Microwave heating of slaughterhouse confiscations to increase the feed value

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Abstract. In the production of cooked feed, non-food waste from the meat industry is taken. The purpose of the research is to preserve the feed value of cooked feed during ultrahigh-frequency heat treatment. Implementation of design criteria for installations and resonators; evaluation of operating modes using multi-criteria regression models; justification of electrodynamic parameters and operating modes of installations for effective work in a farm environment. Various plant designs are proposed. Based on the criteria: continuity of technological processes of grinding, dewatering, heat treatment and disinfection of raw materials; high intrinsic Q-factor of resonators; high electric field strength in raw materials; achievement of bactericidal effect; radio-tightness of the installation and uniform distribution of the electric field in the resonators-the optimal installation is selected.

1. Introduction
Boiled feed, non-food waste from meat production and confiscated slaughterhouses that have been cooked for the purpose of coagulation, partial dehydration and destruction of pathogenic microorganisms. For the development of boiled feed, they use slaughterhouse confiscations approved by veterinary supervision for this purpose. Boiled feed, used mainly for feeding pigs, is produced at slaughterhouses that do not have equipment for the production of feed flour of animal origin.

In the production of cooked feed, non-food waste from the meat industry is taken. Raw materials that require grinding to the size of 5-10 mm pieces are sent to the shredder. Next, the raw material is subjected to heat treatment in boilers, then degreasing is carried out. The yield of cooked feed to the mass of the laid raw material is 60%.
For the production of cooked feed from non-food waste from poultry processing, technical waste is used that makes up 12-14.3% of the total volume of raw materials, having a low digestibility coefficient (30-40%), so they should be subjected to heat treatment with sterilization. The raw materials are sterilized in autoclaves under the influence of saturated water vapor at a pressure of at least 0.15 MPa at a temperature of 126 °C for 60 minutes. Since technical waste from poultry slaughter has a high content of fat and collagen, it should be dehydrated up to 40% before loading into the autoclave. The finished feed contains no more than 30% moisture [1].

We solve a scientific problem - increasing the feed value of secondary raw materials of agricultural enterprises by developing technology and ultra-high-frequency (microwave) technology for heat treatment at reduced operating costs. In the world, mainly microwave installations of periodic action with a capacity of 25-50 kW, containing water-cooled magnetrons and complex means of protection against reflected waves, are being developed. The scientific basis for the effect of an electromagnetic field on a dielectric material, including agricultural raw materials, is laid down in the works of many scientists [2-5]. The scientific school of the Nizhny Novgorod State University of Engineering and Economics has been developing microwave installations for heat treatment of raw materials of agricultural enterprises for many years.

Based on the analysis of previous studies on the development and implementation of microwave technologies for heat treatment of non-food waste from slaughtering livestock and poultry, we note that the developed continuous-flow installations can reduce operating costs if the main criteria for equipment and technology in the resonator chamber of unconventional design are implemented [1-3].

The purpose of the research is to develop the methodological basis for the creation of a continuous-flow microwave installation and the technology of heat treatment of secondary raw materials of agricultural enterprises to increase the feed value.

The concept is to develop the basics of creating a microwave installation and raw material processing technology.

The theoretical justification of the electrodynamic parameters of microwave installations with unconventional resonators for heat treatment of raw materials is aimed at solving a complex of interrelated tasks, such as: identifying effective models of continuous-flow microwave installations with the most acceptable resonator designs that provide heat treatment of high-humidity raw materials; matching the parameters of the electrodynamic system ‘generator-resonator’ and the electrophysical characteristics of raw materials with the design and technological parameters and operating modes of the installations [6-8].

2. Methodology
The simulation of the electromagnetic field in unconventional resonators and calculation of the electric field strength, Q-factor and current density were carried out in accordance with the program of three-dimensional computer modeling CST Studio Suite 2017 (CS Group). The simulation was carried out using the least squares method. Identification of effective modes of operation of microwave installations with unconventional resonators was carried out using regression models, in the programs Statistics 12.0 (StatSoft), Excel 10.0 (Microsoft). The reliability of the conclusions is confirmed by the results of studies of the technological process of heat treatment of raw materials and tests of the microwave installation in production conditions; protocols for measuring the power of the radiation flux of microwave installations and studies of the nutritional value of secondary raw materials.

