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EVALUATION OF THE EFFICIENCY OF MICROWAVE HEATING OF SOILS

One of the innovative directions of heat treatment of soil in the technologies of decontamination from pesticides, oil products and disinfection is heating in a microwave electromagnetic field. Numerical studies testify to the effectiveness of the microwave treatment method. This is due to the peculiarities of the interaction of the microwave field with dielectric materials. Unique effects arise, such as the possibility of local heating, volume heating of the material, unidirectionality of pressure and humidity gradients. This contributes to the intensification of transfer processes and the possibility of energy savings. However, the challenge at present is to determine the processing regimes, including load mass, specific microwave field power, electric field strength, material layer thickness, and processing time, under which the microwave method will be energy efficient. Conducting multifactorial experimental studies allows determining the conditions of energy feasibility of microwave soil treatment. Therefore, the object of research is the process of heating a dense layer of soil under the action of a microwave electromagnetic field.

The results of studies on the effect of microwave treatment of soil contaminated with organophosphorus pesticides, contaminated with petroleum products, and under what conditions the qualitative effect was obtained, as well as the results of the effect of the microwave field on the pathogenic microflora of the soil used for growing plants, were considered. The high quality of implementation of soil treatment technologies is determined. Energy efficiency was determined on the basis of data on temperature and moisture content, analysis of thermograms of microwave heating of chernozem and clay soil, analysis of the influence of material layer thickness, influence of dielectric properties and power of the microwave field. According to the results of thermal calculations, the values of the efficiency of the microwave chamber and the intensity of the electric field were determined, which are recommended as the basis for scaling in order to transfer the experimental results to industrial installations.

During the research, specific experimental methods of research under microwave heating conditions, analytical methods of thermal calculations, developed by the authors of the experimental research methodology were used. Experimental studies were carried out on the installation created by the authors. The results of the research are intended for the wide implementation into practice of technological calculations of microwave chambers for heat treatment of soils, intensification of disinfection processes under the conditions of energy efficiency of the transformation of the energy of the microwave field into the internal energy of the soil.

Keywords: *disinfection technologies, experimental studies, energy efficiency, heat of transformation, thermal calculations, efficiency factor.*

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1. Introduction

In recent years, technologies have been developed that use the advantages of selective and volumetric heating under the conditions of the microwave field [1]. There are a number of engineering challenges that need to be addressed to successfully scale up microwave heating processes, in part because the technical science in this field is not yet fully established. The study [2] reports on the development and evaluation of an experimental microwave treatment system for the removal of hydrocarbons from solid materials, and highlights the main challenges in large-scale operation and recommended techniques. It has been shown that microwave heating removes organic pollutants from the soil [3], which can be an alternative to traditional thermal desorption processes.

Microwave treatment of contaminated soils can be used for gradual improvement of soil condition. Studies have shown effective removal of polyaromatic hydrocarbons (PAHs) from two samples of contaminated soil [4, 5]. The levels of organic removal depend on the electric intensity of the field created in the microwave applicator. High electric field strength results in high power density and corresponds to higher levels of organic removal than low field strength. The study of the pathways of chemical reactions of detoxification from toxic chemicals (TRC) during microwave heating was carried out on organophosphorus pesticides: karbophos, metaphos, thiophos. Since the level of soil contamination with pesticides depends on the properties and consumption rate of pesticides, the properties and type of soil, weather conditions and other factors, as well as taking into account the scattered and scarce literature information about their content in the surface layer of the soil up to 30 cm deep (from 0.01 mg/kg up to 3–5 mg/kg), the initial density of pollution in experiments with pesticides [5] was taken as 10 mg/kg. The time for complete removal of karbophos from the soil is 8 minutes, that is, the method of microwave heating is quite effective for decomposition of karbophos. The kinetic curve of thiophos decontamination shows that the duration of complete decontamination was 17 minutes. Complete decomposition of metaphos in the samples was observed after 10-minute exposure in the microwave field.

In the course of decontamination of the soil from TPR, the following processes mainly take place:

1) evaporation and sublimation of substances when heated in a microwave field;

2) hydrolysis of substances under the action of soil moisture;

3) thermal destruction of substances followed by evaporation, sublimation or desorption of decomposition products.

The specific gravity of each of them and the efficiency of neutralization as a whole largely depends on the speed of energy supply and the amount of heat absorbed by the contaminated soil.

