination of available data shows that the mechanism of interaction between RF radiation in the different bands and biological organisms has not been totally established (Zaitsev at al, 2001).

The experiments were conducted at the National Scientific Center, Kharkov Institute of Physics and Technics (NSC KIPT, Ukraine). The HF generators operated at frequencies 47.5, 900, and 2450 MHz. The physical and biological investigations showed that one of the most important factors affecting the insects is the electric field strength (Nelson and Charity, 1972, Nelson 1981, 2001, Rashkovan et al. 2003).

Consider the device driven by a generator operating at 47.5×10^6 Hz and a pulsed mode duty cycle of 0.5%. (off-on time ratio 200). The coaxial-line feeder is used for applying the electromagnetic energy from the HF-generator to the infested grain load. The electromagnetic field within the coaxial line can be described by the equations

$$H_\varphi = \frac{r_0 H_0}{r} e^{i\left(\omega t - \frac{\omega}{V_\varphi} z\right)}, \tag{5.3}$$

$$E_r = \frac{r_0 H_0}{\varepsilon r} \cdot \frac{\omega}{V_\varphi} e^{i\left(\omega t - \frac{\omega}{V_\varphi} z\right)}, \tag{5.4}$$

where H_φ , amperes/m, is the magnetic field strength, E_r ,volts/m, is the electric field strength, H_0 , amperes/m, is the magnetic field strength amplitude, V_φ , m/s, is the phase velocity, ω, rad/s, is the angular frequency, ω/ V_φ , rad/m , is the phase constant and z is the wave propagation direction. From the equations 5.3 and 5.4 the nonuniform character of the RF fields can be noted. The flow of electromagnetic power W across the whole section of the coaxial line is

$$W = \frac{c}{4} \cdot \frac{\ln \frac{R}{r_0}}{\sqrt{\varepsilon}} \left(r_0 H_0\right)^2 \tag{5.5}$$

where c, m/s, is the speed of light in vacuum, R, m , is the internal radius of the outer conductor, r_0, m, is the radius of the center conductor and ε, farads/m is the dielectric permittivity. Therefore the electric field strength is related with the generator power and is determined

$$E_r = \frac{1}{2} E_0 e^{i\left(\omega t - \frac{\omega}{V_\varphi} z\right)} \tag{5.6}$$

For the coaxial line used at the frequency 47.5 MHz, $r_0 = 0.035m$ and $R = 0.080m$. Thus the field nonuniformity along the radius is large: $\left[E(R)/\,E(r_0)\right] = 0.44$. In order to reduce this nonuniformity, the use of the additional dielectric tube is needed. One can assume that the volume with grain and insects surrounds the central conductor from $r = r_0 = 0.035m$ to $r_1 = 0.060m$. Then $E(r_1)/E(r) = 0.6$ or $E^2(r_1)/E^2(r_0) = 1/3$ and this means that the heat generated within insects near the outer channel radius will be 3 times less than that generated at the internal conductor. So one will obtain the following values as a function of the electromagnetic power radiated by the HF generator:

$$\begin{gathered} W_1 = 1\times10^6\,\text{w} \;\ldots..\; E_0 = 6\times10^5\,\text{V/m}\ldots..\; E = 4.2\times10^5\,\text{V/m} \\ W_2 = 1.6\times10^6\,\text{w}\ldots\; E_0 = 7.5\times10^5\,\text{V/m}\ldots..\; E = 5.15\times10^5\,\text{V/m} \\ W_3 = 2\times10^6\,\text{w}\ldots..\; E_0 = 8.4\times10^5\,\text{V/m}\ldots..\; E = 5.15\times10^5\,\text{V/m} \end{gathered} \tag{5.7}$$

The values E_0 and E are defined as the electric field near the inner conductor at the radius 0.035 m (from the coaxial line to the point, where the electric field is measured) and near the outer conductor at the radius 0.06 m respectively, both are in the coaxial configuration.

The moderate energy output within the single kernel or insect will be equal to 0.31w or within 10^{-6} $m^3$of the irradiated mass it will be 6.2 J/s at the power 1.5×10^6 w. But these calculations have been done with the continuous wave (CW) mode of generator operation at the frequencies 900 and 2450 MHz. In order to achieve complete suppression of the insects the periods with the following duration are needed: 1980 seconds at a power of 1×10^6 w; 1380 s at 1.5×10^6 w and 1020 s at r 2×10^6 w.

Experimental Studies

The experimental investigations were conducted with two types of facilities. Each one has its advantages and disadvantages but both can be used as part of the equipment for the technology of grain processing. The system with the coaxial irradiation chamber has the generator power voltage limit U = 10.5 kV and is economical due to the comparatively low energy consumption. The system with the irradiation chamber with plane capacitor is more effective for pest suppression.

a. *The coaxial type irradiation chamber*

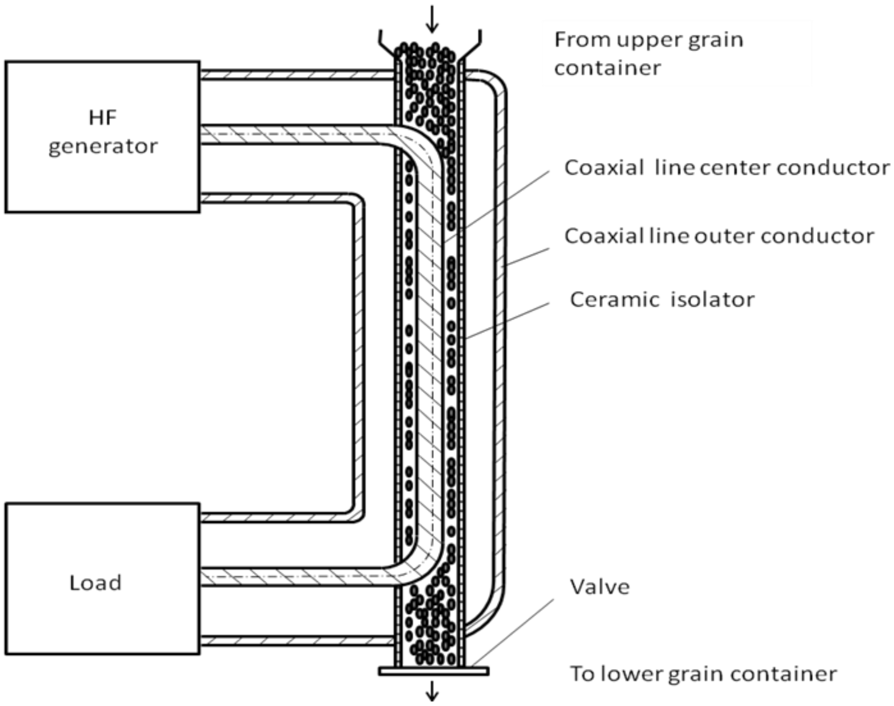


Fig. 5.5. The schematic diagram of the coaxial irradiation chamber.

