Methodology of integrated evaluation of installation efficiency for collecting fluff from rabbit skin

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Abstract. Increasing the profitability of rabbit breeding is possible due to the introduction of decontaminated fluff using microwave installations with low-power air-cooled magnetrons and unconventional resonators that provide electromagnetic safety and reduce operating costs. The development of a methodology for a comprehensive assessment of the effectiveness of continuous microwave installations for collecting fluff from rabbit skins is a novelty. The method of developing and creating microwave installations is developed on the basis of step-by-step integration optimization of the design parameters of resonators, analysis of mathematical models and a block diagram of the installation operation model. The methodology is reduced to determining the efficiency of the generator when using a reasonable structural design of the resonator, which provides a continuous-flow mode of exposure in compliance with electromagnetic safety standards. Effective parameters of the created installation: own Q-factor of 8280; productivity of 19.2 kg/h; power consumption of 5.55 kW; the radiation flux density is 10-20 W/cm²; specific energy costs are 0.313 kWh/kg; the electric field strength is 0.9-1.0 kV/cm. The efficiency of ultrahigh-frequency heating reaches 0.8 when loading rabbit skins soaked in ice-pickle, with a dielectric loss factor at a frequency of 2450 MHz equal to 13.

1. Introduction
To determine the possibility of reducing the retention force of fluff in the skin at a certain dose of exposure to an electromagnetic field of super-high frequency, the dielectric parameters of the components of the raw materials (fluff, leather, mezdra fabric) and the components stimulating the process (sourdough, ice and brine) were analyzed. Knowledge of the nature of changes in the dielectric parameters of raw materials such as: dielectric permittivity, the tangent of the angle of dielectric losses, the dielectric loss factor, the depth of wave penetration in a wide range of frequencies...
and temperatures allows us to develop a scientific basis for the process and develop models of the interaction of ultrahigh frequency electromagnetic field with raw materials [1-4].

The share of imports of rabbit products to Russia is up to 85%. In the near future, the production of these products is planned to increase three times. Farms supply 13,000-15,000 tons of rabbit meat to the market per year, while producers have difficulties with processing skins and collecting rabbit fluff, respectively [5-8].

In order to increase the profitability of rabbit breeding (along with the sale of meat products) it is proposed to sell fluff raw material collected from rabbit skins, sent by farms for disposal. The research relates to agriculture and can be applied in rural areas. Currently, rabbit fluff is not recycled, but disposed of [9,10]. Processing of down will increase the profitability of agricultural production. The aim of the study is to select the most optimal design from our patented designs of continuous microwave installations for collecting fluff from rabbit skins based on the method of comprehensive efficiency assessment. Existing methods of separating the down from the skin involve either the use of manual labor or high energy consumption.

The scientific problem: increasing the profitability of rabbit breeding is solved by implementing the collected disinfected fluff from rabbit skins using innovative technology with the help of continuous-flow microwave installations with low-power magnetrons and non-traditional resonators that provide electromagnetic safety.

Guided by the principles of weakening the retention force of fluff in hair bulbs (when impregnating scraping of rabbit skins with sponge dough or ice brine, which exclude skin overheating when exposed to ultrahigh frequency electromagnetic field – ultrahigh frequency electromagnetic field), a scientific and technical task was solved – development and substantiation of indicators of microwave installations of continuous-flow for separating fluff from rabbit skins.

Rabbit down is used as a raw material in the textile, knitting and felt industry. Down has high thermal insulation properties, surpasses goat and sheep wool by 10 times. It is characterized by hygroscopicity, lightness, silkiness, low thermal conductivity, does not contain fat and does not require additional processing. 2,000 meters of yarn are obtained from 1 kg of down. The fluff of the worst quality is sent to the manufacture of felt and velour. Therefore, the collection of down from the skins of rabbits, especially the “White Giant” breed (the mass of the collected down from one skin reaches up to 5-6 kg, the length of the snow-white thick fur reaches up to 60 cm), is of great importance. To do this, the task is to dewatering the skin, i.e. ensuring the process of removing the hair from the skins by weakening the hair follicles and destroying the epidermis, which together with the hair is easily separated from the dermis.

The aim of the work is to develop a methodology for a comprehensive assessment of the effectiveness of continuous-flow microwave installations for collecting fluff from rabbit skins.

