Представлені результати експериментального дослідження впливу мікрохвильового електромагнітного поля на рослинну тканину. Вивчено ефекти мікрохвильового нагрівання насіння, зерна і зволоженої соломи при реалізації відповідних технологій біостимуляйи, сушки і стерилізації. Показано вплив будови рослинної тканини і вмісту вологи на структурні зміни при мікрохвильовому нагріванні. Запропоновано метод оцінки величини енергії мікрохвильового поля, перетвореної у внутрішню енергію тіла

Ключові слова: мікрохвильова енергія, нагрівання, рослинна тканина, біостимуляція, сушка, коефіцієнт корисної дії

Представлены результаты экспериментального исследования влияния микроволнового электромагнитного поля на растительную ткань. Изучены эффекты микроволнового нагрева семян, зерна и увлажненной соломы при реализации соответствующих технологий биостимуляции, сушки и стерилизации. Показано влияние строения растительной ткани и влагосодержания на структурные изменения при микроволновом нагреве. Предложен метод оценки величины энергии микроволнового поля, преобразованной во внутреннюю энергию тела

Ключевые слова: микроволновая энергия, нагрев, растительная ткань, биостимуляция, сушка, коэффициент полезного действия

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STUDY INTO EFFECTS OF A MICROWAVE FIELD ON THE PLANT TISSUE

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1. Introduction

Thermal treatment of materials of plant origin is determining for the majority of technological processes, specifically, drying, sterilizing and bio-stimulation. The energy crisis and increasing demand for products with enhanced quality necessitated improvement of traditional technologies and development of the new ones. In this direction, methods that utilize energy of a microwave electromagnetic field (MW EMF) have long proved to be highly effective [1]. Application of microwave heating is considered advisable for the modernization of a range of technological schemes of production [2–5]. However, an incomplete knowledge about effects of a microwave field on plant materials does not make it possible to accept efficient microwave technologies.

Studying the processes of interaction between a microwave electromagnetic field and materials of plant origin, as well as determining treatment conditions, are important objectives for the development of performance-effective and energy-rational technologies.

2. Literature review and problem statement

It was established in [3, 4] that the effectiveness of application of each of the considered methods is related to a change in the structure of plant material in the course of MW treatment. While a method of seed bio-stimulation implied, as one of the tasks, the exclusion of regimes that violate integrity of the cell walls [6], the process of preparing a substrate based on straw involves a desirable destruction of plant structure. Study [7] showed that the surface of the original straw material is a smooth and relatively uniform surface by height, while the surface of the treated sample is characterized by considerable roughness. The results obtained suggest the expansion of capillaries due to micro-explosions.

At present, there has been created a basis for practical application in agriculture of a microwave pre-sowing technology of seed treatment [2, 3]. An assessment of the impact of time of microwave exposure on the stimulation of germination [8] demonstrates the presence of an optimum; the germination peaked at 10 s of treatment. However, the authors fail to determine specific energy costs (per a kilogram of seeds) taking into consideration performance efficiency of the chamber. It was unambiguously determined that the impact of treatment in a MW field better manifests itself on the seeds with primary low germination than on the seeds whose laboratory germination exceeded 95 %. The effects of microwaves significantly increased germination energy and germination as a whole for the 8-year-old carrot seeds [9]. Maximum carrot seed germination was established at a frequency of 9.3 GHz during treatment over 5 min. The action of a microwave electromagnetic field on seeds can lead to a significant bio-stimulating effect, which manifests itself at all stages of plant vegetation [10, 11]. The manifestation of bio-stimulation includes an increase in the energy of germination, germination energy, and when growing plants from the treated seeds – to strengthening the root system, reduction in vegetative phases. This effect was observed both during seed treatment and while treating potato tubers [12]. Upon exposure to 20 minutes at 38 GHz, 46 GHz and 54 GHz, the researchers did not observe the influence of microwave radiation on the weight of potato harvest of the tubers Felka Bona. Radiation at a frequency of 2.45 GHz, for 10 seconds and with a microwave generator power of 100 W, resulted in the largest increase in the biomass of seed potato germs and an increase in the Felka Bona tuber weight. The experiments [13] revealed a significant increase in the biomass (up to 66 %) with increasing the exposure time from 12 minutes to 20 minutes compared to the control. In some cases, bio-stimulation proceeds simultaneously with disinfection [14, 15]. Seed treatment with MW EMF is an environmentally friendly and effective method [16]. However, there are no definitive data on the treatment regimes for various seeds in a microwave field, which does not make it possible to accurately predict the result. This reduces effectiveness of the applied method.