This chamber (Fig. 5.5) was made from standard copper coaxial 160mm/70mm feeder line 1 meter in length with a ceramic tube mounted coaxially between the center and outer conductors. Special windows were made for entrance and exit of grain. The infested grain flowed from the upper grain container through the ceramic isolator tube around the inner conductor (Fig.5.5). The ceramic isolator (dielectric permittivity $\varepsilon \approx 1$) helped to limit the variation in the radial electric field intensity between the coaxial line center conductor and outer conductor. At one end, the coaxial-line feeder was connected to the RF-generator output, and the other end was connected to the active generator load. In this case, an electric field of 6.2×10^5 V/m was achieved close to the surface of the inner conductor (radius = 0.035 m) and decreased to 4.5×10^5 V/m at the inner surface of the ceramic tube (radius = 0.06 m) at the pulse power level ~ 1.0×10^6 W. Both radii are given from the coaxial-line axis to the point where the electric field is estimated inside the coaxial line processing zone.

One can note that in this coaxial applicator the amplitude of the radio-frequency electric field is limited. The pulsed mode helps to overcome this problem and to achieve pulsed electric field strength of approximately 3×10^6 V/m.

The experiments carried out on granary weevil (Sitophilus granarius L.) in the coaxial feeder chamber in the pulse modulated regime (Tables 7 and 8) were presented at exposures 5-60 seconds, voltage reducing from 10.5 kV to 5.5 kV that corresponds to the electric field intensity reducing from 350 to 180 kV/m. The radiating power also decreased from 9.4 to 2.45 kJ/m^2 in a pulse. For each time exposure a series of 3 replications was made. The RF-radiation was applied at 900 and 2450 MHz to granary weevil (Sitophilus granarius L.) in the coaxial feeder chamber with stationary mode (Table 10) at the time exposure 5-60 seconds and 60-90 seconds at 900 and 2450 MHz respectively. The microscopic fungi (Aspergillus fumigatus, Cladosporium cladosporioides, Aspergillus candidus) were also treated in the coaxial feeder chamber at time exposures 60, 120 and 180 seconds at 47.5 MHz, voltage 5.75 kV and at 900 and 2450 MHz at the stationary mode (Table 11). Series of 3 replications were made for each time exposure for these experiments.

The experimental investigation showed that insect mortality at the frequency 47.5 MHz was observed with a RF electromagnetic field strength ~ 5×10^5 V/m by direct electric shock. It was learned that RF-radiation at 47.5 MHz (Tables 7 and 8) can be used for insect control in grain and foodstuff with boosted generator voltage from 12 kV up to 15 kV. Under these conditions insect mortality on the level of 95-100 % can be achieved with 5-10 seconds exposure. It is necessary to search for biological effects on pests by increasing the power with voltage increasing up to 12-20 kV.

b. The irradiation chamber with a plane capacitor

The schematic diagram, of the irradiation chamber with a plane capacitor is shown in Fig.5.6.

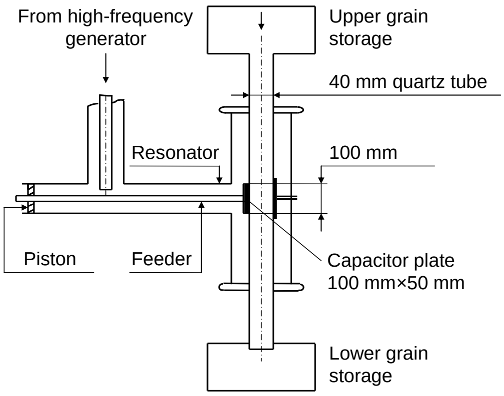


Fig. 5.6. The schematic diagram of the irradiation chamber with capacitor.

The method of the electric field formation in this type of facility is distinctly different from the coaxial system described above. The main difference is that in the first type the traveling waves are used, and in the second type, the situation is stationary. This method of high electric field formation permits higher levels of electric field strength (>30×10^5 V/m in pulsed mode) and improvement of the whole facility efficiency. The constructive features of this device are the presence of the capacitor in the irradiation volume. The experiments in this configuration were carried out at the applied frequency of 47.5 (Tables 9). The pulse modulated RF-radiation at 47.5 MHz on granary weevil (Sitophilus granarius L.) in the irradiation chamber with a plane capacitor (Table 9) gave good results at the field intensities 350, 700, 1000 and 2000 kV/m and time exposure varying from 0.5 to 30 seconds. It should be considered as the model for prediction of electric energy expenses in the industrial use of this kind of device for grain protection at the level of $2 per tonne.

Physical and biological experiments

After the radiation treatment of insect-infested grain, biological evaluation was done in the Institute of Experimental and Clinical Veterinary Medicine (Ukraine). The ecological-faunal and entomological investigations were carried out at the storehouses of grain, bread-products enterprises, and at the cattle breeding farms. A wide range of insects was included in the investigation, namely weevil (*Curculionidae*), such as barn weevil (*Seratophilus granarius*), rice weevil (*Sitophilus oryzae*), black mealworm (*Tenebrionidae*) and yellow mealworm (*Tenebrio molitor*), confused flour beetle (*Tribolium confusum* Jacquelin du Val), pitch-brown cockchafer (*Alphitibius diasperinus*), Angoumois grain moth (*Sitotroga cerealella*) and barn moth (*Nenapogon granellus).* Twenty-six species of mites were revealed, among which it is necessary to note a number of barn mites (*Acariformes*) and bread mites *(Acaridae*), belonging to the grain mite (*Acarus siro* Linnaeus). The experimental results are given below for granary weevil *(Sitophilus granarius L.)* and microscopic fungi (micromictets).

Chapter V

Results

The investigations at 47.5 MHz (Fig.5.1) showed that the biological action of the RF electromagnetic field depends more on the generator power voltage (U, kV) than on treatment duration (See Table 7).

Table 7: Action of RF-radiation at 47.5 MHz on the warehouse pest granary weevil (Sitophilus granarius L.) in the coaxial feeder chamber. Pulse modulated radiation treatment; repetition rate: two pulses per second.

Exposure, seconds	U, kV	$\overline{\overline{E}}$, kW/m	Radiating power, J/m^{2}in a pulse	Mortality of insects,%, (adult &larva)
5	10.5	350	0.940×10^4	85.5±8.0
10	10.5	350	0.940×10^4	96.2±2.7
20	10.5	350	0.940×10^4	89.3±8.9
60	10.5	350	0.940×10^4	71.3±11.8
60	8.5	280	0.615×10^4	53.8±4.4
60	5.5	180	0.245×10^4	42.5±28.9

The mortality of granary weevil (*Sitophilus granarius* L.) at 47.5 MHz treatment in the coaxial type irradiation chamber (Fig.5.1) is given in Table 8.

Table 8: Action of RF radiation at 47.5 MHz on the warehouse pest Sitophilus granarius L. in the coaxial feeder chamber. Pulse modulated radiation treatment.

