INTERACTION OF ELECTROMAGNETIC WAVES WITH GRANULAR AGRICULTURAL PRODUCT AND INSECTS

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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 relative dielectric permittivity and the relative loss tangent as a function of grain moisture content are measured. Drying and disinfestation of wheat grain by electromagnetic methods are observed.

Key Words: electromagnetic radiation, frequency, permittivity, insects, grain.

Protection of the grain from harmful insects, mites and microscopic fungi is a worldwide problem of great importance to 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 two positive effects. On the one hand, 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 by pests.

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 (Kudryashov, 1980 and Akimov, 1984). The nature of work was mainly experimental because the problem was physically complicated. The success in solving electromagnetic boundary problems (Khizhnyak, 1986) makes theoretical research on electromagnetic wave interaction with granular agricultural products possible as has been realized in the present work.

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

$$W = \rho V C_x \Delta T, \qquad (1)$$

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

$$C_x = L_0 C + (1 - L_0) C_0 \qquad (2)$$

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depending on moisture contentL_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 ($C_c = 1.32\ kJ / kg \bullet K$[1]).

According to all these notes one can define:

$C_{5\%} = 1{,}54,.J/g \bullet$ deg.... $(kJ/kg \bullet$ deg.)
$C_{10\%} = 1{,}604,.J/g \bullet$ deg.... $(kJ/kg \bullet$ deg.)
$C_{15\%} = 1{,}750,.J/g \bullet$ deg.... $(kJ/kg \bullet$ deg.)
$C_{20\%} = 1{,}894,.J/g \bullet$ deg.... $(kJ/kg \bullet$ deg.)
$C_{25\%} = 2{,}035,.J/g \bullet$ deg.... $(kJ/kg \bullet$ deg.)

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 parameterρ, 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 (Nelson, 2001) for wheat in the Table 1.

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 (Nelson, 1981).

The given data permit estimation of heat expenditure for heating of a grain mass of different moisture contents through temperatures of both 1° C and 40° C.

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

At 0° C	$W_c = 2480 kJ / kg$
At 30° C	$W_c = 2421 kJ / kg$
At 99.96° 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° C,
121 kJ per 1 kg of grain at 30° 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 (Atomizdat, 1980) that decreasing atmospheric pressure leads to a reduction of the water boiling temperature at equilibrium but increases the specific heat of vaporization.

Basic Electrodynamics Equations

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

$$\varepsilon_0 = \varepsilon'_0 - i\varepsilon''_0 \tag{3}$$

(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 (Khizhnyak, 1986):

$$\frac{\varepsilon - 1}{\varepsilon - 2} = C\frac{\varepsilon_0 - \varepsilon_1}{\varepsilon_0 + 2\varepsilon_1} \tag{4}$$

where C is the volumetric concentration, or volume fraction, of granular particles. As well known, the Clausius-Mosotti Formula (4) for quasistatic conditions is valid in the limiting case of particles very much

Table 1: *The relative ε' and imaginary part ε'' of dielectric permittivity at 11.7 MHz of grain in relation to moisture content*

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

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/m³).*

Heat for		$1^\circ C$	$40^\circ C$
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

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 4.

The physical model of any individual seed of grain is a stretched ellipsoid of rotation with permittivity (3), 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

$$tg\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{4\pi\sigma}{\omega\varepsilon'} \qquad (5)$$

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

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

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 tgδ by Equation 5.

The task leads to the definition of the field $\bar{E}$ 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 (Khizhnyak, 1986) is presented as

$$\vec{E}\begin{bmatrix} \dfrac{1}{1+\dfrac{a^2c}{2}(\varepsilon-1)j_1} & 0 & 0 \\ 0 & \dfrac{1}{1+\dfrac{a^2c}{2}(\varepsilon-1)j_2} & 0 \\ 0 & 0 & \dfrac{1}{1+\dfrac{a^2c}{2}(\varepsilon-1)j_3} \end{bmatrix} \bullet \begin{bmatrix} E_{ox} \\ E_{oy} \\ E_{oz} \end{bmatrix} \qquad (6)$$

where

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

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

are depolarization parameters of the ellipsoid with semi-axis a,a and c, E_{ox}, E_{oy} and E_{oz} 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

$$\vec{E} = 3\vec{E}_0^2 \cdot (\varepsilon+2)^{-1} \qquad (7)$$

If the deviation from the sphericity is not considerable, then

$$l_1 = l_2 = \frac{2}{3a^2\sqrt{1-e^2}}\left\{1-\frac{2e^2}{5}+0(e^4)\right\}$$
$$l_3 = \frac{2}{3a^2\sqrt{1-e^2}}\left\{1-\frac{13}{5}e^2+0(e^4)\right\}$$