The microwave method significantly depends on the ability of the material to convert the energy of the microwave field into thermal energy, which directly depends on the dielectric properties of the material, which includes the dielectric loss coefficient. Dielectric loss (ε'') can be considered as a measure of the ability to convert microwave energy into heat. The higher the dielectric loss, the better the material will generate heat in the microwave field. Materials with a tangent of the loss angle $\mathrm{tg}\delta > 0.1$ are considered good dielectrics for microwave heating [6]. Materials with a loss coefficient $\varepsilon'' < 0.005$ will be considered transparent to microwave radiation [7]. Thus, in a mixture of bulk soil, hydrocarbon pollutants and water, it is the water phase that will be heated selectively due to the volume of the solid substance. Provided sufficient power density is achieved in the soil, rapid microwave heating converts the water in the soil to steam, which then cleans the soil of organic pollutants. This effect was also observed during microwave heating of contaminated drilling muds [1] and oil-bearing sands [8], which are structurally similar to contaminated soils because they contain minerals, oil, and water. Work [9] showed that, although the bulk temperature of soil contaminated with hydrocarbons remains around 100 °C, surfactants with boiling points of 218–400 °C are completely removed. This may be due to local heating. Local temperatures are created in the soil structure, sufficient to attract hydrocarbon pollutants into vapors with boiling points of 218–400 °C.

The ability of each soil to heat up in a microwave field at a given frequency can be estimated by calculating its tangent of the loss angle ($\tan\delta$), which is the ratio of dielectric loss to the real part of the dielectric constant. A higher tangent of the loss angle indicates a greater ability of the material to heat up in the microwave field. At temperatures below 100 °C, all soils can be classified as good dielectrics. The tangent of the loss angle rapidly decreases at temperatures above 100 °C. This corresponds to the evaporation of free water and indicates that this water will be the primary phase heated in the soils. These results show that residual organic and mineral inclusions are transparent to microwave (MW) radiation, and this is consistent with studies [10]. The authors of [11] investigated the influence of the microwave (MW) field on the rate of thermal desorption of polychlorinated biphenyls (PCBs) from long-term contaminated soil in laboratory conditions. For these purposes, a modified MX furnace with a power consumption of 200–600 W was used. The weight of the soil samples was 100 g, the PCB concentration was on average 264 mg/kg of dry matter. It was experimentally proven that the efficiency of PCB desorption in the MH field was high, over 99.9 %. As the level of organic pollution increases, higher capacities are required [12]. Thus, remediation of soils contaminated with petroleum hydrocarbons using MX irradiation is a promising technology due to high decontamination efficiency and low energy consumption. Research [13] is aimed at experimentally determining the effectiveness of soil remediation contaminated with light and heavy crude oil using microwave heating on a laboratory device. The results show that 98.95 % and 96.39 % of the total petroleum hydrocarbons (POHs) in light and heavy crude oil-contaminated soil can be removed in 15 and 20 minutes at 1000 W, and the residual POHs are about 143.2 and 401.4 mg/kg, respectively. This indicates that the removal of light crude oil from the soil is much more efficient and consumes less energy due to differences in the nature of removal for different fractions. The main removal of C_{10}–C_{16}, C_{16}–C_{22} and C_{22}–C_{40} at 200 °C, 300 °C, and 400 °C shows [14] that the removal of both small and large molecular fractions is effective during microwave irradiation, since it occurs at a temperature much lower than their boiling point. Moreover, organic matter in light and heavy crude oil-contaminated soil is maintained at a moderate level (i. e., 19 and 21.7 g/kg at 400 °C) after microwave treatment, which provides an opportunity for soil reuse. There is a trade-off between organic removal efficiency and power allocation, and single-stage power application has been found to be 20–30 % more energy efficient, but the overall organic removal is limited to 60 %. Removal of 75 % was possible using two consecutive treatment steps, but the removal of organics is ultimately limited by the amount of energy that can be safely and reliably transferred to the treated material.

Microwave treatment of soils can also be carried out in order to increase productivity. Yield declines are now being partly halted by soil sanitation strategies such as fumigation. However, there are fewer suitable fumigants on the market and there is growing concern about chemical effects on the environment and humans. Therefore, thermal remediation of the soil was considered for some time. Microwave soil treatment has a number of important advantages compared to other thermal methods [15]. Microwave soil sanitation has been found not to sterilize the soil, but to support beneficial biota and make more nutrients available for better plant growth. Soil remediation (e. g., by fumigation or heating) is a common procedure in many agricultural systems [16]. Over time, individual reviews for different types of plants and pathogens have developed [17]. After all, heat can be just as lethal as chemicals, and so has been used in soil remediation processes for some time.