Exposure, seconds	Average mortality for two replications, per cent
7 kV. Field intensity at the sample location: 190-250 kV/m	
5	42.3
10	62.8
10 kV. Field intensity at the sample location: 270-350 kV/m	
2	61.6
3	66.7
10	71
15	66.3
25	86.3

As shown from experimental results (Tables 7 and 8) at 47.5 MHz, the biological effect is connected with power flow and voltage. Thus, increasing the voltage from U=3.5 kV to 10.5 kV increases the mortality from 42.5% to 71.3 % all with a treatment duration of 60 seconds. At the voltage U=10.5×10^3 V, increasing the treatment duration from 5 to 60 sec did not increase the insect mortality. Obtained results (see Table 9) showed that the equipment with chamber with a plane capacitor (Fig.5.2) is the most effective as the means of insect control. Important is the fact that the small number of surviving insects were not able to reproduce. This equipment will be advanced in industrial conditions as well. Use of frequencies of 900 MHz and 2450 MHz demonstrates the direct dependence upon the irradiation time (Table 10). Results of RF-radiation treatment at 900 and 2450 MHz (Fig.2) on granary weevil (*Sitophilus granarius* L.) in the coaxial irradiation chamber with stationary mode are presented in Table 10. Increasing exposure from 5 seconds to 60 seconds increased insect mortality from 68.3 % to 100%. The seed heating temperature in this process varied from 36 to 45 C. Increasing the RF-radiation treatment exposure to 120 seconds increased grain temperature to 56-68 C. Thus the RF-radiation treatment of the grain and insects during the short time provides insect suppression at a temperature level that does not influence the biological quality of the grain. As is well known**,** one of the most dangerous contaminants in grain and grain products is microscopic fungi. In our investigations, sterilized corn meal was contaminated by fungi cultures. Then the contaminated samples were irradiated by RF-waves with different exposure times and power radiation levels. The biological action was generally determined. It was found that fungi reaction to RF-radiation was not adequate for control (see Table 11). The fungi were sensitive to both the wave length and generator power variations. The fungi growth activity increased at some 47.5 MHz exposures. At frequencies of 900 and 2450 MHz, some suppression of fungi was observed. At exposures of 120-180 seconds the fungi growth was suppressed 21-97 % for *Cladosporium cladosporioides* and *Aspergillus candidus* .

Table 9. Action of pulse modulated RF-radiation at 47.5 MHz on granary weevils (Sitophilus granarius L) in the irradiation chamber with a plane capacitor

Exposure, seconds	Insect mortality, %	
	Separate investigations	Average
Field intensity: 350 kV/m		
0.5	50, 60, 75, 85	67.5
1	50, 100, 100	83.3
5	100, 100, 100	100
10	100, 100, 100	100
20	100, 100, 100	100
30	85, 90, 100	89.5
Field intensity: 700 kV/m		
0.5	60, 80, 90	80
1	100, 100, 100	100
5	65, 100, 100	91.5
10	100, 100, 100	100
20	90, 100, 100	96.6
30	100, 100, 100	100
Field intensity: 1000 kV/m		
0.5	70, 80, 100	72.0
1	100, 100, 100	100
5	100, 55, 100	88.0
10	50, 80, 90	76.1
20	100, 100, 100	100
30	100, 100, 100	100
Field intensity: 2000 kV/m		
1	100, 100, 100	100
3	100, 100, 100	100
5	100, 100, 100	100
10	100, 100, 100	100
20	100, 100, 100	100
30	100, 100, 100	100

Table 10. Action RF-radiation at 900 and 2450 MHz on granary weevil (Sitophilus granarius L.) in the coaxial feeder chamber with stationary mode.

Frequency, MHz	Exposure, seconds	Specific power radiation, W/m^3	Exposure dose, J/kg	Mortality, per cent
900	5	2.3-2.8×10^6	5.05×10^3	68.3±19.4
900	10	2.3-2.8×10^6	11.0×10^3	80±28.3
900	15	2.3-2.8×10^6	16.6×10^3	79.3±7.9
900	30	2.3-2.8×10^6	33.1×10^3	97.1±2.0
900	60	2.3-2.8×10^6	66.2×10^3	100±0
2450	60-90	0.8-1.1×10^6	66-122×10^3	90 - 100
2450	120	0.8-1.1×10^6	136-155×10^3	100

Table 11. *Action of continuous-wave-RF-radiation at 47.5 , 900 and 2450 MHz on microscopic fungi (micromictets).*

Fungi species	×10^6 spores of fungi species in 1 kg of grain			
	Untreated control	Exposure, sec		
		60	120	180
900 and 2450 MHz, stationary mode				
Aspergillus fumigatus	23.78±1.7	17.37±3.19	23.95±3.17	18.8±2.94
Cladosporium cladosporioides	5.72± 0.73	1.05± 0.21	0.55± 0.33	2.62± 1.12
Cladosporium cladosporioides	7.30± 0.94	1.96± 0.29	0.25± 0.25	0.05± 0.05
Aspergillus candidus	11.5 0.5	7.36 1.50	5.27± 1.08	2.12± 1.28
Aspergillus fumigatus	13.26± 0.71	6.85± 0.76	2.64± 0.33	0.62± 0.12
47.5 MHz, 2 pulses/second, U=5.75 KV				
Aspergillus fumigatus	13.64± 0.62	19.94± 3.54	15.44± 1.38	15.5± 1.84
Cladosporium cladosporioides	5.72± 073	2.94± 1.54	5.16± 2.13	4.31± 1.38
Cladosporium cladosporioides	7.30± 0.94	1.95± 0.31	2.25± 0.28	1.60± 0.17
Aspergillus candidus	11.44± 1.14	3.80± 0.73	3.65± 0.53	3.88± 1.63

Chapter V

In this work a promising method of grain and grain product treatment was investigated in which grain containing the pests was subjected to RF-electric fields. There are two interpretations for the response to the application of the RF-fields.

For the first, the RF fields influence on the treated material causes considerable heating of the living pest organisms that causes their death.

The second possible explanation is of great interest as it does not attribute the action to heating of the organisms. For example, the application of RF-fields of $10^7 - 10^8$ Hz, which satisfies the relationship $h\upsilon < kT$, where $h\upsilon$ is the quantum energy of the RF-fields, k is Boltzmann's constant and T is the absolute temperature of the treated body, has a specific effect on the biological objects that cannot be explained only from the thermal influence of the RF fields.

In the case of insects treated by short pulses of RF-radiation, one can take into consideration the following:

Insects have higher structural organization than lower biological forms and have higher sensitivity to RF-radiation. During the realization of the selective overheating effect, insect death directly depends upon nervous system damage and is related with electromagnetic irradiation parameters: frequency and intensity (strength) of the electric field. At the selected exposures the reproductive capability disappears and the biotype population does not multiply.

The experiments on granary weevil at 47.5 MHz in the pulse modulated radiation regime showed that insect mortality depends more on the generator power voltage (U, kV) than on exposure time. The mortality of granary weevil at 47.5 MHz in the coaxial irradiation chamber during the pulse modulated treatment is related with the field intensity and voltage. At the voltage U=10.5 kV the treatment duration lasting from 5 to 60 seconds did not provide 100% insect mortality. To solve this problem the irradiation chamber with the plane capacitor was designed and used as a part of the technological equipment. The highest granary weevil mortality level (100%) was reached at pulse modulated RF-radiation at 47.5 MHz in the irradiation chamber with a plane capacitor at high field intensity 2000 kV/m, which is the most effective as the means of the insect control. The action RF-radiation at 900 and 2450 MHz on granary weevil (*Sitophilus granarius*) in the coaxial irradiation chamber with stationary mode also gives good results as 90-100% insect mortality at exposures of 60-120 seconds.