2. Methodology
The study of the processes of the effect of ultrahigh frequency electromagnetic field on rabbit skins to weaken the strength of the retention of hair in the dermis of the skin was carried out in order to scientifically substantiate the choice of rational methods and optimal modes necessary for the design and calculation of a continuous-flow installation.

The theoretical and methodological rationale is based on the analysis of electrophysical indicators of rabbit skins, the theory of electromagnetic field of centimeter waves, the properties of the formation of closed and open volume resonators and the theory of active planning experiments.

The experimental part of research was carried out using measuring equipment and software. The justification of the operating modes of the units was carried out using regression models in the programs Statistica 12.0, Excel 10.0 and Math cad. The reliability of research results was checked by experimental and analytical methods. The reliability of 18 new developed technologies and technical solutions was confirmed by expertise of the Federal State Budgetary Institution “Federal Institute of Industrial Property”.

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We propose a methodology (table 1) for development of technologies and microwave installations for fluff separation from rabbit skins includes 8 stages. Appropriate methods are used in each of them. These methods allow step-by-step substantiate structural and technological indicators and operating modes of installations with different unconventional resonators that ensure the implementation of the main technological requirements for the process.

To justify the preferred designs of non-traditional resonators, it is necessary to compare their main parameters with each other and with the parameters of traditional volumetric resonators.

Table 1. Methodology for development of microwave installations and technologies of separating fluff from rabbit skins.

| № | Sequence of project implementation |
|---|-----------------------------------|
| 1 | Solving the problem of increasing profitability of rabbit breeding by collecting fluff before recycling rabbit skins, by implementing the innovative idea of reducing the strength of fluff retention in the skin by exposure to ultrahigh frequency electromagnetic field – EMFUHF |
| 2 | Development of criteria and conditions for implementation of technological process of exposure to ultrahigh frequency electromagnetic field. Development of structural design of installations and operational and technological schemes enabling to implement the design criteria for microwave installations. |
| 3 | Substantiation of electrodynamic indicators of unconventional resonators according to the CST Microwave Studio program (designed for modeling resonators and waveguides); according to the derived formulas, which take into account the dimensions of the structure and electric capacitances. Preparation of flowchart for the implementation of technological process with possible limits for varying the main criteria. |
| 4 | Substantiation of the technology of soaking the scraping side of the skin in sponge dough or ice brine as accelerators of the fluff separation process. Substantiation of dynamics of selective heating of raw material components and possibility of fluff disinfection. |
| 5 | Development of calculation algorithm for reasonable selection of resonator design according to the criteria for of continuous-flow microwave installations. Evaluation of resonators by the method of least deviations in multicriterial optimization. |
| 6 | Development of structural diagram of model for operation of continuous-flow microwave installation with identification of input, output and controlled parameters. Substantiation of effective design of resonator by means of three-factor multicriterial regression analysis. |
| 7 | Production of effective construction of continuous-flow microwave installation, which enables to realize the process conditions. Conduct experimental studies to substantiate the operating modes of installations and evaluate the quality of the collected fluff. Study of radiation flow power near the installation and determine the working conditions of the operator in compliance with electromagnetic safety. |
| 8 | Comparative economic assessment of efficiency of structural designs of installations; development of technological documentation. Testing of prototype installation with the most effective resonator, its experimental testing with the decision on readiness for operation in rabbit farms. Development of technical specifications for production and replication of installation. |

The ability to perform its functions is estimated by five quality indicators of the resonator, such as [9]:

- The intrinsic Q-factor, determined from the energy stored in the volume of the system and the sum of the energy loss capacities of the oscillatory system. The higher the value of the resonator’s own Q-factor, the better the frequency selectivity and less loss. The losses are noticeable in open resonators (with slits, slits, etc.).
- Multimode is an indicator that characterizes the density of wave vibrations in the resonator.
• Temperature stability of the resonator Q-factor (a change in temperature that caused a change in the resonator’s own Q-factor).
• The temperature stability of the resonant frequency (the shift of the resonant frequency when the temperature of the material changes, hence the change in its permittivity).
• The indicator that characterizes the overall dimensions of the resonators at the selected wavelength is the ratio of the volume of the resonator to the wavelength in the cube.