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

Finally one can define that

$$W=\sigma\cdot V\sum_{s=1}^{3}\frac{E_{0s}^2}{\left[a+\frac{3V}{8\pi}\left(\frac{\varepsilon'}{\varepsilon_1}-1\right)\cdot l_5\right]^2+\left(\frac{3V\sigma}{2\omega}l_5\right)^2}$$

for a stretched ellipsoid of rotation, and

$$W=\frac{9V\varepsilon_1E_{00}^2}{(\varepsilon+2\varepsilon_1)^2+(4\pi\sigma/\omega)^2} \tag{8}$$

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

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

where W_1 is only a function of geometry of a dissipating body.

For the ellipsoid:

$$W=\frac{1}{9}\sum_{s=1}^{3}\frac{\varepsilon_1(E_{0s}/E_{0,on})^2}{\left[1+\frac{3V}{8\pi}\left(\frac{\varepsilon'}{\varepsilon_1}-1\right)l_5\right]^2+\left(\frac{3V\sigma}{2\omega}l_5\right)^2} \tag{10}$$

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

$$W=\frac{\varepsilon_1}{(\varepsilon+2\varepsilon_1)^2} \tag{11}$$

One can evaluate the function W_2 by the formula:

$$W_2=\frac{9}{4\pi}\omega_0V_{0n}tg\delta\cdot E_{0,on}^2\left(\frac{V}{V_{on}}\right)\left(\frac{E}{E_{0,on}}\right)^2\left(\frac{\omega}{\omega_0}\right) \tag{12}$$

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. $1cm^3$ 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 and its dielectric permittivity. If $\varepsilon \approx 2.5$ and the spherical form of an individual seed is selected,

$$W_1 \approx 0.05 \tag{13}$$

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

$$W_2=0.35\left(\frac{V}{V_{on}}\right)\left(\frac{E}{E_{0,on}}\right)^2\left(\frac{\omega}{\omega_0}\right), J/s \tag{14}$$

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:

$$W_2=\frac{0.35}{\gamma}\left(\frac{V}{V_{on}}\right)\left(\frac{E}{E_{0,on}}\right)^2\left(\frac{\omega}{\omega_0}\right), J/s \tag{15}$$

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
$\Delta Q_1 = \rho \bullet V \bullet C_p \bullet \Delta T$, kJ, 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:

$$W_2 = \frac{0.35}{m_{0\rho}\gamma C_\rho}\left(\frac{E}{E_{0,on}}\right)^2\left(\frac{\omega}{\omega_0}\right) \qquad (16)$$

where $m_{0\rho} = \rho \bullet V_{on}$ 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

$$\Delta Q = \Delta Q_1 + \Delta Q_2, \qquad (17)$$

where $\Delta Q = \frac{m_{0\rho}}{100}\left(L_F - L_I\right)q_n$, $L_{F,I}$ 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

$$\Delta T = \left[\frac{0.35}{m_{0\rho}\gamma C_\rho}\left(\frac{E}{E_{0,on}}\right)^2\left(\frac{\omega}{\omega_0}\right) - \frac{L_F - L_I}{100}\left(\frac{q_n}{C_\rho}\right)\right] \qquad (18)$$

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-sized 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.

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 $a = 0.1cm, c = 0.175cm, V = 7.3 \bullet 10^3 cm^3$. 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:

$$W_2 = 14.6\left(\frac{V}{V_{on}}\right)\left(\frac{E}{E_{0,on}}\right)^2\left(\frac{\omega}{\omega_{on}}\right), J\ /\ s \qquad (19)$$

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

$$W_2 = \frac{0.32}{\gamma}\left(\frac{V}{V_{on}}\right)\left(\frac{E}{E_{0,on}}\right)^2\left(\frac{\omega}{\omega_{on}}\right) \qquad (20)$$

Comparing Formulas (20) and (15), 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 (15) 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:

$$W = N_1 W_g + N_2 W_b =$$

$$\frac{0.32}{\gamma}\left(\frac{E}{E_{0.on}}\right)^2\left(\frac{\omega}{\omega_{on}}\right)\left\{N_1\left(\frac{V}{V_{on}}\right)_g + N_2\left(\frac{V}{V_{on}}\right)_b\right\} \quad (21)$$

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).