To reduce the operating costs for the technological process of obtaining protein feed from non-food waste of animal origin, we have proposed a microwave technology for heat treatment and disinfection of crushed and dehydrated raw materials. For this purpose, we have developed various unconventional configurations of volumetric resonators (Nizhny Novgorod State Engineering and Economic University, Russian Federation) that ensure the implementation of the main design criteria for microwave installations, presented in this article. To increase the number of types of vibrations excited in a given range in the resonator, allowing to increase the uniformity of heating of raw materials (crushed secondary meat raw materials - for example, cuticles, goiters, claws) (poultry farms, Russian
Federation), we used three magnetrons (Nizhny Novgorod State Engineering and Economic University, Russian Federation). To avoid the transfer of microwave energy from one waveguide to another, we placed magnetrons (Nizhny Novgorod State Engineering and Economic University, Russian Federation) around the perimeter of the resonator with an offset of 120 degrees. Then the energy input from each emitter will be in the region of the magnetic field nodes of those vibrations that are excited by the neighboring emitter. The humidity of the raw material was determined according [9].

3. Results and discussion
Criteria for development and design of microwave installations:
- ensuring the continuity of combining the processes of grinding, dewatering, heat treatment and disinfection of raw materials with a high Q-factor of the resonators and a high voltage of the electrical converter (EP) in the raw material to achieve a bactericidal effect;
- creation of radio-tightness of the installation and versatility of the working chamber for heat treatment of raw materials of different composition;
- uniform distribution of the electric field in resonators excited by several magnetrons;
- the ability to vary the performance and dismantle the installation units.

The developed microwave installations with different designs of volumetric resonators for heat treatment of secondary raw materials are evaluated with respect to the possibility of implementing these criteria by calculating the smallest deviations.

The estimation of the deviation from the average value of the intervals of variation of the criteria for each resonator shows that out of 12 non-traditional resonators, three microwave installations with combined resonators have the smallest deviation from the average value according to four criteria: a combined resonator in the form of cones docked to a sphere; cascading resonators formed by a hemisphere and a cone; the resonator formed by a hemisphere and a cylinder (made and tested sample) as figure 1. Assessment of deviations from the mean values of the intervals of variation of the criteria for each of the resonator shows that 3 plants with combined resonators smallest deviation (1.075) of the average of four criteria is the most effective microwave installation with a resonator formed a hemisphere and a cylinder (No. 3), (table 1).

### Table 1. The results of the evaluation of microwave installations for heat treatment of raw materials.

| Parameters                               | Installation number | Ideal parameters |
|------------------------------------------|---------------------|------------------|
|                                          | 1       | 2       | 3       |                  |
| Q-factor of the resonator, $10^3$        | 7       | 5       | 8       | 10                |
| EP strength, kW/cm                       | 0.6     | 1.0     | 0.9     | 1.0               |
| The degree of uniformity of heating of raw materials, relative units | 0.7     | 0.7     | 1.0     | 1.0               |
| Radiation power density, µW/cm² (without shielding housing) | 100     | 300     | 50      | 10                |
| Deviation                                | 2.5     | 7.45    | 1.075   | -                 |

