Justification of structural and technological parameters of microwave installations for heat treatment of wax raw materials

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Abstract. The article is devoted to the development of a method and technical devices that allow separating honey when melting beeswax under the action of an ultra-high frequency electromagnetic field. Analyzed electrical properties of beeswax and honey; the dynamics of heating of components of raw materials; three models of installations with different resonators; investigated the electrodynamic parameters of the system; substantiated the structural-technological parameters of the installation. Three variants of installations for wax melting with different resonators have been developed. In the first installation, the modules contain cylindrical and spherical resonators. In the second installation, a spherical resonator inside a toroidal resonator is installed. In the third installation, two cylindrical resonators in series are connected. In the second installation, the wax raw material is dosed with rolls onto a perforated disk inside a spherical resonator, where the raw material is heated to 40°C, increasing its fluidity, which allows the honey to be separated when the disk rotates. Effective modes of heating beeswax are: specific power of the generator 0.85 W/g; duration of exposure to ultrahigh frequency electromagnetic field 240 sec; heating temperature of the wax 64°C.

1. Introduction
In apiaries, wax is melted from wax raw materials using a wax press, a high-temperature wax press (VVT-1P "Melissa"), a wax centrifuge (PVTS-1M), and an aggregate for melting wax. Having studied them, as well as wax burners of foreign production [1], it was found that their principle of operation is based on the melting of wax due to steam and separation of apiary merv by filtration or pressing. Wax raw materials collected in an apiary contain a lot of honey (5–7 %) [2–4].
When using these technical means, it is not possible to separate the honey from the wax. There are positive results of processing zabrus (signet of honey) in a microwave oven. There is a microwave installation for melting beeswax, but it works in a periodic mode [5]. At the same time, it is not possible to preserve the honey contained in the wax raw materials using existing wax burners of both Russian and foreign production.

Scientists from different countries have proved that the use of microwave EMF for processing agricultural raw materials can reduce energy costs and improve the quality of the resulting product [6–8]. Therefore, the scientific task is to develop a continuous installation that ensures the melting of beeswax after the separation of honey from the wax raw materials by the influence of an ultra-high frequency electromagnetic field (UHFEMF). Due to the fact that crystallized honey begins to melt at a temperature of 40–45 °C, and beeswax melts at a temperature of 62–70 °C [9, 10], it is difficult to carry out these processes in a single resonator. Therefore, microwave installations with two modules have been developed.

Scientific novelty is represented by two-resonator microwave installations of continuous-flow action, which ensure the melting of beeswax with the release of honey.

The purpose of this work is to substantiate the structural and technological parameters of microwave installations for heat treatment of wax raw materials.

2. Materials and methods
As the studied raw material, apiary wax was selected, obtained in the farm "Paseka 52" of the Nizhny Novgorod region, Sergachsky district, which is dominated by the production of flower honey.

The heating temperature of raw materials was measured using a differential thermometer "Testo 925" (Testo AG, Germany), as well as an infrared thermometer "FLUKE 62 Mini IR THERMOMETER" (Fluke Corporation, USA).

The CST Microwave Studio program (CST of America, USA) was used for three-dimensional modeling of EMF distribution in resonator chambers of different configurations. The sources of microwave energy were magnetrons 2M253K(JT), 850 W, frequency 2450 MHz, wavelength 12.24 cm (Toshiba, China). Justification of regime parameters was carried out through active planning of a 3-factor experiment of type 2³.

The quality indicators of the product were studied in accordance with GOST 21179-2000 (organoleptic indicators) and GOST 31747-2012 (microbiological indicators) [11, 12]. The rationale for the design of resonators was carried out taking into account the main design criteria for microwave installations.

The experiment was held in the scientific laboratory of the Nizhny Novgorod state engineering-economic university, Knyaginino, Russia. Scientific and technical problems in the following sequence were solved. By analyzing the dynamics of heating beeswax and honey at different specific capacities of the microwave generator, the optimal rate of heating of raw materials is revealed.

Three versions of microwave installations with non-traditional resonators have been developed, and their electrodynamic parameters have been analyzed to determine the maximum possible intrinsic q-factor and electric field strength. It was revealed the effective design and technological parameters and modes of operation of microwave installations through regression models by implementing the method of active planning of a three-factor experiment of type 2³. The quality of the melted beeswax was evaluated according to organoleptic and microbiological parameters. The technical and economic indicators of using two-module microwave installations in apiary conditions are calculated.