Studying the drying at a microwave heating shows that it is possible to significantly reduce energy consumption [17]. Microwave heating under drying regimes demonstrates a considerable intensification of the process [18]. At an increase in the output power of a magnetron by 4 times, the duration of drying reduces by about 5 times. However, the paper does not report an analysis of the impact of the type of material and the amount of loading on such required characteristics as treatment duration and power output of the magnetron. Research into microwave drying of fruits and plants is still under way [18, 19], however, the drying of raw materials with a high moisture content is not feasible. This leads to loss of quality and high energy costs, since the primary substance that absorbs electromagnetic energy is water. The microwave drying of grain crops whose moisture level is 20–22 % appears to be promising. Using the study into kinetics of the drying of buckwheat groats in a microwave electromagnetic field as an example, it was shown that drying curves contain the periods observed when exploiting other ways to supply heat [20].

Special attention is paid to studying a temperature field in a material in order to establish rational modes [21, 22]. Of great importance is the analysis of the heterogeneity of heating, caused by the shape of the material and its composition, as well as the uneven distribution of an electromagnetic field in a microwave chamber [22].

An analysis of data from the scientific literature [9, 12, 17] allows us to draw the following conclusion. Essential limiting factors in the use of methods of microwave heating in different technologies are the insufficient completeness of theoretical and experimental studies. The lack of data does not make it possible to predict effects that occur in the material under the action of a microwave field.

3. The aim and objectives of the study

The aim of present research was to study the effects of a microwave field on the plant tissue. This would enable the creation of new energy-saving and highly-efficient technologies, which would make it possible to exploit the features of microwave energy conversion into internal energy of the material.

To achieve the set aim, the following tasks have to be solved:

– to investigate the effect of microwave treatment on seeds and to determine conditions for obtaining an optimal bio-stimulation effect, to estimate a threshold time for the exposure to a MW field;

– to explore the sterilizing effect of microwave field exposure on damp straw, to determine the optimal treatment mode;

– to explore the features of the process of drying a layer of grain under different conditions for the removal of evaporated moisture;

– to estimate energy efficiency of converting microwave energy into internal energy of the material.

4. Materials and methods of research

4. 1. Characteristics of materials

We exposed to the microwave treatment the grain intended for drying, seeds as a sowing material, and straw. Selection of straw is explained by its extensive use as a substrate for growing wood-destroying fungi. The research into phenomena of the bio-stimulation was conducted using the seeds of wheat, the variety of Odessa-267; ordinary soy, the variety of Hadzhibey; corn, the variety of Odessa-10. When studying the drying in a microwave field, we used grains of buckwheat and wheat. The initial moisture content of grain changed from 20 % to 22 %; initial temperature ranged from 17 to 26 °C; weight – from 0.05 up to 1.2 kg; layer thickness ranged from 0.008 to 0.07 m; the surface area of the sample open to remove moisture – from $8{\cdot}10^{-3}$ to $94{\cdot}10^{-3}$ m^2. Power of the magnetron ranged from 80 to 800 Watts.

4. 2. Schematic of experimental installation and research procedure

Schematic of the experimental installation designed to study effects of a microwave field on the plant tissue is shown in Fig. 1.

Microwave energy arrived at the working chamber with a rectangular cross section through the waveguide from the magnetron with a generation frequency of 2.45 GHz. The design of the microwave chamber enabled, simultaneously with feeding MW energy, blowing with air above the layer. At simultaneous microwave and convective heat feed, the air along an inlet duct was forced to chamber 2 by fan 6. To control air heating, there is heater 7 with measuring kit 8 and voltage regulator 9.

The research procedure of grain drying implied the following. We placed the examined material in the experimental cell and switched on the magnetron. At specific intervals, we determined by a weight method the amount of evaporated moisture and calculated humidity (when studying the drying process).