The developed and manufactured microwave installation (figure 1a). Figure 1b show dewatering of the ground raw materials, heat treatment and disinfection of the solid fraction. The installation consists of a grinding and centrifuging device, a combined resonator with magnetrons, and a shielding housing. The upper part of the combined resonator is represented by a hemisphere, the central part-forming a cylinder, and the lower part – an inclined cone. At the bottom of the resonator there is a disc and a discharge pipe with a ball valve. The crushed raw material with a moisture content of up to 65% enters the centrifuge, then the solid fraction falls on the surface of the hemisphere, freely suspended from the central point. The diameter of the guide tube is smaller than the diameter of the hemisphere. There is
an annular gap between them, through which the solid fraction of the raw material, when the hemisphere vibrates, slides off its surface and falls into the combined resonator. By adjusting the height of the suspension of the hemisphere, you can change the volume of the resonator. The gap intended for loading raw materials into the resonator chamber and the diameter of the non-ferromagnetic nozzle with a ball valve for unloading the product cannot exceed a quarter of the wavelength. The magnetrons are mounted with a 120-degree shift on the outside of the side surface of the resonator. The solid fraction of soft non-food waste is exposed in the resonator to the action of EMPHWH, cooked, decontaminated and discharged through a branch pipe with a ball valve.

When the magnetrons are located along the perimeter of the side surface of the cylindrical part of the resonator with a shift of 120 degrees, the magnetrons work reliably, without breakdown.

The systematization of formulas for determining the intrinsic Q-factor of standard resonators proves that for many resonators of complex structural designs, there are no simple analytical dependencies that are valid in a wide frequency band. Therefore, the intrinsic Q-factor of non-traditional resonators, along with the study under the CST-Studio 2017 program, was calculated as the ratio of twice the volume in which the energy of the electromagnetic field is stored to the volume in which it is consumed, taking into account the skin layer [10-11]. The values of the intrinsic Q-factor in terms of the volume and surface area of the developed unconventional resonators are calculated: spherical, toroidal, cylindrical, bionic, tetroconic, coaxial, combined, etc. The values of the natural Q-factor of the resonators, calculated according to the program and through the design parameters, with an equal volume, coincide with a sufficient confidence probability 95%.

![Figure 1](image1.png)

**Figure 1.** A microwave installation with a combined resonator: a prototype of the installation (a); a diagram of the technological process of the effect of Ultrahigh frequency electromagnetic field (UHFEMF) on raw materials (b): 1 – a feed unit for crushed and dehydrated raw materials; 2 – a cylindrical resonator with an inclined base; 3 – hemisphere; 4 – magnetrons; 5 – dielectric disk; 6 – a unit for unloading heat-treated protein feed.

When exposed to UHFEMF on multicomponent wet raw materials, temperature stresses appear, so a mathematical model has been developed that reflects the physical processes in the raw materials. In this case, the boundary conditions were taken into account: the power of the emitters and their location in the resonator; the speed of movement of raw materials through the resonator; the change in volume, electrophysical and thermophysical parameters of multicomponent raw materials under the influence
of UHFEMF; the loss of the radiation flow through the slots and windows; the values of the natural Q-factor of the resonators.

The specific dielectric loss, and therefore the amount of heat released per unit volume of raw materials, depends on the frequency and square of the electric field strength \( E \), on the factor of dielectric losses and the thermophysical properties of the raw materials. The variety of forms of moisture binding in the raw material and its heterogeneity cause the nonlinear dependence of the dielectric characteristics on the temperature and humidity of the raw material. Taking into account the changes in the dielectric parameters, heat capacity and density of raw materials during the heating process, the equation of the dynamics of heating of non-food waste from animal slaughter, for example, for blood, was determined in the UHFEMF (1):

\[
T^{6.88} = 0.105 \cdot 10^4 \cdot E^2 \cdot \tau + 162.58
\]  

(1)

The graphs obtained on the basis of this equation for different electric field strengths are shown on figure 2.

Empirical expressions describing the dynamics of heating the blood of slaughtered animals at different EP strengths (2)-(4):

\[
T = 6.66 \cdot \tau^{0.51} \quad (5 \text{ kV/cm})
\]  

(2)

\[
T = 7.24 \cdot \tau^{0.44} \quad (4 \text{ kV/cm})
\]  

(3)

\[
T = 7.91 \cdot \tau^{0.38} \quad (3 \text{ kV/cm})
\]  

(4)