When studying the effect of MW processing on the pathogenic microflora of the soil, it was found [16] that the processing of 1 kg of soil at a humidity of 37 % for 150 seconds destroyed the populations of *Pythium*, *Fusarium* and all nematodes, except for *Heterodera glycines*, in all studied soils. At this treatment dose, marginal survival of

Rhizoctonia, *H. glycines* cysts and vesicular-arbuscular mycorrhizal fungi was observed in some soils. Treatment of 4 kg of soil for 425 seconds gave comparable results. Compared to autoclaving (1 hour every 2 consecutive days) or fumigation with methyl bromide-chloropicrin (98^{-2}), 0.454 kg/45 kg soil, MW treatment resulted in the release of less nutrients into the soil solution, had less effect on soil prokaryotes, which resulted in less soil re-colonization by fusarium and other fungi. The analysis of literature data proved how feasible it can be to treat soil in a microwave field for disinfection. However, at the moment, the energy efficiency of microwave treatment has not been determined, and methods for increasing the efficiency of converting microwave energy into soil internal energy have not been proposed.

The aim of research is to evaluate the effectiveness of soil heating when using microwave technology, for which research was carried out on the process of soil heating in a microwave field and determination of energy-efficient processing modes.

2. Materials and Methods

2.1. Description of the experimental unit. Experimental studies were carried out on a laboratory unit, the scheme of which is presented in Fig. 1. Energy was supplied to the working chamber through a waveguide from a magnetron with a generation frequency of 2.45 GHz and adjustable power.

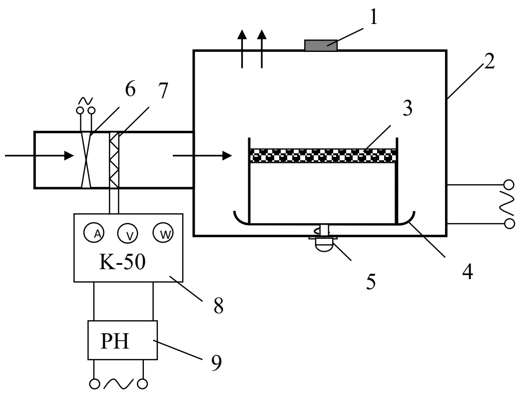

Fig. 1. Scheme of the experimental unit for studying the heating of dielectric materials in the microwave field: 1 – waveguide; 2 – working chamber; 3 – experimental cell; 4 – stand; 5 – drive mechanism; 6 – fan; 7 – heater; 8 – measuring set; 9 – voltage regulator

For a laboratory unit, the strength and frequency of the microwave field are constant values. The type of soil (sand, clay, chernozem, etc.) can be considered quite concrete in this case, of course, bearing in mind changes in a number of indicators when moving to another type of soil or pollutants. The coefficient of dielectric losses of the soil depends on its humidity, the presence of chemical additives in it that improve its electrophysical properties (in particular, the dielectric constant).

2.2. Methodology of the experiment. The material was loaded into a moisture-proof container and weighed. The container was tightly closed with a lid. The sample with the required mass was placed in a microwave chamber, where it was kept for a certain period of time, after turning off the sample was removed from the chamber. Then the temperature was measured using copper-constantan thermocouples at 3 points of the layer (surface, center, bottom).

Two types of soil were chosen for research: clay soil and chernozem soil. It was determined that the density of chernozem soil was $\rho = 1150$ kg/m^3, the density of clay soil was $\rho = 1360$ kg/m^3. To determine the initial moisture content, the soil was dried to zero and the initial value was calculated based on the difference between the weighings.

3. Results and Discussion

3.1. Results of the study of soil heating in the microwave field. Fig. 2 presents the curves of changes in the temperature of chernozem and clay soil with the same initial moisture content (20 %). The initial moisture content of 20 % was obtained by adding the appropriate amount of water to the soil with the equilibrium moisture content. During the experiment, the container with the soil was closed, which did not allow moisture to evaporate, so the moisture content did not change. Holes were made in the lid for thermocouples, which were immersed in the soil layer when it was removed from the microwave chamber with an interval of 1 min.

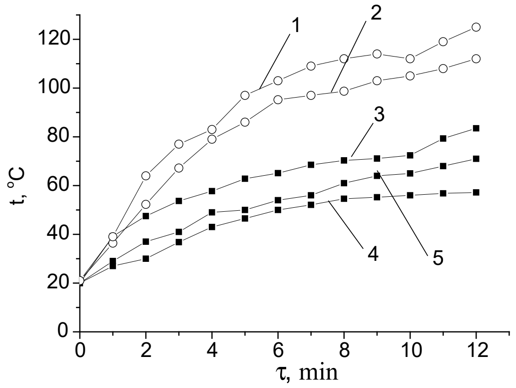

Fig. 2. Thermograms of different types of microwave soil heating. Moisture content $u = 20$ %, magnetron output power $P = 600$ W: ○ – chernozem soil; ■ – clay soil; 1, 3 – mass $m = 1.2$ kg; 2, 4 – mass $m = 1.2$ kg; 5 – mass $m = 0.8$ kg

According to Fig. 2, an increase in the mass of clay soil by 1.5 times led to a decrease in the heating rate by 2.35 times (for a mass of 0.8 kg, the heating rate is 1.83 K/min, for a mass of 1.2 kg – 4.3 K/min). For chernozem soil, the corresponding increase in mass led to a 1.32-fold decrease in the heating rate. That is, there is a smaller effect of mass on the heating rate of chernozem soil compared to clay soil.