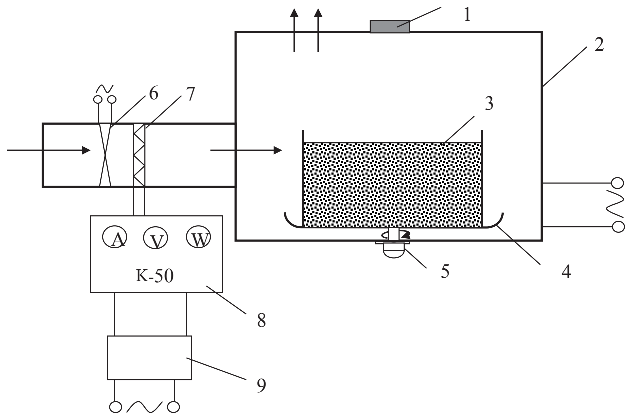

Fig. 1. Schematic of a microwave experimental installation: 1 — waveguide; 2 — working chamber; 3 — experimental cell; 4 — stand; 5 — drive mechanism; 6 — fan; 7 — heater; 8 — measuring kit; 9 — voltage regulator

The research procedure into the influence of MW field on straw implied the following. Wheat straw was preliminary poured with hot water and pressed out to the moisture content 73–75 %. We formed packages weighing 0.4 kg, which were next placed to MW cell. The magnetron was turned on over a specified period. Upon treatment, the package was taken out and we measured the temperature of the straw.

When examining bio-stimulation, the seeds were put into paper packets of 0.1 kg. Output power of the magnetron was 800 W. We also placed a glass of water (200 ml) to the microwave chamber in order to reduce the power received by the seeds.

5. Experimental study into effect of a microwave field on the plant tissue

The scope of research of the present work covers the following applications of microwave heating of materials of plant origin: pre-sowing seed treatment (bio-stimulation), sterilization of plant substrate for the production of wood-destroying fungi, grain drying. Despite their diversity, plant materials have common specificity, which involves the structure of plant cells, anisotropy, and the presence of substances with properties of polar dielectrics. The basic distinction between the treated plant materials in given techniques is a significant difference in the moisture content. Thus, at pre-sowing seed treatment, moisture content corresponded to the equilibrium; during preparation of the substrate – to the level of humidity 73 %; at drying, moisture content was within the range of 20–22 %. Accordingly, we set different objectives in microwave treatment, which specifies a number of particular tasks for each of the developed methods.

5. 1. Study into effects of a microwave electromagnetic field on the properties of seeds

An example of the effect of a microwave field on seeds is shown in Table 1. The data are acquired in line with the procedure described above. As the data reveal, the value of germination energy and laboratory germination rate changes depending on the exposure.

Table 1

Effect of MW EMF on seed germination: 1 — wheat, the variety of Odessa-267; 2 — ordinary soy, the variety of Hadzhibey; corn, the variety of Odessa-10

No. of entry	Regime	Germination energy, %			Laboratory germination rate, %		
Grain crop		1	2	3	1	2	3
1	Control	71	42	53	74	48	72
2	MW, 20 s	71	55	53	74	56	72
3	MW, 30 s	73	55	53	76	57	74
4	MW, 60 s	86	64	62	86	66	77
5	MW, 90 s	86	68	68	88	68	81

We made the following assumption about the mechanism of occurrence of a bio-stimulation effect. Under sufficiently mild modes of MW-exposure, the plant tissue integrity is not disrupted. At the same time, transport properties of the capillary system (intercellular structures, pores of plasma membranes, etc.) improve due to the development of large pressure gradients in the closed microvolumes. The action of a microwave field leads to active heat release in a cell. The temperature rises, as a result of which liquid in cellular tissue tends to expand. The volume of a cell can somewhat grow due to the air-bearing intercellular. However, increasing the time of MW exposure leads to the state when all reserved space is taken up by the increased volume while pores in the plasma membrane are not intended for the massive outflow of fluid. That is why the volume of a cell can be considered fixed, with the process of temperature rise in a cell proceeding by isochore. Estimates show that an increase in the temperature by 10 °C causes an increase in the pressure under conditions of constant volume up to 60 bars – such a pressure is definitely unacceptable for the living cell. The decisive role of relation between a growth in the internal pressure and rigidity of the cell wall is indicated by the fact that, for example, the cellulose destruction has an explosive character. Large hydraulic resistance leads to the event when the resulting mass flow cannot escape to the outside, the pressure increases rapidly, and this process ends up destroying the tissue. Such regimes are not acceptable.

