Interaction of Radio-Frequency, High-Strength Electric Fields with Harmful Insects

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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 2,450 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 a frequency of 47.5 MHz and field intensities 350-2000 kV/m. 100% of insect mortality is reached at the exposures of 1-30 seconds, at field intensity of 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 2,450 MHz. Stationary generator mode also permits 21-97% fungi (Cladosporium cladosporioides, Aspergillus candidus) control at voltage U = 10.5 kV, frequencies 900 and 2,450 MHz and exposures of 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.

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INTRODUCTION

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, and 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 to their nervous system, depends considerably on the frequencies, field strength and their complex dielectric permittivity, with

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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 Celsius. 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^1 [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 2,450 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].

METHODS

Theoretical Approach

Consider the device driven by a generator operating at 47.5 MHz 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 propagating electromagnetic field within a coaxial line can be described by the equations

$$H_\phi = \frac{r_0}{r} H_0 e^{i(\omega t \square \frac{\omega}{V_\phi} z)} \tag{1a}$$

$$E_r = \frac{r_0}{r}\frac{\omega}{\varepsilon V_\phi} H_0 e^{i(\omega t \square \frac{\omega}{V_\phi} z)} \tag{1b}$$

where H_φ [A/m] is the magnetic field strength, E_r [V/m] is the electric field strength, H_0 [A/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 wave number and z is the axial dimension of the wave propagation direction. From Eqs. 1a and 1b, the nonuniform character of the RF field distribution can be noted. The flow of electromagnetic power W across the whole section of the coaxial line is

$$W = \frac{c}{4} \cdot \frac{1n\frac{R}{r_0}}{\sqrt{\varepsilon}} \left(r_0 H_0\right)^2 \tag{2}$$

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.

For the coaxial line used at the frequency 47.5 MHz, and . Thus the field nonuniformity along the radius is large: $[E(R)/E\,(r_0)] = 0.44$. In order to reduce this nonuniformity, the use of the additional dielectric tube is needed as shown in Fig. 1 (note that Eqs. 1a, b are no longer valid for a non-uniformly loaded coaxial waveguide).

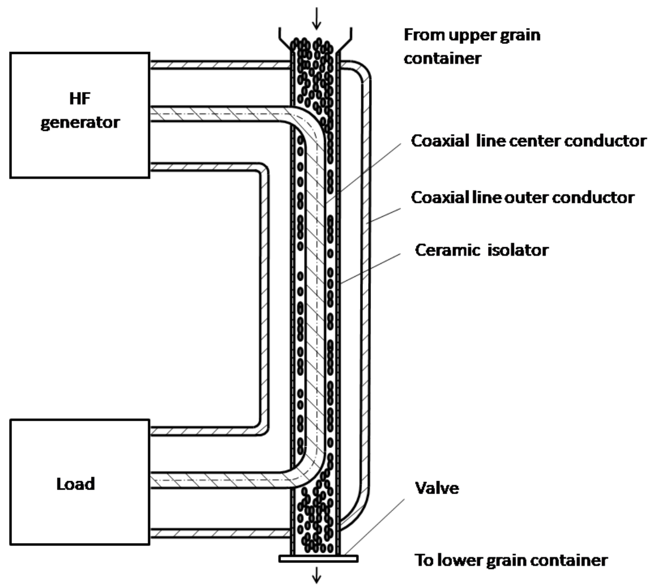

Figure 1. *Schematic diagram of the coaxial irradiation chamber.*

One can assume that the volume with grain and insects surrounds the central conductor from to. Then $E(r_1)/E(r)=0.6$ or $E^2(r_1)/E^2(r_0)=1/3$, which 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 for an electromagnetic power of $W_1=1\times10_6$ W radiated by the HF generator one will obtain $E_0=6\times10^5$ V/m and $E=4.2\times10^5$ V/m, where 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. Similarly, for $W_2=1.6\times10^6$ W, the electric fields result in $E_0=7.5\times10^5$ V/m and $E=5.15\times10^5$ V/m, etc.