The continuous-wave RF treatment of wheat at 900 and 2450 MHz at exposures of 120-180 seconds, some 55-97% of fungi suppression was observed for *Cladosporium cladosporioides* and *Aspergillus candidus*. The experience on fungi control shows their sensitiveness to the wave length and the generator power variations. At the frequency 47.5 MHz and the generator power voltage U=10.5 kV fungi growth increased. Microscopic fungi suppression is normally difficult to predict. For example, for the frequencies 900 and 2450 MHz the *Aspergillus fumigatus* suppression of 27% and 21% was achieved at exposure times 60 and 180 seconds respectively, but 0.7 % of fungi reproduction was observed at exposure time 120 seconds in one series of replications. Nevertheless, the frequencies 900 and 2450 MHz gave 21-97% fungi suppression in majority of cases for different species and exposure times (Table 11).

Physical and biological investigation showed that electric field intensity increasing in the processed zone is one of the most important factors for insect control. For this reason, the experiments were performed on two types of the equipment distinct by the mode of the radio-frequency high-strength electric field application to the biological objects. Both systems have their advantages and disadvantages. The system with the coaxial feeder chamber gives experimental results on granary weevil *(Sitophilus granarius)* mortality of 85-96% at maximum generator power voltage U=10.5 kV and exposure times of 5-25 seconds. The experiment on granary weevil at 47.5 MHz in pulse modulated radiation regime depends on both the generator power voltage and exposure time. If the electric field intensity is not sufficiently high, the time of exposure has very little influence. If it is high enough to be effective, then no longer expose time than what is necessary to achieve 100% insect mortality should be used. The system is economically profitable due to the comparatively low energy consumption. The system with the irradiation chamber with a plane capacitor gives better biological effect on granary weevil that can not be definitely predicted (67-100% insect mortality) at the exposures 0.5-30 seconds and field intensity 350-1000 kV/m but it reaches the best results (100% insect mortality) at the exposures 1-30 seconds and the field intensity 2000 kV/m. Continuous-wave RF-radiation at frequencies 900 and 2450 MHz of granary weevil *(Sitophilus granarius)* in the coaxial irradiation chamber with stationary mode reaches 100% insect mortality at major exposure times for both frequencies (Table 10). If a frequency and exposure time are sufficiently high, it requires less of power radiation to achieve 100% insect mortality. The exposures 120-180 seconds at frequencies 900 and 2450 MHz in the irradiation chamber with a plane capacitor give to 90% of microscopic fungi suppression. But fungi suppression is normally very difficult to predict, because at certain conditions some species (*Aspergillus fumigatus)* continue to reproduce. Further investigation is needed for microscopic fungi control. The system with the irradiation chamber with plane capacitor is an effective means of insect and fungi control. The experiments show that the RF-technology for fodder and product treatment to destroy contaminating micro flora and pests is promising, since it is the safest method for environmental protection.

5.II. INSECT CONTROL BY USE OF THE COMPLEX METHOD OF GRAIN PROCESSING WITH ELECTROMAGNETIC RADIATION

The advanced experimental results of the insect control after grain processing with electromagnetic radiation are given here. The complex method used in this investigation includes three factors of influence on pests such as vacuum, high frequency and plasma. The combined technological equipment was designed in the frames of this work. Optimal combination of vacuum, high frequency and plasma leads to high efficiency on pest suppression.

The experimental results given below are considered as a search of new possible methods of insect control. The principle of combination of three factors of influence (high-frequency radiation, vacuum and plasma) on pests in pulse modulated regime provided noticeable advance in the area. The general scheme of the designed laboratory equipment is presented in Fig.5.7.