It is known that during the development of ultra-high-frequency exposure installations, the uniformity of the distribution of the impact of the electromagnetic radiation field in the raw materials is crucial. Therefore, studies of the distribution of the electromagnetic field in the developed volumetric resonators were carried out in the transient mode in the CST Microwave Studio program. For various forms of resonant working chambers, patterns of distribution of the electromagnetic field strength, current density and intrinsic Q-factor of the resonator were calculated, designed and considered, after which the configuration and volume of the resonator were justified. In the process of designing volumetric resonators in a three-dimensional representation, boundary conditions were set using this program, and the location of radiation sources was determined. Computer modeling made it possible to optimize the structural design of individual units of the microwave installation at the design stage of resonators of various standard sizes.

It is also necessary to take into account other indicators of the quality of resonators: permissible operating power, weight, cost, manufacturability, reliability, radio leakage. When choosing and optimizing the structural design of resonators, difficulties arise associated with contradictory indicators. The improvement of some indicators of the quality of resonators leads to a deterioration of others. Therefore, the solution of the electrodynamic problem is possible taking into account the boundary conditions of many parameters, including changes in dielectric parameters, diffraction phenomena during wave scattering, etc.

3. Results and discussion

To determine the possibility of reducing the retention force of fluff in the skin at a certain dose of exposure to ultrahigh frequency electromagnetic field, the dielectric parameters of the components of the raw materials (fluff, skin, mezdra tissue) and the components stimulating the process (sourdough, ice cream) were analyzed. Knowledge of the nature of changes in the dielectric parameters of raw materials such as: dielectric permittivity, the tangent of the angle of dielectric losses, the dielectric loss factor, the depth of wave penetration in a wide range of frequencies and temperatures allows us to develop a scientific basis for the process and develop models of the interaction of ultrahigh frequency electromagnetic field with raw materials. The studied raw materials belong to semiconductors, where polarization processes and a current due to the active conductivity of the raw materials occur under the influence of ultrahigh frequency electromagnetic field. The amount of heat released selectively in each elementary particle of the raw material is determined by the coefficient of dielectric losses and losses caused by the through-conduction current. When applying ice pickle to the mezdra fabric of the skins, the humidity increases, therefore, the value of the electrophysical characteristics increases significantly. Therefore, in the process of exposure to ultrahigh frequency electromagnetic field, there comes a moment when the amount of heat released in the volume of raw materials decreases, and the heating rate begins to decrease. For the selected wavelength of 12.24 cm, it is necessary to determine the conditions for ensuring uniform selective heating of the raw material. In bulk resonators, during the appearance of standing waves, when the wavelength is commensurate with the length of the skin, overheating of raw materials is possible in the places of the wave antinode, and low temperature is possible in the wave nodes. Therefore, to ensure a more uniform distribution of energy in the volume of raw materials, taking into account the depth of wave penetration, it is necessary to transport it through a volumetric resonator, but observing the norms of electromagnetic safety. Methods for solving these problems are given below.
Based on the review of analytical materials, we analyze the technologies for processing fur raw materials and taking into account the experience of operating microwave installations with low-power magnetrons in farm conditions designed for dielectric heating:

- we developed microwave technologies for separating fluff from rabbit skins and design diagrams of installations with ultrahigh frequency electromagnetic field sources and unconventional resonators that provide continuous operation at reduced operating costs;
- we obtained results of calculation and visualization of electromagnetic field distribution in developed volumetric resonators according to CST Microwave Studio program, which made it possible to justify their effective design versions with high natural quality, and providing high electric field tension;
- we obtained mathematical dependencies describing the dynamics of skin heating with scraping impregnated with sponge dough in ultrahigh frequency electromagnetic field, taking into account changes in dielectric and physical and mechanical indicators;
- it was developed a method for matching the indicators of electrodynamics system “generator-resonator-load” (generator power, electric field tension, natural quality factor and resonator volume) with the structural and technological parameters of the continuous-flow installation for separating disinfected fluff from rabbit skins;
- regression models were obtained taking into account the multicriteria evaluation of technological process of separating disinfected fluff from leather with scraping impregnated with sponge dough or ice brine, which made it possible to substantiate a set of indicators and operating modes of microwave installations with different design of volumetric resonators;
- we developed microwave installations of continuous-flow with new design versions of resonators (cylindrical, toroidal, coaxial, ellipsoidal, biconic, etc.), ensuring the separation of fluff from rabbit skins when implementing a set of reasonable design and technological indicators;
- microwave installation with biconic resonator was developed and tested in production conditions; the technical and economic efficiency of its implementation in rabbit farming was evaluated; scientifically based practical recommendations for operation of microwave installations were developed.