Depending on the composition of the soil, its dielectric characteristics change. For estimated thermal calculations of soil heating, it is possible to take into account the properties of its components, including the main ones, which are listed in the Table 1. Analysis of the Table 1 shows that the largest contribution to dielectric losses is made by water. Therefore, if it is necessary to intensify the microwave heating of the soil, it is necessary to increase the moisture content.

Fig. 3 shows the kinetics of heating black earth soil with a moisture content of 20 % and a mass of 800 g in a microwave field with a magnetron output power of 600 W. Unlike the previous conditions, the soil container was not closed.

When heating wet soil with microwave currents, the initial (3.5 min) uniform, more intense release of heat in the entire volume of wet material due to the conversion of electrical energy into heat is characteristic. Then, as a result of heat exchange with the environment, a temperature field is created, which causes the evaporation of moisture contained in the soil (a section of constant temperature of the order of 83 °C) and, accordingly, the formation of a field of moisture content. In turn, the fields of temperature and moisture content affect the intensity of heat generation of the electric field, which as a result leads to the further course of the heating process. Starting from 11 min, the temperature of the soil increases, reaching values of 127 °C.

Table 1

Dielectric properties of materials at 25 °C and a frequency of 2450 MHz [18]

Material	Dielectric constant ε′	Dielectric loss coefficient ε″
Water	77	13
Fuel	2	0.002
Quartz	3.8	0.001
Mica	1.6	0.005
Feldspar	2.6	0.002

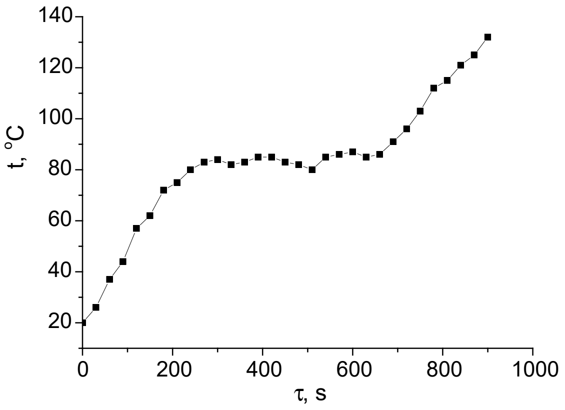

Fig. 3. Microwave heating of chernozem soil weighing 800 g. The output power of the magnetron is 600 W, the layer thickness is 4 cm

Studies have shown that there is no unequivocal dependence of temperature change on mass. The reason is that the temperature of the material depends not only on its mass, but also on the dimensions of the layer (thickness and open surface area F_{sur}). An increase in the thickness of the layer at a fixed area of the sample leads to an increase in temperature. An increase in the output power of the magnetron also leads to an increase in temperature. An increase in the surface of the sample F_{sur}, which is open to steam, leads to a decrease in temperature. The dependence for calculating the average drying temperature by layer thickness in the range of parameter changes $660 \le Q_{us} / F_{sur} \le 1875$ has the following form:

$$\bar{t} = 56.7 \cdot \left(\frac{Q_{use}}{F_{sur}} \right)^{0.24} \cdot \delta^{0.18}, \tag{1}$$

where Q_{use} – the useful heat, that is, the heat of heating the material and evaporation of moisture; F_{sur} – area of the open surface of the sample; δ – thickness of the material layer.

The error of this formula is ±11.5 %. An increase in mass at a fixed layer thickness leads to a slight decrease in the temperature of the material, and an increase in the layer thickness at a fixed mass leads to a significant increase in temperature. The influence of mass growth is less significant than the increase in layer thickness at a fixed mass, which is expressed by a positive exponent of the layer thickness depending on formula (1).

The electrophysical properties of the moistened soil agree well with the applied MW frequencies. So, at a frequency of 2450 MHz, the penetration depth for the soil is 7.0 cm. When microwave radiation passes through the soil, energy is absorbed according to the coefficient of dielectric loss (ε″).

3.2. Evaluation of the energy efficiency of microwave soil heating. Indicators characterizing the operating modes of microwave devices [19] are the efficiency of electricity use and the power used to increase the temperature of the sample and evaporate moisture. These indicators determine the efficiency of the magnetron η_m, the camera η_c and the coefficient of thermal energy use η_t. The magnetron efficiency is determined by the following ratio:

$$\eta_m = \frac{P_{out}}{P_c}, \tag{2}$$

where P_{out} – the output power of the magnetron, W; P_c – the power of the microwave chamber, which is determined according to the passport characteristics.