Measurement of Dielectric Parameters of Grain Crops and Insects.

The measurement of dielectric parameters of both wheat and weevils was conducted with the use of the Q-meter (Figure 1).

Main parts of the Q-meter are:

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

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

1. reconfigureurable 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 th 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 (Figure 2) was used; and in the range from 30-150 MHz the cylindrical measuring capacitor was applied.

The dielectric ring of boundary effects limiting with ε = 3.3 was put inside the measuring capacitor. The method of the measuring is the same used by Boyarsky (1991). The accuracy of measurement is 33-37%.

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 4 and 5.

Examination of Tables 4 and 5 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 (Nelson, 2001) at $\approx 24°C$, 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.

The results of measurement of dielectric parameters of grain at different moisture contents at the frequency 80 MHz are presented in Figures 3 through 5.

One can see a monotonic increase of the relative dielectric constant as the grain moisture content

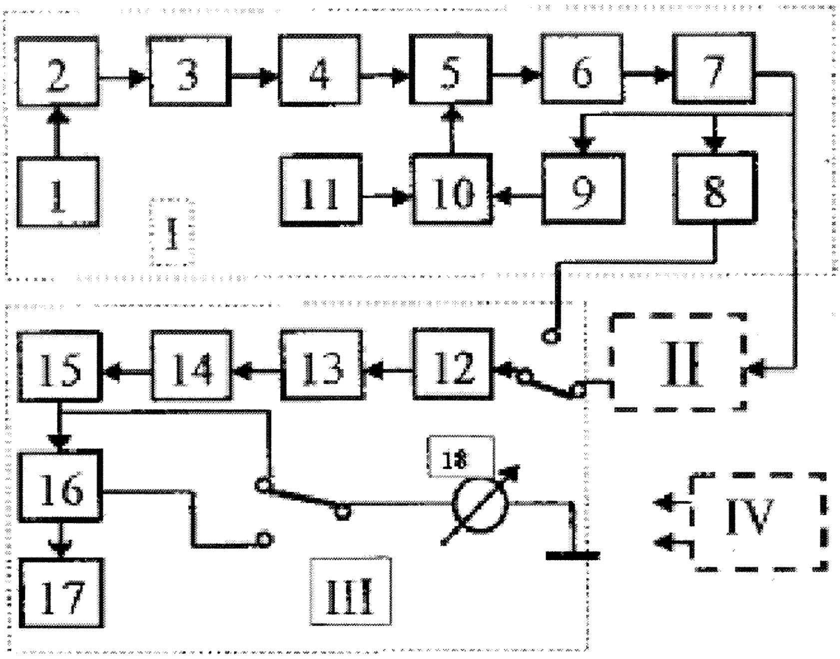

Figure 1: *Structural scheme of a typical Q-meter.*

increases (Figure 3). Both the imaginary part of the permittivity and the loss tangent also increase as the grain moisture content increases (see Figures 4 and5). 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 6.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 (Nelson, 2001).

Discussion of Initial Data of Experimental Facilities Design

Equation (9) 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) are defined experimentally not for an individual seed but for some bulk grain mass (Nelson, 1981 and 1984). 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 (4). 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 (Nelson, 1981) 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 $0.025cm_3$). The parameters W_1 and W_2 were calculated separately. The results of calculating the parameter W_2 ($E = E_{on} = 300kV/m$) 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.

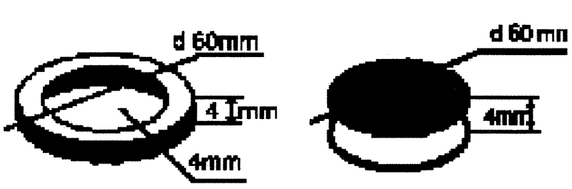

Figure 2: *Measuring capacitor and dielectric ring*

. 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 $(33E,kV/m)^2$.

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 ($\tilde{W}/\gamma$) $kj / m^3 \cdot s$

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 ≈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.

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 $10^3 kW / m^3$. To evaporate $1.5 \cdot 10^{-4}$ kg of moisture, 200 second of heating is required. Therefore, the wheat exposure in a high-frequency field at an 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 (Boyarsky, 1991), 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.