Practical significance and value of scientific works are:

- made design documentation, developed and tested in production conditions a continuous-flow microwave installation with biconic resonator that provides electromagnetic safety and selective heating of skins, the scraping side of which is impregnated with sponge dough or ice brine to weaken the retention force of fluff raw materials in the skin;
- developed microwave installations of continuous-flow for collecting fluff from rabbit skins, containing unconventional resonators (toroidal, coaxial, cylindrical, semi-cylindrical, biconic, ellipsoidal, prismatic); the results of experimental studies that have led to recommendations for development and operation of microwave installations in farm conditions;
- the method of matching design and technological indicators with operating modes of installation and identified effective modes of influence of ultrahigh frequency electromagnetic field on raw materials impregnated with sponge dough or ice brine, during which fluff raw materials are separated from rabbit skins.

In this work, when evaluating the effectiveness of the structural design of resonators that provide a continuous flow mode, we took into account the following possibilities:

- achieving the maximum volume with the minimum surface area of the resonator, affecting its own Q-factor, i.e., the efficiency of the installation;
- compliance with electromagnetic safety;
- the excitation of an electric field with a voltage greater than the critical one, at which the viability of the bacterial microflora of the vegetative form stops in the downy raw material;
• uniform distribution of the electric field in the raw material and selective endogenous heating of the hair sac in the adipose tissue;

• control of the plant’s performance by using several low-power air-cooled magnetrons and changing the power of each generator;

• regulation of the dose of the effect of ultrahigh frequency electromagnetic field on raw materials (the heating temperature of the raw materials components), depending on the size of rabbit skins, by changing the speed of movement of raw materials and the specific power of the generator (by changing the volume of loading of raw materials and the power of generators);

• impregnation of the mezdra with sourdough or ice cream.

The closest to ideal resonators according to four criteria (maximum Q-factor, high intensity of the electric field, the degree of uniformity of selective heating of raw materials, the minimum density of the radiation power flow through the slots) are: a prismatic resonator with bases in the form of an astroid; a coaxial resonator and a biconic resonator.

Through an installation with a four-sided prismatic resonator, the faces of which form an astroid in the cross-section, it is possible to transport skins, the mezdra sides of which are impregnated with sourdough or ice-pickle, with the help of a working branch of a mesh dielectric conveyor. To do this, there are slots on opposite sides at the joints of the prism faces, the height of which does not exceed a quarter of the wavelength. If the cross-section of the slots does not overlap the critical cross-section near the junction of the faces, then the waves are attenuated. Such slots do not significantly affect the structure of the electromagnetic field or the resonant frequencies. By choosing the appropriate structural dimensions of the resonator, it is possible to form a high-intensity electric field to disinfect the fluff, as well as to exclude the degeneration of parasitic types of vibrations. Therefore, the diameter and length of a conventionally inscribed cylinder in a prism are multiples of half the wavelength. The installation contains a fluff collection unit, in the form of a drum with pegs and a pneumatic conveyor. Air-cooled magnetrons are installed on the upper faces of the prism.

The second installation with a coaxial resonator is presented as a system of two coaxially arranged cylinders with common bases. The average perimeter of the resonator should be a multiple of half the wavelength and at least three skin lengths. The outer cylinder has three slots along the side surface and dielectric flexible pegs on the inner surface. In the annular space between the cylinders, a dielectric perforated drum with dielectric pegs on the side surface from the outside is coaxially installed. The size of the annular gap between the dielectric pegs corresponds to the thickness of the skin. Magnetrons are installed on the side surface of the outer cylinder with a shift of 120 degrees. On one end side of the resonator, an electric drum drive is installed, transporting a non-ferromagnetic roller and dielectric rollers and on the other – a hatch. The slot in front of the dielectric rollers is connected to the pneumatic pump. A storage tank is docked to the other slot, and dielectric rollers are installed between these slots so that they cover the gap between the pegs.

The third installation with a truncated biconic resonator also contains slots whose dimensions are consistent with the wavelength. By increasing the angle of inclination of the generator, it is possible to increase its own Q-factor.