To determine the listed parameters, it is necessary to know what part of the microwave energy has turned into thermal energy:

$$Q_t = Q_{mat} + Q_{evap} + Q_c + Q_r + Q_{cell}, \tag{3}$$

where Q_{mat} – heat of heating the material itself; Q_{evap} – moisture evaporation; Q_r – heat loss from the material through radiant heat exchange; Q_c – heat loss from the material through convective heat exchange; Q_{cell} – heat of heating the cell.

During dielectric heating under the influence of an electromagnetic field, the containers, air and walls of the working chamber are practically not heated. But in connection with the occurrence of a temperature difference between the cultivated soil and the surrounding environment as a result of heating, heat losses occur. Therefore, the thermal energy generated in the sample can be defined as the sum of its components.

The coefficient of useful action of the camera is determined by the ratio of heat Q_t to the output power of the magnetron P_{out}:

$$\eta_e = \frac{Q_t}{P_{out}}. \tag{4}$$

As heat losses increase, the coefficient of thermal energy utilization η_T decreases, which is determined by the following ratio:

$$\eta_T = \frac{Q_{use}}{Q_t}, \tag{5}$$

where Q_{use} – the useful heat flow, which is calculated as the sum of heat of heating and evaporation: $Q_{use} = Q_{mat} + Q_{evap}$.

Losses to the environment through convective heat exchange:

$$Q_c = \alpha \cdot F \cdot \Delta t, \tag{6}$$

where α – the heat transfer coefficient, W/(m^2·K); Δt – the temperature difference of the surface of the body and the environment, °C; F – the area of the heat transfer surface, m^2.

Heat transfer is carried out by natural convection. The defining temperature is the air temperature far from the surface.

Rayleigh number:

$$Ra = \frac{g \cdot d^3}{\nu^2} \cdot \beta \cdot \Delta t, \tag{7}$$

where ν – the coefficient of kinematic viscosity; λ – the thermal conductivity coefficient; Pr – Prandtl number; β – the thermal expansion coefficient; d – the diameter of the experimental cell.

Thermophysical properties of air at $t = 18$ °C:

- coefficient of kinematic viscosity $\nu = 14.88 \cdot 10^{-6}$ m^2/s;
- thermal conductivity coefficient $\lambda = 0.025$ W/(m·K);
- Prandtl number $Pr = 0.7034$;
- thermal expansion coefficient $\beta = (273.15+18)-1 = 0.00343$ K^{-1}.

Under these conditions $Ra = 1.822 \cdot 10^7$.

Since the Rayleigh number lies within $10^3 \le Ra \le 10^8$, the Nusselt number is determined by the following relationship:

$$Nu = 0.5 \cdot Ra^{0.25} \cdot \left(\frac{\mathrm{Pr}}{\mathrm{Pr}_{cB}}\right)^{0.25} =$$

$$= 0.5 \cdot (1.822 \cdot 10^7)^{0.25} \cdot \left(\frac{0.7034}{0.698}\right)^{0.25} = 33,$$

where $Nu = (\alpha \cdot d)/\lambda$, P_{st} – the Prandtl number at the surface temperature.

According to calculations, the coefficient of heat transfer: $\alpha = 8.7$ W/(m^{2}K), the area of the heat transfer surface: $F = (\pi \cdot d^2)/4 = 0.00785$ m^2. Losses to the environment through convective heat exchange: $Q = 4.9$ W. Losses to the environment due to radiant heat exchange Q_r:

$$Q_r = \varepsilon_{giv} \cdot C_0 \cdot \left[\left(\frac{T_m}{100}\right)^4 - \left(\frac{T_{st.cam.}}{100}\right)^4\right] \cdot \varphi_{1-2} \cdot F, \tag{8}$$

where ε_{giv} – the given degree of blackness; C_0 – the constant radiation of an absolutely black body, $C_0 = 5.67$; φ_{1-2} – the average angular coefficient relative to the inner surface of the microwave chamber, $\varphi_{1-2} = 1$.

To calculate ε_{giv}, let's take into account that we have radiation in relation to one body (heated material) in the cavity of another:

$$\varepsilon_{giv} = \left[\left(\frac{1}{\varepsilon_1} - 1\right) \cdot \varphi_{1-2} + 1 + \left(\frac{1}{\varepsilon_2} - 1\right) \cdot \varphi_{2-1}\right]^{-1},$$

where ε_1, ε_2 – the degree of blackness of the walls of the microwave chamber and the material in the cell; φ_{1-2} and φ_{2-1} – angular coefficients.