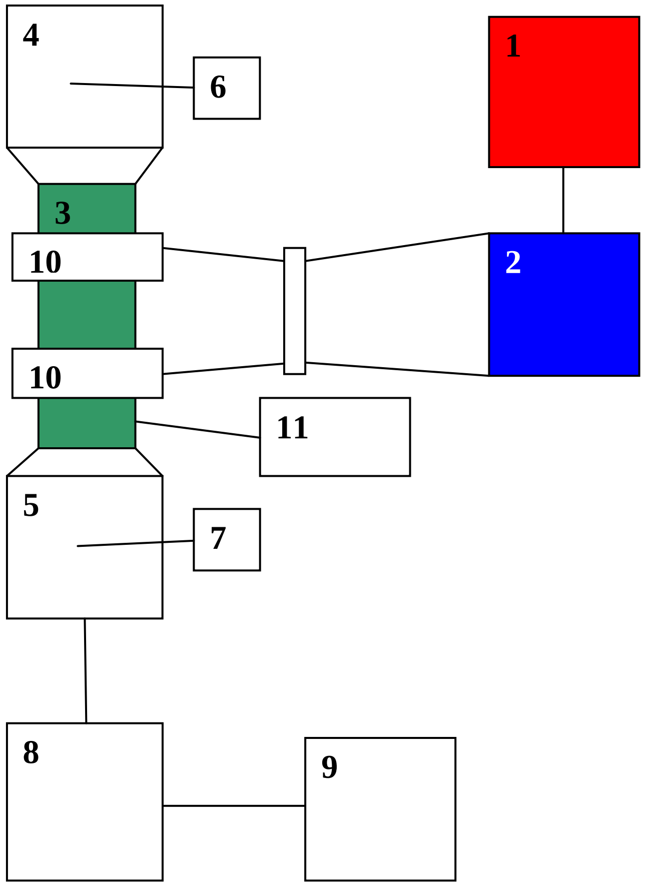


Fig.5.7. The general scheme of the laboratory equipment

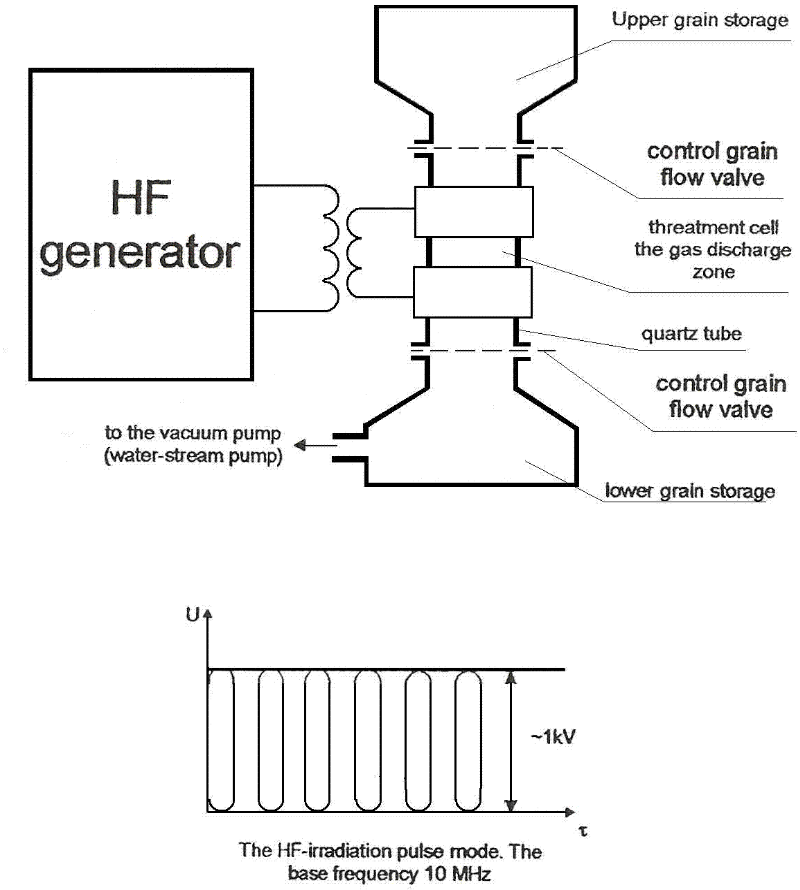
1 – power (feeding) source accorded with a HF-generator (power level 1-2.5 kW).
2 – HF-generator. The probable frequency 1-50 MHz. For laboratory experiments the power of 1-2 kW is appropriate.
3 – Channel of a quartz tube, through which the grain is poured. In the previous experiments there was a mechanism serving to push the grain. The mechanism material was dielectric, e.g. tephlon.
4-5 – delivering and receiving tanks made of stainless steel. The pressure in these tanks 10-50 torr is maintained by the vacuum pump 9 and the valve 8. This is needed to initiate electrodeless high-frequency discharge. At that the grain is poured or pushed through the discharge zone. Plasma interacts with grain surface or insect that is immediately the purpose of our work. The working parameters in the chamber are controlled with thermo pairs 6 and 7 and with manometer 11.

Insect Control of Grain with Electromagnetic Wave Sources

The energy from the stable electromagnetic wave sources was applied within the processing chamber as the method of insect control. Output power in the range 0.5-5.0 kW generate the electromagnetic waves with electric field intensity E_0~ 200-500 V/cm. The lowest level of electric field intensity E_0=200 V/cm in the volume of single grain releases 0.025 W of heat that is 0.5 W per 1 cm^3 of grain mass. In order to heat 1cm^3 of grain at 10% moisture content 80 sec are required or 100 sec at 20% moisture content. If we consider grain – insect mixture in high-frequency fields, it allows approximately 1-1.5% grain drying with total energy expenses approximately 1 J per each gram of mixture.

Combined Laboratory Equipment

The experimental part of the work [1-4, 12] was done on the Combined Laboratory Equipment Fig. 5.8. The main parts of the equipment are: 1) high-frequency generator; 2) feeder track and active load and 3) irradiation chamber (for grain processing).



The HF-irradiation pulse mode. The base frequency 10 MHz

Fig.5.8. The Combined Laboratory Equipment scheme and mode.

The high-frequency generator includes three booster cascades, high-voltage supply system (modulator), the positive back-coupling system.

The first booster cascade is fabricated on the base of a power pulse triode in the metal-ceramic box with the tungsten gaffer cathode, outer water cooling anode and with trans-electrode capacitors: the input capacitor ≤ 120 pF, the output capacitor ≤ 2.3 pF, the auxiliary capacitor ~40 pF. Anode is a coaxial tube with outer diameter 0.4 m and inner diameter 0.21 m, with wall thickness 2 mm. The outer cylinder is made with exits for air from radiator. The length of resonance counter for this frequency is equal to 1384mm. The mobile capacity piston is used for adjustment in the lower part of resonance counter. The calculation of coupling capacity with the next stage gives C = 24.4 pF. With input signal of 2kW this cascade boosts up to 10kW. The second booster cascade is the power pulse tetrad in metal-ceramic box with tungsten thorodized- carbidized cathode with direct heating. Trans-electrode capacitors are: the input capacitor ~125±25 pF, the output capacitor ~$37\pm^{8}_{7}$ pF, the auxiliary capacitor ≥0.5 pF, but ≤1500 pF. The anode cooling is water type with water expense ~ 20 l/min. The resonator is coaxial. The calculated length of resonators is equal to 1535mm. This cascade input power is 10kW and the output power is 300 kW. The third booster cascade is based on a triode of the higher power and the scheme analogue to the one of the first cascades. The input power of this cascade is 300 kW and the output one is 1000 kW.

The generator cooling system needed for the generator and its components provides the appropriate temperature regime. The cooling is provided with non-salt water with specific electric resistance equal to 500 kOhm/sm at temperature +20ºC. The total water expenses are ≤ 29L/min at the entrance water temperature not exceeding +40ºC and not lower than +18ºC.The pressure difference between input and output of the cooling system is not exceeding 3.0±0.1 atm. The maximum pressure of free salt water at the entrance of the cooling system is ≤ 6 atm. The total expenses of technical water at temperatures 16ºC< T <25ºC are ~ 6 L/min. The autonomy air cooling system for generator components is like a circuit system that provides the temperature not exceeding 40ºC inside the generator. The air expenses are ≤70m^3/h. The modulator (high-voltage source) supplies the energy to the anode from high-frequency generator and its components.

The modulator includes:

- The sources of alternating current:
  1) three-phase source - 220/127 V, 400 Hz, power 1.15 kW; 2) three-phase source with insulated neutral – 720 V, 50 Hz, power 32 kW; 3) three-phase source – 380/220, 50 Hz, power 1 kVA; 4)one-phase source – 220/127 V, 400 Hz – power 0.11 kVA; 5) one-phase source – 380/220V, 50 Hz – power 7 kVA; 6) one-phase source – 24 V, 50 Hz – power 0.3 kVA.
- The power part of the modulator consumed energy from three-phase alternating current source of voltage 720 V, 59Hz, conversion into the energy of high voltage pulses;
- The control blocks for the internal and external signals control;
- The control blocks of modulator on-off switching, formation of initial pulses, for selection of modulator operating mode, control and stabilizing of outer parameters.

The modulator provides the following parameters:

- The pulse duration – 300 mcsec;
- Non-uniformity of pulses ±1.5 per cent;
- Pulse frequency 10-25 Hz.

The following parameters were obtained in the generator equivalent load:

1) Exit power in the circuit +27 kV – 2000 kW;
2) Exit power in the circuit +10 kV – 600 kW;
3) Exit power in the circuit +6.0 kV – 35 kW;
4) Exit power in the circuit +2.5 kV – 2.5 kW.

The technical water is used for the ballast resistors cooling. The water expenses are 12±0.5 L/min with exit pressure 2.5±0.5 atm. The entrance water temperature is not higher than +25ºC. Maximum allowable pressure in the cooling circuit is ~600 kPa. The water cooling must be provided with the water supply 500±70 m^3/h.

The coaxial type irradiation chamber and active load are the parts of the Combined Laboratory Equipment (Fig.5.8). These are needed for high-frequency energy transmission from generator to biological objects in the processing chamber.