An algorithm for matching the design parameters of the resonator and the parameters of the electrodynamic system with the technological criteria implemented in the installation is developed. It includes the determination of the required power of electromagnetic radiation to reduce bacterial contamination of raw materials: from 1 million tons. CFU/g to MPU (500 ths. of CFU/g) containing coli bacteria (5):

\[
(\text{ } k = 2400 - 2500 \mu \text{W} \cdot \text{s/cm}^2) \]

(5)

with a plant capacity of (6):

\[
Q = 36 \text{ kg/h} \quad (10 \text{cm}^3/s)
\]  

(6)

and an efficiency = 0.75. The volume of the resonator providing the critical electric field strength at the required generator power is calculated. In the volume of a 17-28 l resonator with three sources of microwave energy, with a power of 2400 W and a Q-factor of at least 6000, it is possible to excite an electric field with a voltage of 1.5 kV/cm.
Figure 2. Dynamics of heating of non-food waste of animal slaughter (blood) at electric field strengths: 1-3 kV/cm; 2-4 kV/cm; 3-5 kV/cm.

Continuous operation of the microwave installation can be achieved by transporting raw materials through the resonator, mobile or rotating parts of the resonator, but using exorbitant waveguides to limit electromagnetic radiation.

In the case of using the plant (figure 1), the movement of raw materials through the UHFEMF occurs without transporting mechanisms, therefore, heat treatment should occur at reduced operating costs. On the basis of the data obtained and verified by the methods of mathematical statistics, the effective technological parameters and operating modes of the proposed installation are determined. If rational regimes are observed, the total microbial number in the product is reduced from 1.2 million to 0.5 million CFU/g, with a plant capacity of 30-40 kg/h, specific energy costs - 0.15-0.2 kWh/kg.

Theoretical studies show that an electric field with a voltage of 1.5 kV/cm can be excited in a resonator with a volume of 17-28 liters with three magnetrons with a total power of 2400 W.

4. Conclusion
According to the conducted research, the following conclusions can be drawn that the theoretical and practical significance are:

- methodological foundations for the creation of a microwave installation that implements the technology of heat treatment of secondary raw materials of agricultural enterprises to increase the feed value;

- analytical dependences that allow us to justify the parameters of an electrodynamic system with unconventional resonators and to obtain an equation of the dynamics of endogenous heating of raw materials with changes in dielectric and physico-mechanical parameters during heat treatment.

The evaluation of the proposed installations allowed us to conclude about the practical significance of the conducted research. The use of any of the proposed plant designs allows you to preserve the nutritional value of feed during heat treatment in an ultra-high frequency electromagnetic field. This conclusion was made on the basis of the following results:

We have developed methodological foundations for creating a continuous-acting radio-hermetic microwave installation with low-power magnetrons that implements the technology of heat treatment of raw materials at reduced operating costs. A model of the operation of plants for the impact of ultra-high frequency electromagnetic field on raw materials has been developed.

Analytical dependences are obtained that allow us to justify the parameters of the electrodynamic system ‘a generator – a resonator- a raw material’ and to obtain an equation of the dynamics of endogenous heating of raw materials with changes in the dielectric and physical-mechanical characteristics.
Design and technological schemes of continuous-flow microwave installations with unconventional resonators for heat treatment of secondary raw materials of agricultural enterprises have been developed. The parameters of the electrodynamic system with the visualization of the distribution of electromotive force in the resonators in the CST Microwave Studio program are justified, with the identification of their effective execution, which ensures high intensity of the electromotive force, high intrinsic Q-factor and compliance with electromagnetic safety.

A set of design and technological parameters and operating modes of microwave installations is justified and an algorithm for their coordination is developed, taking into account the revealed empirical dependencies, regression models, and the results of studies of physico-mechanical, microbiological, and organoleptic indicators that characterize the feed value of raw materials.

A continuous-flow microwave installation with a combined resonator has been created, which provides grinding, dewatering, heat treatment and disinfection of secondary raw materials of agricultural enterprises.

The combination of well-founded scientific provisions opens up prospects for improving technologies and installations of continuous-flow operation with low-power generators for heat treatment of raw materials, which reduce operating costs in the conditions of farms.

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