Table 2 shows the results of measurements and data processing. The temperature was measured at three points using thermocouples and their values were averaged based on the results of the measurements. Magnetron output power $P = 1000$ W. Initial moisture content $u_0 = 37$ %. To determine the moisture content, the mass of the dry substance was first determined, for which the sample was dried to zero moisture content: $m_d^{100} = 0.073$ kg. At the same time, the mass of moisture in 0.1 kg sample was $m_m^{100} = 0.027$ kg. In the studied sample weighing 0.4 kg $m_d^{400} = 0.292$ g, $m_m^{400} = 0.108$ g.

Table 2

Experimental data on the study of the effectiveness of microwave soil heating

No.	τ, s	$\bar{t}$, °C	m, g	Δm, g	m_m, g	u, kg/kg
1	0	18	400	0	0.108	0.37
2	10	19	398.7	1.3	106.7	0.365
3	20	21	396.8	1.9	104.8	0.359
4	30	25	394.7	2.1	102.7	0.351
5	40	26	392.1	2.6	100.1	0.343
6	50	27	389.6	2.5	97.6	0.334
7	60	25	386.7	2.9	94.7	0.324
8	70	27	383.0	3.7	91	0.312
9	80	33	379.8	3.2	87.8	0.301
10	90	31	376.4	3.4	84.4	0.289
11	100	34	372.7	3.7	80.7	0.276
12	110	29	368.4	4.2	76.4	0.262
13	120	31	363.5	4.9	71.5	0.245
14	130	34	359.2	4.4	67.2	0.230
15	140	39	353.3	5.9	61.3	0.210
16	150	31	349.2	4.0	57.2	0.196
17	160	33	343.7	5.5	51.7	0.117
18	170	33	339.4	6.9	44.9	0.154
19	180	39	334.7	4.6	40.2	0.138
20	190	41	329.5	4.4	34.9	0.12
21	200	39	333.6	4.1	29.6	0.101
22	210	40	329.5	3.7	20.7	0.08
23	220	42	326.2	3.3	15.1	0.052
24	230	44	322.9	3.3	11.8	0.04
25	240	47	320.2	2.7	9.08	0.031

It is worth noting that, despite the decrease in moisture content (practically to zero), the increase in temperature continued, which indicates fairly high values of dielectric characteristics, probably due to a large amount of organic substances. Since the moisture content of the original soil is significant, a monotonous decrease in the mass of the material is observed. Fig. 4 shows the graph of the material temperature change over time. It can be seen that even when averaging the temperature values, the fluctuations are significant. This is due to the simultaneous transfer of heat and mass (evaporation of moisture).

The moisture yield is accompanied by a loss of energy and, accordingly, a decrease in temperature, as the action of a negative heat source. But the introduction of microwave energy leads to an increase in temperature, and it can be seen that this positive source of heat is much more intense than the heat of evaporation. Nevertheless, the non-uniformity of the temperature change is significant, which makes it difficult to calculate the thermal efficiency.

Fig. 5 shows a graph of changes in the moisture content of soil weighing 400 g over time at a magnetron output power of 800 W. The graph shows that the course of the curve changes after τ=220 s. This is due to a significant decrease in moisture and a decrease in drying speed. In this case, the heating period is not pronounced.

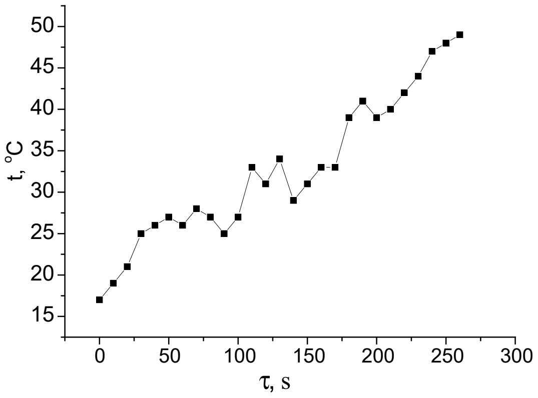

Fig. 4. Change in the average temperature of the material over time. The mass of the material is 400 g, the output power of the magnetron is 1000 W

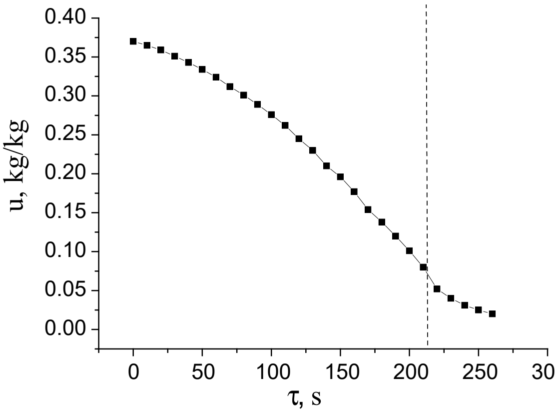

Fig. 5. Change in moisture content over time of soil weighing 400 g at the magnetron output power of 800 W

The analysis of the results shows that to evaluate the efficiency, it is rational to conduct an experiment over a period of time without removing the material, which will reduce the error of the experiment. At the same time, the duration of the experiment should be correlated with the first experiment on the study of drying kinetics. The results are given in the Table 3.