In a general form, calculation of boundary temperature is proposed to perform employing the following algorithm:

1. For each estimated unit, to determine maximum permissible volume V_K, that is, the volume that can be achieved at thermal expansion of the protoplasm.

2. A temperature change in the process of volume increase from V_0 to V_K is determined from equation:

$$\Delta t = \frac{V_к - V_0}{\beta V_0},$$

where β is the coefficient of thermal expansion of water.

3. The amount of heat absorbed in this process:

$$Q = Mc_p \Delta t + P\Delta V, \text{ J.} \tag{1}$$

For further calculations, in order to improve accuracy, it is recommended that the dependence be used, which makes it possible to determine the amount of heat spent on heating the total grain mass M up to the design temperature:

$$Q = M \cdot c \cdot \Delta t, \text{ J.} \tag{2}$$

4. The period over which this heat was received:

$$\tau = Q/(q \cdot V),\ \text{s}, \qquad (3)$$

where V is the volume of material, the value of q is determined from the following dependence:

$$q = 0.556 \cdot 10^{-10} \varepsilon' \cdot tg\delta \cdot E^2,\ \text{W/m}^3. \qquad (4)$$

Over this time, an increase in the pressure will not be critical, with the seeds undergoing a stage of bio-stimulation.

The cell walls cannot further increase their volume. Inside the object, at subsequent energy supply of MW field, pressure begins to rise sharply. In general, heat is used in order to increase body temperature and to change pressure according to the first law of thermodynamics:

$$Q = \Delta H - V\Delta P,\ \text{J}. \qquad (5)$$

The relationship between temperature and pressure can be assigned only approximately because the equations of state of such complex mixtures as the protoplasm are lacking. In the first approximation the calculation is recommended to perform by adopting the properties of the protoplasm equal to the water properties.

Applying these dependences, we performed calculations aimed at determining pressure and temperature at the end of the treatment process, depending on the moisture content and exposure time. When estimating the pressure, it was assumed that the body shells are rigidly fixed by the cell walls, that is, the case that the most characteristic of spores and sclerotium. The calculation is of estimated character, but it allows us to predict the reaction of a biological object for MW field. It was accepted that the volume of plant cell of a grain germ was V_0=3.35·10^{-14} m^3. Maximally permissible cell volume is V_K=3.366·10^{-14} m^3. Calculations were performed for the grain of mass 0.1 kg. Heat capacity of grain for wheat depends on humidity W. Thus, at W=33 %: c=2,398 J/(kg·K)' at W=14 %: c=1,852 J/(kg·K).

Fig. 2 shows results of calculation of boundary curves for the wheat seed treatment time in the microwave chamber at output power of the magnetron P=1 kW depending on seed humidity and at different values of the initial temperature. Initial temperature exerts a significant impact on the value of permissible treatment time, which is related to the dependence of dielectric characteristics and the coefficient of volumetric expansion on temperature. In the calculation, it was assumed that the initial temperature of the grain and the ambient temperature were the same.

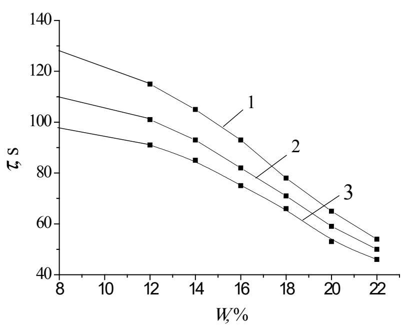

Fig. 2. Boundary curves for the wheat seed treatment time in a microwave chamber. Output power of the magnetron – 1 kW: 1 – initial temperature 10 °C; 2 – initial temperature 15 °C, 3 – initial temperature 20 °C

An analysis of the results of research into effect of a microwave field on seeds revealed the following. At the heating rate of seeds in a microwave chamber $\Delta t/\tau$=0.14–0.17 K/s, with a moisture content of u_0=8–12 %, at duration τ=50–130 s (depending on the variety of seeds), there occurs a bio-stimulation effect that manifests itself in an increase in the energy of germination and germination rate. At lower specific power, a bio-stimulation effect is achieved by increasing the duration of treatment: at treating wheat seeds for specific power q_v= =3.7·10^4 W/m^3, the exposition is τ=180 s.