The operating chamber was designed as a quartz tube with outer diameter ~21.5 mm and inner diameter ~25.7 mm in the volume ~43.5 cm^3. The tube was fixed with plumb and sustained in its top and bottom edges. The vacuum rubber rings enclosed the external surfaces of the tube. The top provided the air access to the internal volume of the working chamber from the gas supply system. The bottom contained valves for connection with vacuum system and pointer vacuum-meter. Fast top disjunction was possible due to the special construction of both connection sets. To avoid the material penetration into the quartz tube bottom after high-frequency processing, the bottom was fixed with the plastic grid that gave minimum losses of the chamber evacuation speed.

The Combined Laboratory Equipment high-frequency part included the high-frequency generator and the coordination adaptor with electrode system of the working chamber. The high-frequency furnace was used as the high-frequency generator. The outer inductor of the furnace was used as the unit that delivered power from the generator through the chamber. The connective inductor was added to the main inductor and supplied the transmission of high-frequency energy by double wire to the electrode system of the working chamber. There was the obvious necessity of the cooling system design since the high-frequency generator power was exceeding 1.5 kW. The inductor air cooling originated from the generator construction. The connective inductor was made of cooper that allowed including both transformer elements into the cooling contour. The conductors were fixed one relative to another with the ceramic elements (Al_2O_3 and SiO_2) that provided the excellent dielectric properties during heating to high temperatures. The system of ring electrodes surrounded the quartz tube provided the high-frequency fields (at the working generator frequency ~ 10 MHz) induced in the working chamber of the Combined Laboratory Equipment. Different types of electrodes were used that gave the opportunity to vary the discharge distances that influenced the high-frequency field distribution in the Combined Laboratory Equipment. The designed working chamber provided three factors of influence during the biological objects processing that were the low pressure (vacuum), the high-frequency irradiation and plasma processing in high-frequency discharge of E-type. Moreover, the possibility of the three factors combination is essential in this investigation and perspective for the future technology development.

When the generator was switched off, the vacuum processing takes place. The switched on generator made possible the high-frequency processing only at the atmospheric pressure. At the certain pressure value within the operating chamber the high-frequency discharge appears and the three factors of influence are presented. The research confirmed that the discharge existed in a wide range of pressure from 10^{-4} to 50×10^{-3} Pa and even more. There was the necessity to maintain the high-frequency power at high pressure that was the condition of discharge existence. At relatively high pressure the discharge existence depends on generator power. It was observed that before discharge disappearing and high-frequency increasing the thermal damage of grain was possible. The optimal parameters in the working chamber were determined and the discharged electrodes were chosen in order to resolve the problem of thermal damage of grain. The highest pressure level achieved in the experiment was 20×10^{-3} Pa and the high-frequency power not exceeding 1 kW. During the experiment with the different biological objects the precise control of parameters series was necessary as for the discharge volume and the medium of the biological object processing. Among them the following parameters were: the power level supplied to working chamber electrodes (or the voltage supplied to the chamber electrodes and the consumed current), the processing zone temperature, the processing zone pressure, the moisture content of the radiated medium, etc. The Combined Laboratory Equipment required the design of the gas supply system to control the pressure level within the range from 10^{-3} Pa to 0.2 Pa at the proper power level. The Combined Laboratory Equipment scheme is given in Fig.5.4.

The chamber (Fig. 5.1) was made from standard copper coaxial 160mm/70mm feeder line 1 meter in length with a ceramic tube mounted coaxially between the center and outer conductors. Special windows were made for entrance and exit of grain. The infested grain flowed from the upper grain container through the ceramic isolator tube around the inner conductor (Fig.2). The ceramic isolator (dielectric permittivity $\varepsilon \approx 1$) helped to limit the variation in the radial electric field intensity between the coaxial line center conductor and outer conductor. At one end, the coaxial-line feeder was connected to the RF-generator output, and the other end connected to the active generator load. In this case, an electric field of 6.2×10^5 V/m was achieved close to the surface of the inner conductor (radius = 0.035 m) and decreased to 4.5×10^5 V/m at the inner surface of the ceramic tube (radius = 0.06 m) at the pulse power level ~ 1.0×10^6 W. Both radii are given from the coaxial-line axis to the point where the electric field is estimated inside the coaxial line processing zone.

One can note that in this coaxial applicator the amplitude of the radio-frequency electric field is limited. The pulsed mode helps to overcome this problem and to achieve pulsed electric field strength of approximately 3×10^6 V/m.

Experiments

After the radiation treatment of insect-infested grain, biological evaluation was done in the Institute of Experimental and Clinical Veterinary Medicine (Ukraine). The ecological-faunal and entomological investigations were carried out at the storehouses of grain, bread-products enterprises, and at the cattle breeding farms. Thirty-six species of insects were allocated, belonging to three orders and thirteen families. The biological features of the most widespread kinds, namely weevil (*Curculionidae*), such as barn weevil (*Seratophilus granarius*), rice weevil (*Sitophilus oryzae*), black mealworm (*Tenebrionidae*) and yellow mealworm (*Tenebrio molitor*), confused flour beetle (*Tribolium confusum* Jacquelin du Val), pitch-brown cockchafer (*Alphitibius diasperinus*), Angoumois grain moth (*Sitotroga cerealella*) and barn moth (*Nenapogon granellus)* were investigated. Twenty-six species of mites were revealed, among which it is necessary to note a number of barn mites (*Acariformes*) and bread mites *(Acaridae*), belonging to the grain mite (*Acarus siro* Linnaeus). The experiments show that the RF-technology for fodder and product treatment to destroy contaminating micro flora and pests is promising, since it is the safest method for environmental protection. The results given below were achieved in the experiments with three factors of influence, which are vacuum (the pressure not exceeding 40×10^{-3} Pa), high-frequency (the working frequency was 10 MHz) and plasma at variable time of treatment and generator power. The O_3 treatment was applied in the high-frequency plasma. The investigation confirmed a very high efficiency of the complex method of grain processing. The control tests (the separate experiments with vacuum or high-frequency radiation without discharge) showed that the insect mortality level was sufficiently low. The Tables 12-15 show that the three factors influence (with plasma applied) on pests cause them a nervous shock (insects turn on the back with frequent and lasting convulsions, often immovable in the first minutes after the treatment) and the consequent mortality. The few insects survived after the treatment lost their reproduction capability. The investigation results confirm that the most perspective grain processing is the complex technology based on the high-frequency radiation with gas discharge formation.

Table 12. Complex factor influence on the grain pests (vacuum, HF radiation, plasma).

Pest Kinds	Generator Electric current, mA	Treatment time, sec.	Mortality, %	
			Shock	5 days later
Granary Weevil (Sitophilus granarius)	200	20	100	100
	200	10	60	100
	250	10	60-80	100
	250	5	20	60
	300	10	100	100
	300	5	60	100
	350	5	60-70	75-100
	400	5	100	100
Drugstore Beetle (Stegobium paniceum)	200	20	100	100
	200	10	50	100
	250	5	60	50
	300	5	60	100
	400	5	100	100
Destructor Fluor Beetle (Tribolium Desctructor)	200	20	100	100
	250	10	60	100
	300	10	100	100
	350	5	50	100
Laemostenus Ferreigenineus	200	20	100	20
	250	10	20-60	40-60
	350	5	40	100
	400	5	100	100

Table 13. Complex factor influence on the grain pests (vacuum, HF radiation, plasma).