3. Results and discussion
Analyzing the features of existing microwave installations, three versions of two modular installations designed for heat treatment of beeswax have been developed, which differ in the structural versions of volumetric resonators. In the first installation, the modules contain cylindrical and spherical resonators. In the second installation, a spherical resonator is installed inside a toroidal resonator. In the third installation, two cylindrical resonators are connected in series.
To separate honey from wax raw materials, it is necessary to increase the fluidity due to dielectric heating up to 40 °C [13-15]. If you heat honey above 40–45 °C, it destroys enzymes and vitamins, as the structure of honey begins to change – it becomes more fluid and darker [16, 17]. All these recommendations are provided in the installations developed and described below.

The first microwave installation contains in one module coaxially arranged non-ferromagnetic truncated cones 5, 7, between which a dielectric conical dish 6 with slots on the side is coaxially located [18]. The lower base of the inner truncated cone 5 coaxially-mounted cylindrical cavity 3, the lower base of which are presented in the form of a non-ferromagnetic scratch disk 8 is located with a gap less than a quarter wave length, rigidly mounted on the motor shaft 10 with a conical dielectric plate 6.

On the upper base of the resonator there is a receiving container 1 containing fluted non-ferromagnetic rolls 2, and on the side surface, there are air-cooled magnetrons 4. The outer truncated non-ferromagnetic housing 7 contains a drain pipe 9 and a discharge hole 12 located above the edge of the dielectric conical dish 6, and docked with a hole 13 on the surface of the spherical resonator 14 located in the second module figure 1.

Inside the spherical resonator, a dielectric perforated disk 15 is located, rotating with the help of an electric motor 18, and magnetrons 17 are installed outside, and an out-of-bounds waveguide with a ball valve 16 is provided.

![Figure 1. Microwave installation for melting wax raw materials: 1 – receiving container; 2 – fluted non–ferromagnetic rolls; 3 – cylindrical resonator; 4 – magnetrons; 5 – internal truncated cone; 6 – conical dielectric perforated plate; 7 – external truncated cone; 8 – non–ferromagnetic scratch disk; 9 – drain pipe; 10 – electric motor; 11 – housing; 12 – discharge hole on the outer truncated body; 13 – hole in a spherical resonator; 14 – spherical resonator; 15 – dielectric perforated disk; 16 – beyond the waveguide with the ball valve.](image)

The second microwave installation figure 2 contains a spherical resonator 5, closely adjacent to the surface of a horizontally located toroidal resonator 7 along a small perimeter, and common discharge holes 14, at the junction, with a diameter of less than a quarter of the wavelength. Below the holes inside the spherical resonator 1 is a dielectric perforated disk 6, rotating from an electric motor 13. Magnetrons 4, 8 with a spatial shift of 120 degrees are located on both surfaces. Under the lower perforated surface of the toroidal resonator 7, a non-ferromagnetic storage tank 10 is installed, containing a drainpipe 1. At the top of the non-ferromagnetic spherical resonator 5, a receiving container 1 is installed, containing fluted non-ferromagnetic rolls 2, and at the bottom, there is an exorbitant waveguide 12 with a ball valve.

The third microwave installation with interconnected cylindrical resonators for heat treatment of wax raw materials in a continuous mode is made as follows figure 3. Horizontally arranged cylindrical resonators 2, 9, are made of non-ferromagnetic material, are joined together by a pressure ring 6, inside which is located a grinding mechanism 7 containing a knife and a grate.
Figure 2. Microwave installation that contains a spherical cavity of toroidal cavity: 1 – reception capacity; 2 – non-ferrous corrugated rolls; 3 – fastener; 4 – magnetron spherical cavity; 5 – the spherical resonator; 6 – perforated dielectric disk; 7 – a toroidal resonator; 8 – magnetron with directional emitters inside toroidal cavity; 9 – perforated base non-ferromagnetic toroidal resonator; 10 – holding tank; 11 – drain pipe; 12 – beyond the waveguide with the ball valve; 13 – the electric motor shaft; 14 – discharge holes.

Figure 3. Microwave installation with cylindrical resonators for heat treatment of wax raw materials in continuous mode: (a) schematic image; (b) spatial image; 1 – loading container with a flap; 2 – the first cylindrical resonator; 3 – non-ferromagnetic coils; 4 – the first discharge screw; 5 – a dielectric shaft; 6 – a pressure ring; 7 – a grinding mechanism consisting of a knife and a grid; 8 – magnetrons; 9 – the second cylindrical resonator; 10 – a dielectric discharge screw in the second resonator; 11 – perforated parts of resonators; 12 – receiving tanks with drain pipes containing flaps; 13 – electric motor.