5. 2. Thermal treatment in a microwave field of plant material as the base of substrate for the wood-destroying fungi

The main purpose of thermal treatment is to destroy or oppress microflora, which is competitive to the cultivated fungus.

The effect of MW treatment efficiency under modes at which Trichoderma was destroyed or oppressed was verified according to the following procedure. The crushed straw, pre-soaked for 48 hours, was pressed out to humidity W=73 %. The treatment was carried out at power P=800 W. We formed the samples weighing 0.4 kg on analytical scale, followed by the mycelium inoculation after cooling; next, we placed them into plastic bags. The main results in the observation of samples fouling and fungi yield are shown below. Results of the study into properties of the substrate for growing fungi under different modes of treatment and at different initial humidity are given in Table 2.

Table 2

The nature of the substrate fouling with mycelium at different exposure to a microwave field. Initial humidity is W=73 %

Mode	Exposure	Power (kW)	Initial temperature, °C	Result
1	35	0.85	74	The presence of mold
2	40	0.85	84	Fouling with mycelium is satisfactory
3	45	0.85	87.5	Fouling with mycelium is good
4	50	0.85	93	Fouling with mycelium is good
5	120	0.3	72	The presence of mold
6	140	0.3	83	Fouling with mycelium is excellent
7	160	0.3	86	Fouling with mycelium is good
8	180	0.3	91	Fouling with mycelium is good
Control	–	–	–	The presence of mold and trichoderma

Optimal treatment mode corresponds to the exposure for 140 s. For this mode, the chamber performance efficiency was 80 %. Energy consumption Q, taking into consideration the magnetron's performance efficiency η_M=75 %:

$$Q = \left(m \cdot c_p \cdot \Delta t\right)/\tau/\eta_{\text{м}} = 0,4 \cdot 3600 \cdot 66/140/0,75 = 905\ \text{W}.$$

It was determined that the heat treatment of wet plant material in a microwave field with a heating rate of $\Delta t/\tau$> >0.33 K/s leads to the improvement of its nutritional value, the material is sterilized, treatment time is reduced by

45 times compared to traditional sterilization. Fungi harvest increased by 40 % compared to the yield obtained when using traditional technologies, at the following operating parameters: specific power is q_v=9.6·10^5 W/m^3, duration of treatment is τ=140 s. Under the considered modes, development of competing fungi, specifically Trichoderma, is suppressed.

5. 3. The drying of grain materials using a microwave electromagnetic field

Fig. 3 shows typical experimental moisture content and temperature dependences on the drying duration in a microwave field at different loading mass.

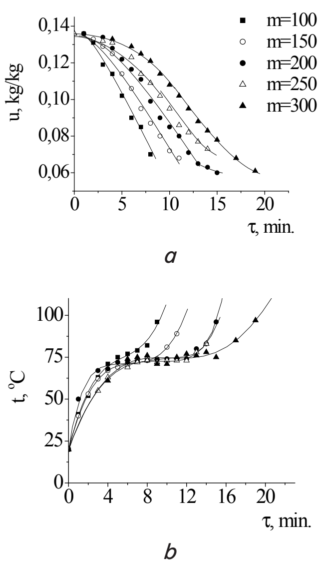

Fig. 3. Kinetics of wheat grain drying in a microwave field at different loading mass: *a* — change in the moisture content; *b* — temperature change

The drying process can be divided into periods, characteristic of colloidal capillary-porous solids at other heat supply techniques: warmup (zero), continuous (first) and falling (second) drying rate. The nature of a temperature change in the first period varied depending on the mass of the load (Fig. 3) and the supplied power. At values of specific power up to q=450 W/kg, the temperature remained largely unchanged. With an increase in the specific power, the temperature grew; at values q>600 W/kg, its change was essential. The period of the falling drying rate was determined by a change in the moisture content curve: the curve became flat. The temperature always increases over this period. The described pattern was typical for all materials.