Pest Kinds	Pressure, × 10^{-3}Pa	Generator Electric current, mA	Treatment time, sec.	Mortality,%		Notice
				Shock	5 days later	
Granary Weevil(Sitophilus granarius)	760	200	20	0	0	
	760	300	20	0	0	
	760	300	40	10	0	
	760	300	60	50	80	
	760	400	20	40	0	
	760	400	40	80	33	
	40	300	20	0	0	
	40	300	40	20	0	
	40	400	20	0	0	
	40	400	40	20	0	
	6	200	20	80	100	Plasma
	7.5	200	10	60	100	Plasma
	7.5	300	20	80	100	Plasma
	7.5	300	10	60	100	Plasma
	7.5	400	10	100	100	Plasma
	7.5	400	5	80	100	Plasma
	7.5	500	5	100	100	Plasma
	7.5	500	3	90	100	Plasma
Laemostenus ferreigineus	6	200	20	80	100	Plasma
	7.5	200	10	60	100	Plasma
	7.5	300	10	80	100	Plasma
	7.5	400	10	100	100	Plasma
Drugstore Beetle (Stegobium Panicemin)	6	200	20	80	100	Plasma
	7.5	300	20	100	100	Plasma
	7.5	300	10	80	100	Plasma

Table 14. Complex factor influence on the grain pests (vacuum, HF radiation, plasma arcing). Vacuum from $3.3 \div 18.4 \times 10^{-3}$Pa, vacuum action time 30 sec.

Pest Kinds	Generator Electric current, mA	Arcing current, A	Treatment time, sec.	Pest Mortality, % for 5 days
Yellow Mealworm (tenebrio molitor).	300	2.45	3.5	100
	300	2.45	5	100
	300	1.8	20	100
	300	1.8	25	100
Granary Weevil (Sitophilus granarius)	300	1.8	5	100
	300	1.8	7	100
	300	1.8	10	100
	300	1.6	13	100
	300	1.8	20	100
	300	1.8	22	100
	300	1.6	30	100
	300	1.8	32	100
	300	2.45	2.5	40
	300	2.45	3.5	55
	300	2.45	10	84 - 100

Table 15. Complex factor influence on the grain pests (vacuum, HF radiation, plasma arcing). Vacuum from $3.3\div18.4\times10^{-3}$Pa, vacuum action time 30 sec.

Pest Kinds	Generator Electric current, mA	Arcing current, A	Exposure, sec	Pest Mortality, % for 5 days
Granary Weevil(sitophilus granarius)	220	1.3	20	100
	220	1.3	30	100
	190	1.1	10	100
	190	1.1	15	29
	190	1.1	20	100
	190	1.1	30	100
	160	0.9	10	100
	160	0.9	20	100
	140	0.7	30	100
	140	0.7	45	63 - 100
	140	0.7	60	100
	120	1	5	100
	120	1	10	91 - 100
	120	1	10	100
	120	1	15	100
	120	1	20	100
	120	1	30	90 - 100
	60	0.5	30	95 - 100

Chapter V

Discussion

The investigation described here [3,4,12] gives the first experience of the technology of grain protection from harmful insects on the base of the high-frequency radiation with other factors of influence such as vacuum, HF modulation with the high voltage pulses (the electric field intensity exceeding 3-4 kV/cm) and the parametric combination of the mentioned above factors. The optimal factors combination leads to more effective results of pest suppression. The analysis of the work presented here permits to make the following conclusions:

- Insects have higher structural organism and are sensible to high-frequency radiation. During the selective overheating an insect death directly depends on a nervous system damage and is related with the electromagnetic radiation parameters such as frequency and the electric field intensity.
- The highest efficiency was observed when the complex factor influenced on pests (vacuum, high-frequency radiation, plasma). During the comparatively short treatment time the insects suppression was achieved.
- It was shown that the efficiency of the developed technology (modulated pulses at frequency 80MHz and combination of vacuum and plasma) was one order higher than the one based on the overheating mechanism.
- Due to the research the technology proved its biological safety and ecological purity.

The Combined Laboratory Equipment design and manufacture and the accomplished experiments gave the fundamental to the perspective high-efficient ecological competitive technology for grain and grain products protection from harmful insects.

General Conclusions

General Conclusions

General Conclusions

During the accomplishment of this work few important observations and conclusions were made. First of all the new mathematical model developed here serves considerably to the development of the technology of grain processing and disinfestation by the electromagnetic fields of high-frequency as an effective and ecological method alternative to the existed chemical methods. The experience gained gives the reasons to conclude that the biological cells of a dielectric body material (grain, insects) are very sensitive to the action of the external electromagnetic fields. And as a consequence the internal electromagnetic field is formed within each individual dielectric particle. Insect as the living creatures with more complex biological structure give different response to the electromagnetic field action in comparison to grain crops of simpler biological organization and also as far as each material possesses its own electrophysical characteristics (dielectric permittivity, magnetic permeability and conductivity) and responses uniquely. The new method of dielectric properties measurement is proposed in this work that contributed to the mathematical model precision and proved to be efficient through the series of the conducted experiments. The mathematical model is simple and has some approximations. The shape of each individual particle is considered as an ideal ellipsoid of rotation or a sphere. The external electromagnetic field is homogeneous that also produces homogeneous internal electromagnetic field within each individual particle of the ellipsoid of rotation form. The models developed in the past concern granular product as a bulk material, the two-componential mixture “air-grain”, penetrated by the external electromagnetic field. The new model presented here is completely different by its methodological approach that permits more precise consideration and calculation of the main physics parameters. The methods based on integral equations of macroscopic electrodynamics and the boundary conditions are used to solve the problem of electromagnetic field interaction with an individual dielectric particle of the ellipsoid of rotation form. The model may be extended and discussed for non-homogeneous anisotropic case which is much more complicated. We need also more profound investigation of thermal and other cellular effects that the high-frequency electromagnetic field produces in insects and microscopic fungi. The author also claims for the future perspective of electromagnetic interaction modeling at the level of human body cells by making the macroscopic electrodynamics serve to complex micro systems, the biological cells, and to produce the appropriate cellular tissue response as an effective electric stimulation methods.

References

References

References

1. Akimov B. et. al. Simulation of Radioactive Affection by Electromagnetic Irradiation, (in Russian), *Proceedens of the I-st Radio-Biological Convention*, 3, pp. 683-687, 1984.

2. Baker V. H., Wiant, D. E., and Taboada O. Some Effects of Microwaves on Certain Insects Which Infest Wheat and Flour., *J. Econ. Entomol*., 49(1), pp.33-37, 1956.

3. Brown G.H., Hoyler C.N. and Bierwirth R.A. *Theory and Application of Radio-Frequency Heating,* New York, Van Nostrand Co, 1947.

4. Frings H. Factors Determining the Effects of Radio-Frequency Electromagnetic Fields and Materials They Infest, *J. Econ Entomol.*, 45(3), pp. 396-408, 1952.