The effectiveness of the structural design of the resonators was substantiated through three-factor regression analysis. The obtained values of natural quality factor, electric field strength, radiation flow density were used in the experiment planning matrix for reasonable selection of the design of microwave resonator. The closest to ideal resonators according to four criteria (natural quality factor, EF tension, degree of uniformity of selective heating of raw materials, density of radiation power flow through slots) are: biconic resonator as figure 1, prismatic with bases in the form of an astroid; coaxial.

The variable factors were:

1) exposure dose ($x_1$) of ultrahigh frequency electromagnetic field, taking into account the number of low-power (800 W) generators and duration of exposure (240 s); the dose was varied at three levels 0.576 W·s/kg; 0.768 W·s/kg, 0.960 W·s/kg;
2) structural design of unconventional resonators, represented by their surface area \((x_2)\) at a constant volume \((0.3 \, \text{m}^3)\); the area was varied on three levels \((4 \, \text{m}^2; 5 \, \text{m}^2; 6 \, \text{m}^2)\);

3) cross-sectional area of slots \((x_3)\), for transportation of raw materials, \(\text{m}^2\); \((0.06 \, \text{m}^2, 0.08 \, \text{m}^2, 0.1 \, \text{m}^2)\), which allow the transport mechanisms to be moved with unfolded rabbit skins.

Response surfaces and two-dimensional cross-sections of models were constructed and regression models were obtained: natural quality factor \((Q)\); power \((P)\) and capacity \((Q)\) of installation; radiation flow density \((p)\); specific energy costs \((W)\); electric field (EF) tension \((E)\) from variable parameters \(x_1, x_2, x_3\)

\[
\begin{align*}
Q &= 11863.86 + 4705.78 \cdot x_1 - 1058.95 \cdot x_2 - 599.64 \cdot x_1^2 - 729.17 \cdot x_1 \cdot x_2 - 22.11 \cdot x_2^2, \quad \text{by } x_1 = 0.08 \, \text{m}^2 \\
Q &= 16530.88 - 1631.58 \cdot x_2 - 29096.49 \cdot x_3 - 36.84 \cdot x_2^2 + 2000 \cdot x_2 \cdot x_3 + 82894.74 \cdot x_3^2, \quad \text{by } x_2 = 0.08 \, \text{m}^2 \\
Q &= -3.83 + 30.21 \cdot x_1 + 0.77 \cdot x_2 - 1.86 \cdot 10^{-12} \cdot x_1^2 - 1.043 \cdot x_1 \cdot x_2 + 9.02 \cdot 10^{-13} \cdot x_2^2, \quad \text{by } x_3 = 0.08 \, \text{m}^2 \\
P &= 1.2 + 6.25 \cdot x_1 - 2.48 \cdot 10^{-12} \cdot x_2 - 1.2 \cdot 10^{-11} \cdot x_2^2 - 2.5 \cdot 10^{-13} \cdot x_1 \cdot x_2 + 2.66 \cdot 10^{-13} \cdot x_2^2, \quad \text{by } x_3 = 0.08 \, \text{m}^2
\end{align*}
\]

Finding the main factors that affect the dependent variable and determining the minimum or maximum of the function was carried out through partial derivatives for each of the parameters, equated to zero. The obtained factors were corrected on two-dimensional cross-sections of the models.

Effective structural and technological indicators of installation with truncated biconic resonator as figure 1 are natural quality factor 8280; capacity 19.2 kg/h; power consumption 5.55 kW; radiation flow density 10-20 μW/cm²; specific energy costs 0.313 kW·h/kg; EF tension 0.9-1.0 kW/cm, exposure dose to ultrahigh frequency electromagnetic field 0.768 Ws/kg (surface area 4 m²) with a cross-sectional area of 0.08 m².