Table 3

Experimental data on the study of the effectiveness of microwave soil heating. The thickness of the layer is 2.0 cm

No.	τ, s	$\bar{t}$, °C	m, g	Δm, g	m_m, g	u, kg/kg
1	0	18	400	0	0.108	0.37
2	240	63	334	0.066	0.042	0.144

The data show that the rate of evaporation decreased: so, by 240 s according to the Table 2, the mass of the material is 320.2 g, which is 20 g less than in the experiment with continuous heating in a microwave chamber. This is due to the fact that, when removing the sample, the conditions for evaporation improved, during the measurements themselves, moisture was additionally evaporated. In the closed space of the working chamber, the exit of moisture was relatively difficult. A Panasonic NN-GD37HBZPE (China) microwave oven was used for these studies.

The total heating time was τ=240 s.

The value of the average mass, g:

$$\bar{m} = \frac{m_{in} + m_{fin}}{2},$$

$$\eta_{use} = \frac{Q_m}{P_{out}} = \frac{820.2}{1000} = 0.82,$$

where m_{in} – the initial soil mass; m_f – the final mass of the soil.

$$\bar{m} = \frac{400+334}{2} = 367 \text{ g}.$$

Mass of evaporated water:

As can be seen from the Table 3, 0.066 kg of water evaporated. Then the heat of vaporization:

$$Q_{evap} = \frac{m_{evap} \cdot r}{\tau} = 655 \text{ W},$$

where m_{evap} – the mass of evaporated moisture; r – specific heat of evaporation; τ – the heating time.

Soil heating costs:

$$Q_{evap} = \frac{\bar{m} \cdot c \cdot \Delta t}{\tau},$$

where c – the heat capacity of the soil; $\bar{m}$ – average (taking into account the initial and final value) mass of the material; τ – heating time; Δt – the change in temperature of the material during heating.

For various mineral and organic components of the soil, the volume heat capacity is almost the same and is $2.0 \cdot 10^3$–$2.7 \cdot 10^3$ kJ/(m^3·K). Therefore, it is obvious that the heat capacity of different soils depends not so much on the composition of the solid part of the soil, but on the amount of air and water in the pores, since the heat capacity of water is equal to $s_r = 4.2 \cdot 10^3$ J/(m^3·K), and the heat capacity of air is $s_r = 1.2$ kJ/(m^3·K). Therefore, with the same inflow or outflow of heat, dry soils heat up or cool down more and faster than wet ones. The heat capacity was assumed equal to $c = 2.0$ kJ/(kg·K) according to [20].

Taking into account the heating of the experimental cell from 18 to 63 °C with a mass of 70 g ($Q_{cell} = 22.3$ W) and losses to the environment ($Q_{env} = Q_l = 5.2$ W), the heat of converting microwave energy into the internal energy of the soil will be:

$$Q_t = 655 + 137.7 + 22.3 + 5.2 = 820.2 \text{ W}.$$

Camera efficiency:

$$\eta_{eff} = \frac{Q_t}{P_{out}} = \frac{820.2}{1000} = 0.82, \text{ or in percentage: } \eta_{eff} = 82\ \%.$$

Thus, the efficiency of the microwave chamber when loading a layer of soil with a thickness of 0.02 m and a weight of 0.4 kg is 82 %, but the overall efficiency, taking into account the efficiency of the magnetron, is η=0.63 %. The efficiency of the power plant that feeds the electrical network to which the magnetron is connected does not exceed 45 %. Therefore, the total efficiency of microwave treatment can be at the level of only 30 %. It can be concluded that the use of MW processing is advisable only when this method gives a unique effect or its duration is much shorter than traditional ones. This is observed in the method of soil treatment: yes, decontamination of soil with steam or boiling water in greenhouses leads to a decrease in its quality due to unevenness and damage to the organic component, and when using the conductive method at a temperature of 250 °C, the duration is 40 minutes. The duration of microwave treatment depends on the mass of the load and the purpose, which allows controlling the heat consumption. Thus, when decontamination of pathogenic microflora, treatment of 1 kg of soil for 150 s destroyed populations of *Pythium*, *Fusarium* and all nematodes, except for *Heterodera glycines*, in all studied soils, treatment of 4 kg of soil for 425 s gave comparable results. Compared to autoclaving (1 hour every 2 consecutive days) or fumigation with methylchloropicrin bromide (98^{-2}) (0.454 kg/45 kg soil), the MW treatment resulted in less nutrient release into the soil solution and less fusarium soil recolonization was observed and other mushrooms.