Research results showed that the rate of MW drying without overheating the grain is (0.8–6.2)·10^{-4} s^{-1}, which is much higher than the values obtained using other techniques of heat supply. Thus, for grain, the conductive drying rate was 0.3·10^{-5} s^{-1}, that of the conductive-convective – to 0.2·10^{-4} s^{-1}. The possibility to significantly intensify the process testifies to the prospects of applying a microwave field in order to dry the grain crops. Experiments have shown that under the optimal mode the rate of microwave drying with a simultaneous blowing a grain layer with air was 12.7·10^{-4} s^{-1}; in this case, specific energy cost per a kilogram of evaporated moisture amounted to 5.65 MJ/kg.

In the process of MW heating of damp grain, overpressure inside the layer starts to rise. The excess pressure at the layer's surface is zero, and it is maximal in the center. A total pressure gradient arises in the layer, which is the driving force of filtration transfer. In order to detect the effect of increasing pressure in the grain layer, we devised the following technique. We placed a container with a layer of buckwheat of height 11 cm in a microwave chamber, and measured excess pressure in the center using a U-shaped kerosene manometer. The choice of kerosene was due to the fact that it did not absorb microwave energy. An exponential increase in the pressure occurred when temperature exceeded 70 °C. In this case, the layer's thickness was 0.1 m. Maximally possible overpressure inside the layer was equal to 640 Pa. When this magnitude was reached, we observed a spontaneous instantaneous pressure relief.

The specificity of microwave heating is in the volumetric character of material's absorption of microwave energy. Microwave energy flux density is maximum in the surface layers, while advancing deep into the material the flow is weakened in line with the exponential law. Therefore, of particular interest for the evaluation of non-uniformity of temperature and moisture content was the kinetics of the layer-wise drying. To this end, we fabricated an experimental cell, which consisted of three layers separated by radiotransparent nets. The weight of each layer was 0.1 kg, thickness was 0.009 m, diameter – 0.135 m, the surface area open to remove steam was 14.3·10^{-3} m^2. In the course of the experiment we determined a change in the moisture content and temperature of buckwheat over the drying process for the height of a layer. Only the upper surface of the sample was open to absorb MW energy and remove the steam, with the side and lower surfaces being heat- and moisture insulated. The curves of layer-wise drying kinetics are shown in Fig. 4, which demonstrate that the drying proceeded most intensively in the middle layer. In this experiment, the layer's mass was m= 0.1 kg, thickness l=0.009 m, P=160 W. Moisture release rate in the upper layer was somewhat weaker (Fig. 4, *a*). This is related to the fact that the temperature of the upper layer was slightly lower than that of the second (Fig. 4, *b*). Another feature was discovered: the third layer's moisture content increased over time, reaching 0.215 kg/kg (the initial moisture content is 0.2 kg/kg). Therefore, the moisture from the upper layers of the material penetrated down, apparently due to the thermal diffusion mechanism and the force of gravity.

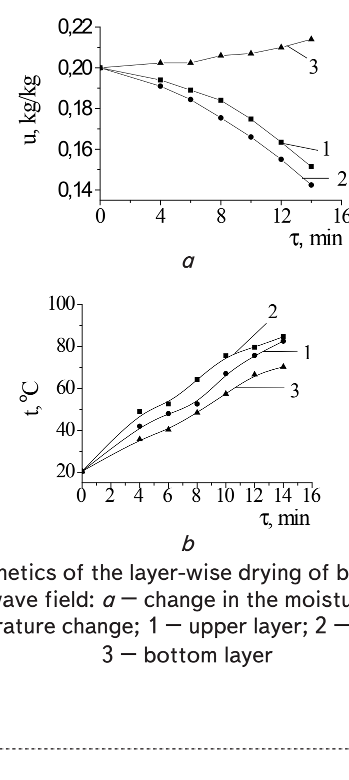

Fig. 4. Kinetics of the layer-wise drying of buckwheat in a microwave field: *a* — change in the moisture content; *b* — temperature change; 1 — upper layer; 2 — middle layer; 3 — bottom layer