![Figure 1. Microwave installation of continuous-flow unit for separation of fluff from rabbit skins with truncated biconic resonator: (a) technological scheme of installation: 1 – symmetrical truncated biconic resonator; 2 – magnetrons; 3 – rabbit skins; 4 – pneumatic duct for fluff collection; 5 – skin without hair cover; 6 – conveyor; 7 – sponge dough or ice brine sprayer. (b) prototype of installation.](image-url)
Taking into account reasonable advantages, a microwave installation containing a symmetrical truncated biconic resonator was developed as figure 1, where there are slots in the area of peaks. Magnetrons are arranged with shift along cones base perimeter. The rabbit skins (the scraping of which is impregnated with sponge dough or ice brine) is moved using a dielectric grid conveyor. Steamed skin in ultrahigh frequency electromagnetic field creates conditions for skin softening, pore expansion, rapid destruction of hair bulbs and hair release. The design of this resonator provides a single working type of oscillations at frequency of 2450 MHz and a minimum decrease in the loaded quality factor with an increase in the resonator’s fill factor. The technological scheme of the installation is shown in as figure 1a. The prototype of the installation is shown as figure 1b.

Due to the fact that the narrow slots in the truncated peaks are located along the current flow lines in the resonator (therefore, regardless of their length, the width of which is less than a quarter of the wavelength) the radiation of microwave energy should be below the maximum permissible level. Nevertheless, conducted studies of power radiation flow using PZ-33M show that electromagnetic safety is provided directly near the installation only with shielding net on the slots during working day as figure 2.

For microwave installations with power supply, the power of radiation flow should not exceed 10 \( \mu \text{W/cm}^2 \) at distance of 0.5 m. The personnel serving the microwave installation can work for 5 hours per day, if the power of the microwave radiation flow does not exceed 50 \( \mu \text{W/cm}^2 \).

It is known that the retention of the hair after applying a jelly made of mustard powder and rye flour decreases after 5-6 hours. Therefore, based on this technology, we have proposed a sourdough made from a homogenized fermented mixture of rye flour, water, yeast and mustard powder.

The calculation of the weight of the sponge was carried out taking into account the average weight of the skin of one rabbit, equal to 400-450 g. With an equal consumption of mustard powder and rye flour for 27% of the weight of the rabbit skin, the required amount of each component is calculated: consumption of mustard powder – 108 g; consumption of rye flour – 108 g; salt consumption – 6 g; yeast consumption – 4-5 g; (for 1 kg of rye flour 40-50 g); consumption of hot water – 324 g. (150 g of water per 100 g of rye flour and mustard powder equally). In total, the weight of the sponge is 551 g.

![Figure 2](image.png)

**Figure 2.** Changes in power radiation flow depending on distance to installation and measurement height: 1) without shielding net, 2) with net.

In the technology of separation of down raw materials from rabbit skins, the use of ice pickle is provided. To do this, a thin layer of vegetable oil is applied to the mezdra side of the rabbit skin, on top of it – ice crumbs and rock salt as figure 3.

To soften the mezdra surface, the skins should be covered with vegetable oil, but to avoid overheating, the surface should be cooled with ice until the brine, through filtration and diffusion processes, permeates the adipose tissue. When exposed to ultrahigh frequency electromagnetic field,
all components (fat, skin, vegetable oil, ice, rock salt) are heated selectively, in accordance with their dielectric parameters.

We will evaluate the effectiveness of a continuous-flow installation with a truncated biconic resonator for collecting down from rabbit skins. Rabbit skins, whose mesdra is covered with ice-glass, have a sufficiently large coefficient of dielectric loss. When they are placed in a volumetric resonator, almost all of the microwave energy of the generators is used for endogenous heating of the raw materials, including selective heating of the hair follicles. This feature allows you to weaken the retention force of down raw materials in the dermis of rabbit skins.

Figure 3. The structure of the skin on which the ice is applied: 1 – rock salt; 2 – ice; 3 – brine; 4 – vegetable oil; 5 – hair sac in adipose tissue; 6 – dermis; 7 – epidermis; 8 – stratum corneum; 9 – hair.

Let a rabbit skin be located inside a truncated biconic resonator with a base radius $R$. In the resonator, $H_{01p}$ oscillations are excited, and the surface of the skin is tangent to the electric field $E(r, z)$, and the center of the field has a coordinate where $q = 1, 3, 5, ..., \lambda = 12.24 \text{ cm} – \text{ the wavelength}$.

If the average radius of the skin $(g_s)$ is equal to the radius of the resonator base, and the thickness of the skin $(d_s)$ is less than two wave penetration depths, then the installation efficiency can be calculated taking into account the filling factor of the resonator with rabbit skins, the maximum efficiency value can be achieved.