The amount of heat q (W/m^3) released per unit volume of the material corresponds to the following dependence:

$$q = 5.56 \cdot 10^{-11} \cdot f \cdot \varepsilon' \cdot \mathrm{tg}\delta \cdot E^2, \tag{9}$$

where E – the intensity of the external electric field, V/m; f – frequency, f=2450 MHz; ε' – relative dielectric constant, or dielectric constant; δ is the dielectric loss angle.

The intensity of the external electric field:

$$q = Q_t / V,$$

where V – the volume of material, $V=0.0003637$ m^3.

$$q = 820.2 / 0.0003637 = 2255155 \text{ W/m}^3.$$

Works on dielectric characteristics research methods and data on measurements of dielectric characteristics of various soils were analyzed [20–23]. According to [24], the relative dielectric permittivity of the soil is $\varepsilon'=13$, the tangent of the dielectric loss angle $\mathrm{tg}\delta=0.0012$ (at a frequency of 2450 MHz). The intensity of the electric field is determined by the dependence:

$$E = \sqrt{\frac{q}{5.56 \cdot 10^{-11} f \cdot \varepsilon' \cdot \mathrm{tg}\delta}} \text{ W/m}. \tag{10}$$

Then, with microwave soil treatment, $E=33908$ V/m.

For the purpose of scaling and moving from experimental data, it is advisable to focus on the value of the electric field strength in the MW chamber.

The results of the work can be used in the design of microwave chambers for heat treatment of soils. The production of industrial microwave chambers is based on thermal calculations based on the efficiency of the chamber. Based on the calculated value of the electric field strength, taking into account the thermal efficiency, the value of the output power of the magnetrons P is determined. The obtained value allows determining the required number of magnetrons.

A limitation of the study is the uncertainty of the dependence of the loading mass in a wide range on the volume of the chamber in relative values. With a significant decrease in loading, the efficiency will decrease significantly. The nature of the dependence will allow determining the optimal load mass for cameras of different volumes. This will allow processing with maximum energy efficiency.

The conditions of martial law in Ukraine affected the research due to the acceleration of research on soils contaminated with oil products. This is explained by the need to restore land resources.

In the future, it is planned to expand the experimental studies of MW soil treatment. It is necessary to clarify the dielectric characteristics, determine the optimal layer thickness, justify the processing time. Generalization of the obtained data is the basis for the development of microwave soil disinfection technology.

4. Conclusions

1. A smaller influence of mass on the heating rate in the microwave field of chernozem soil compared to clay soil was determined. Based on a study of heating in a microwave field with a magnetron output power of 600 W of soil (clay and chernozem) with the same initial moisture content (20 %) and a mass of 800 g. And an increase in the mass of clay soil by 1.5 times led to a decrease in the rate of heating in 2.35 times (for a mass of 0.8 kg it is 1.83 K/min, for a mass of 1.2 kg – 4.3 K/min). For chernozem soil, the corresponding increase in mass led to a 1.32-fold decrease in the heating rate.
2. When heating moist soil in a microwave field with the same initial moisture content (20 %) and at a mass of 800 g with an open surface, the initial (3.5 min) uniform, more intensive release of heat in the entire volume of wet material due to the transformation is characteristic electrical energy to heat. Then, as a result of heat exchange with the environment, a temperature field is created, which causes the evaporation of moisture contained in the soil (a section of constant temperature of the order of 83 °C) and, accordingly, the formation of a field of moisture content. In turn, the fields of temperature and moisture content affect the intensity of heat generation of the electric field, which ultimately leads to the further course of the heating process. Starting from 11 min, the temperature of the soil increases, reaching values of 127 °C.
3. Disinfection of soil weighing 4 kg with magnetrons with a total power of $P=1600$ W lasts 420 s, the heat consumption is $Q_m=6.72 \cdot 10^5$ J, and when decontaminating with boiling water, the consumption $Q_b=13.44 \cdot 10^5$ J: heat consumption for disinfection in MW field compared to the traditional method is 2 times less.
4. Evaluation of the energy efficiency of microwave soil heating was carried out. It was found that the efficiency of the microwave chamber when heating the soil weighing 400 g at the magnetron output power of 800 W is $\eta_{use}=82$ %, which indicates the energy efficiency of converting the energy of the microwave field into soil heat.
5. The calculated electric field strength at $\eta_{use}=82$ % is $E=33908$ V/m. When scaling and designing industrial microwave installations, the value of the microwave field intensity is the basic value in the calculations of the geometric characteristics of the working chamber.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

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