Inside the resonators, two discharge augers 4 with a grinding mechanism between them are arranged in series on one dielectric shaft 5. The second cylindrical resonator 9 with magnetrons 8, a dielectric discharge auger 10 and a receiving capacity 12 is docked with the first cylindrical resonator 2 so that the dielectric shafts of the discharge augers are fixed together, forming a common shaft 5. The initial turns 3 of the first discharge auger are made of non-ferromagnetic material, and its subsequent turns and turns of the second discharge auger 10 are made of fluorooplast. The discharge augers and the grinding mechanism are rotated by an electric motor 13 located on the outside of the unit. The loading capacity 1 is located above the non-ferromagnetic coils 3 of the first discharge screw 4 on the first cylindrical resonator 2. Low power air-cooled magnetrons 8 are installed on the side surfaces of the resonators. The lower parts of the cylindrical resonators are perforated 11 and under them are located non-ferromagnetic receiving tanks 12 with flaps.
The technological process of separating honey from the melted wax raw material in continuous resonators is as follows. Close the flap on the loading container 1 and the flaps in the receiving containers 12, then load the wax raw material. Turn on the electric motor 13 to rotate the discharge screws 4, 10, and the knife of the grinding mechanism 7 using the dielectric shaft 5. Open the flap on the loading container and turn on the microwave generators on the first resonator 2, after which an ultrahigh-frequency electromagnetic field is excited in this resonator (UHFEMF, 12.24 cm, 2450 MHz). Wax raw material, getting into the inter turn space of the first discharge auger 4, is exposed to UHFEMF, endogenous is heated (to a temperature of 35–40 °C), honey is heated and flows through the perforations 11 of the first resonator in the receiving vessel that will separate honey from wax raw materials. Moreover, several initial turns 3, made of non-ferromagnetic material of the first discharge screw, limit the radiation through the loading container, blocking the bottom of the container when the screw rotates. After injection of the wax by the grinding mechanism 7 into the second resonator 9, the corresponding generators should be turned on. Then, under the influence of microwave UHFEMF, the wax is heated (60–65 °C) and flows through the perforation 11 of the lower part of the second resonator 9 into the corresponding receiving container. The dose of exposure to UHFEMF in each resonator is consistent with the melting point of honey and wax and is regulated by changing the power of the generators. The wax raw material is heated selectively due to polarization currents, in accordance with the electrophysical parameters of the honey and wax components. The capacity of the plant is regulated by the number of microwave generators and depends on the state of the original beeswax raw material. In order to verify the adequacy of mathematical models describing the dynamics of heating beeswax, and to argue for the theoretically justified main design and technological parameters, experimental studies of the processes of heat treatment of beeswax by the influence of UHFEMF have been carried out. The dynamics of heating bee honey and beeswax at different specific capacities of the microwave generator is studied. The uniformity of the temperature distribution in beeswax was evaluated; the change in bacterial contamination of the wax raw material during heat treatment in the UHFEMF was analyzed. The performance of a microwave installation corresponding to an effective mode in which the quality of beeswax is maintained is justified. The specific energy costs for the technological process of beeswax melting are investigated.

For three-dimensional modeling of the resonator chamber of different configurations, we used The CST microwave studio program, which allows us to calculate and visualize patterns of distribution of the electromagnetic field intensity, current density, and the resonator $q$-factor.

The parameters of an electro dynamic system with toroidal, spherical, cylindrical, and coaxial resonators at equal volumes are analyzed figure 4. The analysis shows that the spherical resonator has the maximum intrinsic $q$-factor equal to 8000, the toroidal resonator is 7000 in second place, the cylindrical resonator has a $q$-factor of 5000. In this case, the electric field strength in the resonators can reach up to 0.8 kV/cm.

| Resonators operating in the above microwave installations | toroidal | spherical | cylindrical |
|----------------------------------------------------------|----------|-----------|-------------|
| Maximum electric field strength ($E$) and natural $q$-factor of the resonator ($Q$) | 0.8 kV/cm | 0.6 | 0.7 |
| $Q$ | 7000 | 8000 | 5000 |

Figure 4. Visualization of the electric field distribution in resonators operating in the above microwave installations.
A comparative analysis of the evaluation criteria for the developed microwave installations has shown that the smallest deviation 0.03 from the optimal value is the installation containing a spherical resonator inside a toroidal one.

Studies of the dynamics of heating beeswax in the working chamber of a microwave installation. The raw material heating temperature was measured using a differential thermometer “Testo 925” and an infrared thermometer “FLUKE 62 Mini IR THERMOMETER”.

The results of the evaluation of microwave installations according to 7 criteria are presented in table 1.