Conclusions

Solution of the problem of electromagnetic radiation interaction with grain crops and insects requires the designing of electromagnetic models

Table 4: *The relative ε′ and imaginary ε″ part of the dielectric permittivity and the loss tangent tgδ of grain in relation to frequency.*

Frequency, MHz	ε′	ε″	tgδ
20	2.00	0.08	0.04
40	2.05	0.08	0.04
60	2.05	0.10	0.05
80	2.15	0.11	0.05
100	2.20	0.11	0.05
130	2.25	0.13	0.06
150	2.30	0.14	0.06

Table 5: *The relative ε′ and imaginary ε″ part of the dielectric permittivity and the loss tangent tgδ of insects in relation to frequency.*

Frequency, MHz	ε′	ε″	tgδ
20	3.60	0.65	0.18
40	3.75	0.70	0.19
60	3.90	0.80	0.20
80	4.00	0.90	0.22
100	4.10	0.95	0.23
130	4.18	1.05	0.25
150	4.75	1.28	0.27

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 (Boyarsky, 1991). 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

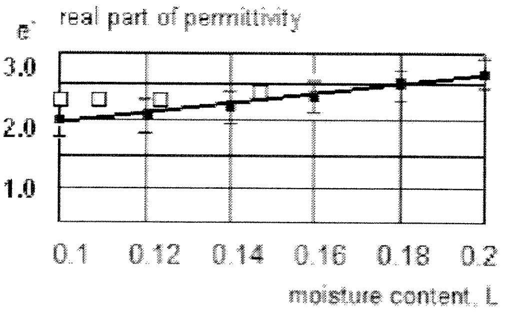

Figure 3: *Relation of the real part of permittivity to the grain moisture content (_-Ref. 10 data for* $\rho \approx 700$ *kg/m*^{3}*)*

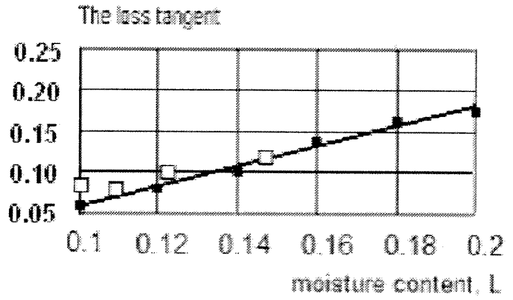

Figure 4: *Relation of the loss tangent to the grain moisture content (_-Ref. 10 data for* $\rho \approx 700$ *kg/m*^{3}*)*

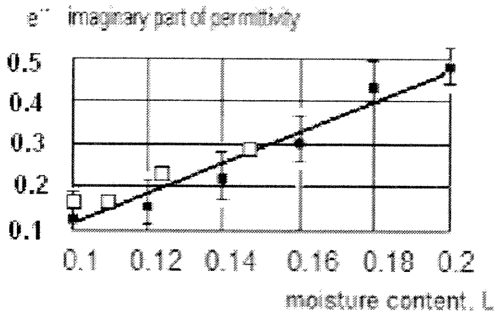

Figure 5: *Relation of the imaginary part of permittivity to the grain moisture content (_-Ref. 10 data for* $\rho \approx$ *700 kg/m*^{3}*)*

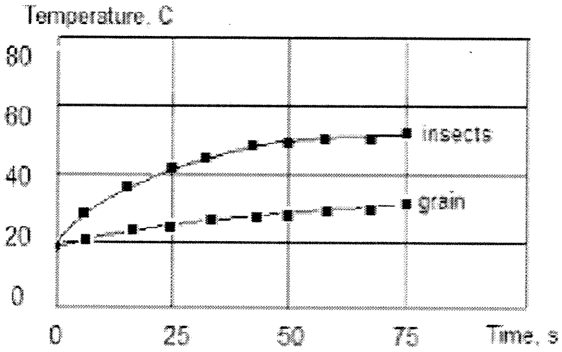

Figure 6: *Increasing of both insects and grain temperature as a function of time variation*

by the following considerations (Mischenko, 2000):

- 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.

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TABLE 6: Values of $\tilde{W}$ 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

TABLE 7: Values W_1 and W as a function of moisture content at frequencies: 80, 150, 900 and 3000 MHz.

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

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