Noteworthy is the following feature – despite the growing moisture content in the bottom layer, that is, an increase in the share of polar dielectric ("receiver" of microwave radiation) in this volume of the material, its temperature remains below temperature of the second and third layers. Experiments on cell, consisting of four layers, showed that the lower (fourth) layer also had the lowest temperature and the highest moisture content, which, as is the case for the previous experiment with three layers, increased over time. Thus, the moisture content of the lower layer increases regardless of the thickness of the sample. The reason for lowering the temperature of the sample at the boundary between the layer and the base of the chamber is the transfer of heat by the conductivity of experimental cell. This irregularity was not observed when using a netted cell that freely passed the steam in all directions. In this case, temperature of the material's layers differed by no more than 4 °C, the humidity – by 0.007 g/kg. Comparing data on the drying kinetics derived at the cell with solid and radiotransparent netted bottom confirmed the importance of rational organization of steam removal. Thus, in the first case the average moisture content of the sample decreased from 0.2 kg/kg to 0.17 kg/kg in 14 minutes, in the second – in 7.5 min. Uneven distribution of temperature and moisture content occurs under conditions when steam removal through the bottom and side surfaces is difficult.

5. 4. Energy efficiency of thermal effect of interaction between dielectric materials and a microwave field

One of the key tasks was to determine the conditions for the greatest possible conversion of microwave electromagnetic field energy into internal energy of the examined material. In order to analyze the specifics of microwave energy absorption by the material, it was of great importance to study dependence of the magnitude of microwave energy absorbed on the chamber's loading. The expression for a general performance efficiency is represented as follows: $\eta=\eta_M\cdot\eta_c$, where η_M is the magnetron's performance efficiency, η_c is the microwave chamber's performance efficiency. A value of η_M shows at which performance efficiency the magnetron converts energy of the electric field of industrial frequency (50 Hz) into energy with a microwave field frequency. This magnitude is technically specified. The value of η_c depends on the conditions of aligning the magnetron with a waveguide and a loaded material; due to the complexity of its prediction, there is a need to conduct large-scale experiments. First of all, we chose water for the research as a substance whose electrophysical properties are well studied. The capability of water to absorb microwave energy approaches to maximum due to the high polarity of molecules. The chamber's performance efficiency is calculated as the ratio of heat, converted by material Q_Σ, to the magnetron's power output P, and includes the value of usable heat flow Q_u, environmental losses as a result of natural convection Q_c, and radiant heat exchange ($Q_\Sigma=Q_u+Q_c+Q_r$) between the sample and the chamber's walls:

$$\eta_c=\frac{Q_\Sigma}{P}. \qquad (6)$$

To study the dependence of performance efficiency on the chamber's loading, we used water at initial temperature 20 °C, the mass varied from 0.05 up to 1.1 kg. The output power of a microwave source was 800 W. One can see (Fig. 5) that with an increase in the mass of water performance efficiency continuously grows, reaching its maximum value of η_c=90 % at m=1.1 kg, which allows us to argue about achieving the optimum loading of the chamber.

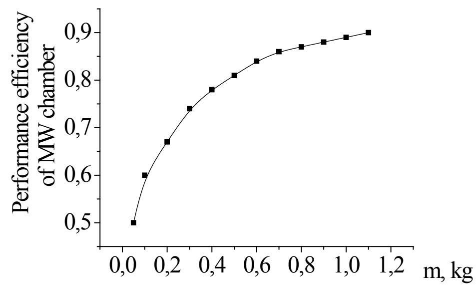

Fig. 5. Dependence of the microwave chamber's performance efficiency on the mass of water at P=800 W

Materials of plant origin have their own specifics that include structural characteristics and chemical composition, but, in order to assess the power released in the form of heat, the most important is the moisture content of these materials. The capacity of plant materials to absorb MW energy is significantly lower than that of water, which is why the chamber's performance efficiency when treating grain materials is less. We obtained empirical dependence for certain grain materials (oats, wheat, barley, buckwheat), which takes into consideration complete loading of the chamber through the introduction of simplex V_M/V_K, where V_M is the volume taken up by the material, V_K is the chamber's volume:

$$\eta_c=0{,}67\left(1-\frac{0{,}45}{1+e^{\left(\frac{V_K/V_M-0{,}003}{0{,}0017}\right)}}\right)\left(\frac{u}{u_0}\right)^{1{,}3}, \qquad (7)$$

where u is the current moisture content, u_0=0.2 (the initial moisture content). At a change in the relative volume V_M/V_K from 0.0015 to 0.03, an error in determining the chamber's performance efficiency is ±17 %. Data on performance efficiency are proposed to be used to measure the heat, converted in a material when interacting with a microwave field, in accordance with the following dependence:

$$q=\frac{P_{out}\cdot\eta_c}{V}, \quad \text{W/m}^3, \qquad (8)$$

where V is the volume taken up by the material, P is the output power of the magnetron.