5. Grumet A.E. Electric Stimulation Parameters for as Epi-Retinal Prosthesis. Thesis for the obtainment of the PhD degree, Massachusetts Institute of Technology, 1999.

6. Hamid M.A.K., and Boulanger R.J. A New Method for the Control of Moisture and Insect Infestations of Grain by Microwave Power, *J. Microwave Power*, 4(11), pp.11-18,1969.

7. Kudryashov Y. B. Biophysical Fundamentals of Microwave Action, *Moscow, MGU*, 160 p., 1980.

8. Landau L.D., and Lifshitz E.M. Electrodynamics of Continuous Media, Vol.8, *Course of Theoretical Physics*, Oxford, England, pp.45-47, 1960.

9. Lawrence K. C., Nelson S.O., and Kraszewski A.W. Temperature Dependence of the Dielectric Properties of Wheat, *Transactions of the ASAE*, 33(2), pp. 535-540, 1990.

10. Lawrence K.C., Nelson S.O., and Bartley P.G., Jr. Measuring Dielectric Properties of Hard Red Winter Wheat from 1 to 350 MHz with a Flow-Through Coaxial Sample Holder, *Trans. ASAE*, 41(1), pp. 143-150, 1998.

11. Lindauer G.A., Liu L.M., Skewes G.W. and Rosenbaum F.J. Further Experiments Seeking Evidence of Nonthermal Biological Effects of Microwave Radiation, *IEEE Trans. Microwave Theory Techn.* MTT-22(8), pp. 790-793, 1974.

12. Metaxas R.C. and Meredith R. J. *Industrial Microwave Heating.* Herts, U.K., Peter Peregrinus Ltd., 1988.

13. Mishchenko A.A., Malinin O.A., Rashkovan V.M., et. al. Complex High-Frequency Technology for Protection of Grain from Pests, *J. of Microwave Power and E. E*., 35(3), pp. 179-184, 2000.

14. Münzel F. Schädlingsbekampfung in Zeralienlagern mittels physikalischen Methoden, *Alimenta,* 14(1), pp. 7-9, 1975.

15. Nelson S.O. and Kantack B.H. Stored-Grain Insect Control Studies with Radio-Frequency Energy. *J. Econ. Entomol.,* 59(3), pp. 588-594, 1966.

16. Nelson S.O. and Walker E.R. Effects of Radio Frequency Electrical Seed Treatment. *Agricultural Engineering*, 42(12), pp. 688-691, 1961.

17. Nelson S.O. and Whitney W.K. Radio-Frequency Electric Fields for Stored Grain Insect Control, *Transactions of the ASAE* 3(2), pp. 133-137, 144, 1960.

18. Nelson S.O. Density Dependence of Dielectric Properties of Wheat and Whole-Wheat Flour, *J. of Microwave Power and E. E*., 19(1), pp. 55-64, 1984.

References

19. Nelson S.O. Electromagnetic Energy, *Chapter 3:* Pest Control – Biological, Physical and Selected Chemical Methods, *eds.*W.W. Kilgore and R.L. Doutt. Academis Press, New York, 1967.

20. Nelson S.O. Insect Control Studies with Microwaves and Other Radiofrequency Energy. *Bull. Entomol. Soc. Am.*19(3), pp. 157-163, 1973.

21. Nelson S.O. Insect-Control Studies with Microwaves and Other Radiofrequency Energy. *Bull. Entomol. Soc. Am.,* 19(3), pp. 157-163, 1973.

22. Nelson S.O. Microwave Dielectric Properties of Insects and Grain Kernels, *J. Microwave Power*, 11(4), pp.299-303, 1976.

23. Nelson S.O. Radio-Frequency and Microwave Dielectric Properties of Insects, *J. of Microwave Power and E. E.*, 36(1), pp.47-56, 2001.

24. Nelson S.O. Review of Factors Influencing the Dielectric Properties of Cereal Grains, *Cereal Chem.,* 58(6), pp. 487-492, 1981.

25. Nelson S.O., and Stetson L.E. Frequency and Moisture Dependence of the Dielectric Properties of Hard Red Winter Wheat, *J. Agric. Eng. Res*., 21, pp. 181-192, 1976.

26. Nelson S.O., Bartley P.G., Jr., and Lawrence K.C. Measuring RF and Microwave Permittivities of Adult Rice Weevils, *IEEE Transactions on Instrumentation and Measurement,* 46(4), pp. 941-946, 1997.

27. Nelson S.O., Stetson L.E. and Rhine J.J. Factors Influencing Effectiveness of Radiofrequency Electric Fields for Stored-Grain Insect Control. *Transactions of the ASAE* 9(6), pp. 809-815, 817, 1966.

28. Nelson S.O., Yung F.D., and Soberholm L.H. Determining the Dielectric Properties of Grain, *Agric. Eng.*, 34(9), pp.608-610, 1953.

29. Nelson, S. O., and Charity. L. F. Frequency Dependence of Energy Absorption by Insects and Grain in Electric Fields, *Transactions of the ASAE*, 15(6), pp.1099-1102, 1972.

30. Ondracek J. and Brunnhofer V. Dielectric Properties of Insect Tissues. *Gen Physiol.Biophys.*, 3, pp. 251-257, 1984.

31. Presman A S., and Rappoport S.M. Electromagnetic Fields and Biology. *Bull. for Experim. Biol*., 59(4), 48p., 1965.

32. Rashkovan V.M., Khizhnyak N.A., Basteev A. V., Bazyma L.A., Niño de Rivera Luis, and Ponomaryova I.A. Interaction of Electromagnetic Waves with Granular Agricultural Product and Insects, *J. Microwave Power and E.E*., 38(4), pp. 1-12, 2003.

33. Schastnaya P.I. HF-irradiation of Biological Objects. *Proceedings of the Kharkov State Medical Institute*, 15 (36), 239p., 1958.

34. Stratton J.A. *Electromagnetic Theory,* 206p., New York: McGraw Hill Book Co, 1941.

35. Stratton J.A. *Electromagnetic Theory*, p.206, New York, Mc Graw Hill Book Co, 1941.

36. Tateya A. and Takano T. Effects of Microwave Radiation on Two Species of Stored-Product Insects. *Res. Bull. Pl. Prot. Japan,* 14, pp. 52-59, 1977.

37. Thomas A.M. Pest Control by High-Frequency Electric Fields, Critical résumé, Tech. Rep. W/T23, Leatherhead, Surrey, England: British Electric and Allied Industries Assoc., 1952.

38. Tinga W.R., and Nelson S.O. Dielectric Properties of Materials for Microwave Processing-Tabulated, *J. Microwave Power*, 8(1), pp.23-65, 1973.

39. von Hippel A.R. *Dielectrics and Waves,* 28, New York: John Wiley & Sons, 1954.

References

40. Witney W.K., Nelson S.O. and Walkden H.H. Effects of High-Frequency Electric Fields on Certain Species of Stored-Grain Insects. Market. Res. Rep. 455. USDA, MQRD, AMS, 1961.

41. Zakladnoi G.A., and Rabanova V.F. Pests of Grain Stores and Combating Measures, *Moscow,"Kolos"*, 254 p., 1973.

Appendix