Generator efficiency (2):

$$\eta = \frac{1}{1 + \left[1 + \left(\frac{2 \cdot \pi}{\mu_{01}}\right)^3 \left(\frac{R}{L}\right)^3 \left(\frac{1}{2 \cdot p}\right) \left(\frac{R}{Z_o}\right) \left(\frac{V_p}{V_s}\right) \right]^{-1} + 2 \cdot \pi \cdot \varepsilon \cdot t g \delta \cdot \left(\frac{2 \cdot \pi}{\mu_{01}}\right)^3 \left(\frac{R}{\lambda}\right)^3 \left(\frac{V_p}{V_s}\right)^{-1}}$$

(2)

where $\mu_{01}$ – the root of the Bessel function $J_1 (3.832)$; $L$ – the length of biconical resonator, m; $p = 1, 2, 3, ...$; $V_p$ – the volume of the resonator, m$^3$; $V_s$ – the volume skins, m$^3$; $R$ – the surface resistance of the cavity, $\Omega$; $Z_o$ – the impedance of free space, $\Omega$, $(Z_o = 377 \Omega)$.

Knowing the specific conductivity of aluminum (36,106 Cm/m) and the thickness of the surface layer of the resonator made of aluminum $(1.716 \cdot 10^{-6} \text{ m})$, it is possible to determine the surface resistance of the resonator. Taking into account the structural dimensions of the truncated biconic resonator, its volume is 0.358 m$^3$, the length along the central axis is 2 m, and the diameter of the base...
is 0.856 m.

Then the efficiency of the generator with a volume of three skins ($10^{-2} \text{ m}^3$), simultaneously located in the resonator, is (3):

$$\eta = \left(1 + \frac{6.28}{3.832} \left(\frac{0.856}{2} \right)^{1/3} \left(\frac{1}{2-1} \right) \left(\frac{11.687}{377} \right) \left(\frac{0.358}{0.01} \right) \right)^{-1} = 0.8 \quad (3)$$

Calculations show that the high efficiency of the generator (0.8) is achieved already with a resonator fill factor of 0.03.

When rabbit skins are found in a volume resonator, the mezdra of which is impregnated with ice-glass, under the influence of an ultra-high frequency electromagnetic field, thermal energy is selectively released in all components, depending on their electrophysical parameters. As the temperature increases, the heat flow rushes into the surrounding air. If we combine the x-axis of the orthogonal coordinate system with the axis of the volume resonator, then the heat equation describing the thermal processes in the system can be represented as (4):

$$\frac{\partial T}{\partial t} = a^2 \frac{\partial^2 T}{\partial x^2} + P / c \cdot \rho \quad (4)$$

where $T$ – the increment of the temperature in the mezdra of the skin at a distance $x$ from the origin above the ambient temperature; $a$ – the coefficient of thermal conductivity; $c$ – the specific heat capacity of the mezdra; $\rho$ – the density of the mezdra; $P$ – the specific heat power for heating the mezdra soaked in ice-glass; $t$ – the duration of processing.

The temperature distribution over the thickness of the rabbit skin can be analyzed using the formula (2), after solving equation (1) as (5):

$$T = \frac{32 \cdot \rho \cdot h^3}{2 \cdot k^3} \sum_{n=1}^{\infty} \left(\frac{n+1}{2} \right)^3 \cdot \cos \left(\frac{2 \cdot n \cdot \pi \cdot x}{2 \cdot h} \right) \left[1 - e^{-\left(\frac{\left(2 \cdot n \cdot \pi \cdot x \right)^3}{2 \cdot h^3}\right)^{t}} \right]$$

(5)

where $h$ – the thickness of the skin; $k$ – the coefficient of thermal conductivity; $n$ – the investigated layer of raw materials; $\rho$ – material density.

To assess the profitability of selective dielectric heating, it is necessary to determine the power absorbed in the volume of the skin mezdra. It will be less than the total power $P$, since some of the power is dissipated. The power generated in the volume of the skin mezdra is determined taking into account the heat capacity, density and area of the heating zone ($S$) by the formula:

$$P_2 = c \cdot \rho \cdot S \int_{x=h}^{x+h} T \cdot dx$$

(6)

where $c$ – heat capacity.