Dependence (8) allows us to determine energy efficiency of converting microwave energy into internal energy of the material.

6. Discussion of results of study into effect of a microwave field on the plant tissue

Due to the obtained data on heating effects in a MW field, there is the possibility to predict changes in the plant tissue. Considerable influence of moisture content on heating rate is confirmed. There is also a certainty in terms of calculating a threshold duration of heating the seeds at bio-stimulation. The procedure for the calculation of a threshold time was compiled on the basis of hypothesis on the emergence of a bio-stimulating effect.

The identified features of heating and drying of wet grain are advisable to apply when designing microwave dryers. It was established that at an increase in the layer's temperature above 70 °C, there occurs the exponential rise in pressure. It was also found that, during microwave drying, the conditions could arise at which the moisture content of the lower layer of grain would increase. In order to enable uniform and intense drying, a layer of grain must be provided with a free outlet of evaporated moisture.

The benefits of the present study include determining the conditions for effective heat treatment in a microwave field, obtained in the course of comprehensive examination of the effects of interaction between MW field and plant materials. Of particular importance is the proposed approach to estimating the heat generated by converting MW energy into internal energy. In addition, we obtained experimental data on the effect of a cascade pressure rise in a layer of wet grain material and on the layered drying. Understanding these phenomena makes it possible to better comprehend the processes of heating in a microwave field.

The shortcomings of present research include the absence of confirmed data on the penetration depth of electromagnetic energy into a layer of a material, as well as the substantiation of rational thickness of the layer. A constraint on the application of results is the lack of specialized microwave equipment; in this case, in order to implement each of the described applications of MW treatment, individual design is required. Otherwise, the effectiveness of using microwave energy will not be optimal.

In the future, we should determine a rational thickness of the layer taking into consideration the depth of penetration of electromagnetic energy into specific plant materials. This will help facilitate the choice of rational regime for microwave heat treatment in different technologies. The main challenge in this direction is correct estimation of the microwave chamber's performance efficiency. To resolve the task, it is necessary to continue the experiments and obtain empirical dependences of the chamber's performance efficiency for different kinds of treated raw materials.

7. Conclusions

1. The study of seeds in a microwave field revealed the occurrence of a bio-stimulation effect. It is shown that the conditions for obtaining an optimal bio-stimulation effect depends on the type of seeds and the duration of treatment. Thus, with a 90-second treatment we observed improvement in the laboratory germination rate and energy germination of wheat, soya, and corn. In this case, the rate of heating under optimal regimes is different: for wheat – 0.15 K/s, for corn – 0.14 K/s, for soya – 0.17 K/s. To calculate a threshold time for seed exposure to a microwave field, we propose a procedure that determines the heating period until reaching an isochoric process in the plant cell. Exceeding this time would result in the destruction of cell walls and oppression of seed growth.

2. An effective sterilizing effect of microwave heat treatment of damp straw was found, which involves destruction of competitive spores and improvement of conditions for the germination of cultivated wood-destroying fungi. We established an optimal mode of microwave treatment of damp straw for the preparation of substrates. For the mass of 0.4 kg, the optimal treatment duration is 140 s at power output of the magnetron 800 W.

3. The study into grain drying in a microwave field, which we conducted, revealed the occurrence of effects of cascade pressure rise in the layer. Under these conditions, the temperature exceeds 7 °C with a layer thickness of 0.1 m; in this case, steam release from the side surface and bottom is difficult. Under the same conditions the drying becomes extremely uneven; moisture content of the lower layer may exceed the initial value. The drying of the middle layer proceeds most intensively.

4. We investigated energy efficiency of conversion of microwave energy into internal energy of a material depending on its type, the loading volume, and moisture content. It was established that in order to dry grain crops with an initial moisture content of 20 %, the microwave chamber's performance efficiency does not exceed 67 %. When heating water, the microwave chamber's performance efficiency can reach 90 %. A dependence is proposed to calculate the value of microwave energy absorbed by the assigned volume of the treated material. In this case, it is necessary to have data on the microwave chamber's performance efficiency, which are derived experimentally.

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