The moderate energy output within the single kernel or insect will be equal to 0.31 W, 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. These calculations have been done with the continuous wave (CW) mode of generator operation at the frequencies 900 and 2,450 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 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*

This chamber (Fig. 1) was made from standard copper coaxial 160 mm/70 mm feeder line 1 meter in length with a ceramic tube mounted coaxially between the center and outer conductors. Special windows were made for the entrance and exit of grain. The infested grain flowed from the upper grain container through the ceramic isolator tube around the inner conductor (Fig.1). The ceramic isolator (dielectric permittivity $\varepsilon\approx1$) 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 con-

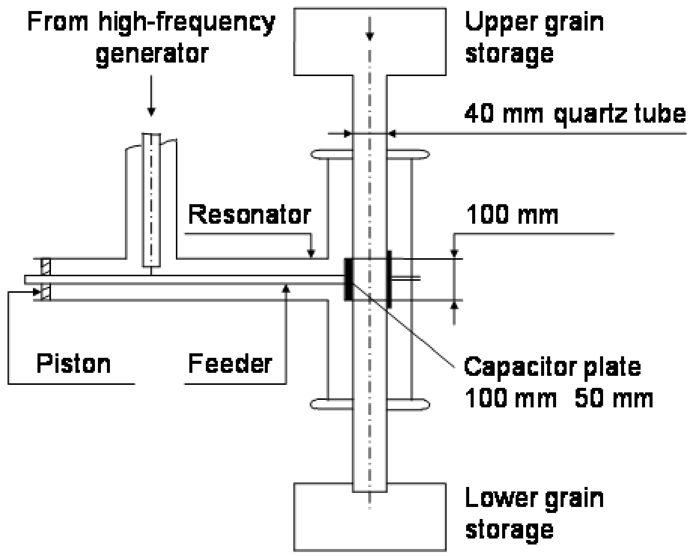

Figure 2. *The schematic diagram of the irradiation chamber with capacitor.*

nected 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 1 and 2) 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 4) 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 5). 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 1 and 2) 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.2. The method of the electric field formation in this type of facility is distinctly different from

Table 1: 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	$\overline{E}$, 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

Table 2: 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

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 (Table 3). The pulse modulated RF-radiation at 47.5 MHz on granary weevil (*Sitophilus granarius L.*) in the irradiation chamber with a plane capacitor (Table 3) 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

Table 3. 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

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).

RESULTS

The investigations at 47.5 MHz (Fig.1) showed that the biological action of the RF electromagnetic field depends more on the generator power voltage (U, kV) than on treatment duration (Table 1).

The mortality of granary weevil (*Sitophilus granarius* L.) at 47.5 MHz treatment in the coaxial type irradiation chamber (Fig.1) is given in Table 2.

As shown from experimental results (Tables 1 and 2) at 47.5 **M**Hz , 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 $U=10.5\times10^3$ V, increasing the treatment duration from 5 to 60 sec did not increase the insect mortality.

Obtained results (Table 3) showed that the equipment with chamber with a plane capacitor (Fig.2) is the most effective as the means of insect control. It is important to note 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 4). 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 4. 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 (Table 5). 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* .

DISCUSSION

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

Table 4. 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	$2.3\text{-}2.8\times10^6$	5.05×10^3	68.3±19.4
900	10	$2.3\text{-}2.8\times10^6$	11.0×10^3	80±28.3
900	15	$2.3\text{-}2.8\times10^6$	16.6×10^3	79.3±7.9
900	30	$2.3\text{-}2.8\times10^6$	33.1×10^3	97.1±2.0
900	60	$2.3\text{-}2.8\times10^6$	66.2×10^3	100±0
2,450	60-90	$0.8\text{-}1.1\times10^6$	$66\text{-}122\times10^3$	90 - 100
2,450	120	$0.8\text{-}1.1\times10^6$	$136\text{-}155\times10^3$	100

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 to 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.

Table 5. Action of continuous-wave-RF-radiation at 47.5, 900 and 2450 MHz on microscopic fungi (micromictets).

Fungi species	$\times 10^6$ 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

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 a majority of cases for different species and exposure times (Table 5).

CONCLUSION

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 4). If a frequency and exposure time are sufficiently high, it requires less 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.

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