The efficiency coefficient is equal to the ratio of the power generated in the volume of the mezdra of the skin to the power of the generator $P_1$:

$$\eta = \frac{P_1}{P_2} \quad (7)$$

Based on the results of theoretical and experimental studies, a technical specification was developed for the creation of a continuous-flow microwave installation with low-power air-cooled magnetrons and an open biconic resonator, which ensures the separation of fluff from skins when exposed to ultrahigh frequency electromagnetic field on rabbit skins, the mezdra of which is impregnated with ice-rassol.
Several technologies have been developed to accelerate the process of reducing the retention force of down in the rabbit skin mezdra when a continuous-flow microwave installation is located in a volumetric resonator. In the volumetric resonator, you can place skins stretched on rules, you can cut them in the form of a plate, or load them in the form of a stocking without rules.

More than 10 installations have been developed for these technologies:

- The first technology. After removing the skins from the carcasses of rabbits, they are stretched on mobile dielectric ropes, with the fur inside. The rules are made in the form of a truncated cone, made of rods and are installed with the ability to move through a volumetric resonator and rotate around its axis. In this case, the resonator is formed by a half-cylinder and a pallet. The pallet simultaneously serves as a container for sourdough. Fluff is removed by pneumatic transportation.

- The second technology. The skins are cut and moved in the form of a plate using a dielectric roller conveyor through a semi-cylindrical resonator. Or you can use a coaxial resonator. Moreover, at the beginning of the process of exposure to ultrahigh frequency electromagnetic field, a node is provided for soaking with sourdough or ice with salt on the mezdra side of the skins.

- The third technology. The skins removed from the carcasses with fur inside should be turned out after the mezdra side has been smeared with vegetable oil. The skin in the form of a stocking from the side of the head should be fixed with a dielectric paper clip, ice and rock salt should be filled in from the open end, after which it should also be fixed with a paper clip and put on dielectric transporting rollers. The thickness of the skin together with salt and ice should be no more than a quarter of the wavelength, so that the slots on the resonators for feeding and unloading raw materials can maintain electromagnetic safety during continuous operation of the installation. For example, when using a microwave installation with a prismatic resonator having a base in the form of an astroid.

Each rabbit-breeding farm has the opportunity to select the appropriate technology and installation, depending on the required productivity and the specifics of the technology provided in the slaughterhouse. When using microwave technology and a continuous-flow installation for collecting fluff from rabbit skins, with a volume of 1 ton/month, operating costs will decrease and the economic effect compared to the basic method, using a shearing machine, will amount to 67,500 RUB/month. The sale of down and granulation of dewatered skins for animal feed additives will not only increase the profitability of rabbit production, but will also reduce soil pollution due to the disposal of skins with down.

4. Conclusion

Microwave technologies for separating fluff from rabbit skins and design schemes of microwave installations with low-power magnetrons of continuous-flow operation with unconventional resonators providing electromagnetic safety were developed. They made it possible to develop a methodology for developing and creating a microwave installation based on step-by-step integration optimization of design indicators of resonators, analysis of mathematical models and block diagram of model functioning of microwave installation.

An effective resonator, identified through a three-factor regression analysis of the three studied structural designs, such as: biconic, prismatic with bases in the form of an astroid; coaxial is biconic. Its own Q-factor reaches 8280. If the power consumption of the plant is 5.55 kW, then the capacity is 19.2 kg/h, the specific energy cost is 0.313 kWh/kg. The high electric field strength of up to 1.0 kV/cm makes it possible to decontaminate downy raw materials.

The calculated value of the heating efficiency, taking into account the dielectric parameters of the raw material components, is quite high (0.8). When filling a resonator with a high reflectivity, it is possible to increase the efficiency of ultrahigh-frequency heating.
The economic effect of introduction of continuous-flow microwave installation with truncated biconic resonator for separating fluff from rabbit skins is 67,500 RUB/month. The profitability of fluff collection increased by 23% compared to the base installation. The research can be used in agriculture.

The obtained research results can be applied abroad in rural farms engaged in rabbit breeding. The basic technology remains the collection of decontaminated down raw materials in the process of exposure to ultrahigh frequency electromagnetic field on the skin, the mezdra side of which is soaked with ice cream or sourdough (a homogenized fermented mixture of rye flour, water, yeast, mustard powder and salt).

The expediency of replicating a microwave installation for collecting fluff from rabbit skins largely depends on the use of standard components and parts for the transporting mechanism, soaking with sourdough or ice cream, collecting fluff and a system for regulating the process mode.

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