**Table 1.** Results of evaluation of microwave installations according to 7 criteria.

| Criteria for evaluating a microwave installation | Dual-resonator continuous-flow microwave installation | Optimal value of the criterion |
|-------------------------------------------------|-----------------------------------------------------|-------------------------------|
| Own the quality factor of the resonator, ×10^3 (the mean value of the resonators) | 7 | 7.5 | 5 | 7.5 |
| EMF intensity, kV/cm | 0.6 | 0.7 | 0.7 | 0.8 |
| Specific energy costs, kWh/kg | 0.13 | 0.1 | 0.15 | 0.1 |
| Annual economic effect, thousand rubles | 13 | 18.5 | 15 | 18.5 |
| Easy to manufacture, relative units | 0.6 | 1 | 0.3 | 1 |
| Honey, % | 7 | 6.5 | 5 | 7 |
| Microbiological index of melted wax, ×10^6 CFU/g | 0.5 | 0.2 | 0.4 | 0.2 |
| Deviation | 0.53 | 0.03 | 0.49 |

**Figure 5.** Beeswax with honey: (a) beeswax (side view); (b) top view.

Some results of the study of the distribution of the temperature field on the surface of beeswax figure 5 under the influence of EMPS of different specific power are presented in figure 6.

**Figure 6.** Timing of the dynamics of heating beeswax with honey content.
The rate of endogenous heating increases with increasing specific power. The quality and color of the finished product improves when exposed to a low specific power UHFEMF. Moreover, the higher the specific power of the flow of electromagnetic radiation, the deeper the wax melts

*Figure 7.* Dynamics of heating of beeswax in UHFEMF at specific capacities: 0.55 W/g; 0.85 W/g; 1.15 W/g.

Empirical expressions describing the dependence of beeswax temperature on the duration of exposure to UHFEMF at different specific generator capacities:

\[
T = 21.297 \cdot \tau^{0.6405} \quad (1.15 \, W / g); \quad T = 19.081 \cdot \tau^{0.5763} \quad (0.85 \, W / g); \\
T = 18.794 \cdot \tau^{0.4392} \quad (0.55 \, W / g).
\]

(1)

Beeswax melts at a temperature of 64°C. If the specific power of the generator is 1.15 W/g, then this happens for 170–180 sec; for 230–240 sec at 0.85 W/g; for ~360 sec at 0.55 W/g. When heated in contact with honey, the wax acquires a more intense color. When the specific power 0.85 W/g and useful power microwave generator 850 W performance microwave setup is 12–13 kg/h. In case of use of three microwave generators of unit capacity up to 40 kg/h.

Results of studies of organoleptic parameters of wax and honey before and after exposure to UHFEMF. According to organoleptic and physical and chemical parameters, apiary wax must comply with GOST 21179-90 "Beeswax. Technical conditions" [11]. Organoleptic evaluation of beeswax was performed using the following parameters: color, smell, and structure at the fracture. Tested 4 samples in 4-fold repeatability.

*Figure 8.* Organoleptic evaluation of wax (a) and honey (b) of the experimental and control variants.
The 1-st control sample – wax without treatment; 2, 3, 4 experimental samples were exposed to microwave UHFEMF at different specific powers up to the melting point of the wax 60–65 °C. 2 sample – specific power 0.55 W/g, 3 sample-specific power 0.85 W/g, 4 sample – specific power 1.15 W/g.

The results of evaluating the organoleptic characteristics of the product, heated at a specific power of 0.85 W/g, are shown in figure 8. They indicate that the quality of the prototype wax is 4 points higher than that of the prototype.

The study of heat treatment modes of wax raw materials in a microwave installation containing a spherical resonator inside a toroidal resonator figure 2 was carried out. Effective modes of heat treatment of apiary raw materials were determined using regression models obtained during the implementation of the three-factor planning matrix of the experiment type 2³. At the same time, the specific power of the generator was varied (x₁, Pₛₚ), duration of exposure UHFEMF (x₂, τ) and diameter of toroidal resonator (x₃, D). The optimization criteria were the heating temperature (T), plant performance (Q), specific energy costs (W), and total microbial number (TMN). Using the program STATISTICA 12, the response surface and their two-dimensional cross-section are constructed in the isolines of models that describe the relationship of these criteria with the variable parameters. The specific power of the microwave generator was varied by changing the load weight of the raw material and the power of the generator from 0.55 W/g to 1.15 W/g. The heating Duration (x₂) varied from 210 to 270 seconds. The diameter of the toroidal resonator was changed from 12.24 to 24.48 cm.

The following regression models are obtained:

\[ T = -320.53 + 0.44 \cdot Pₛₚ + 4843.52 \cdot \tau + 7.54 \cdot 10^{-6} \cdot Pₛₚ^2 - 5.89 \cdot Pₛₚ \cdot \tau + 4185.27 \cdot \tau^2; \]

\[ Q = 132.03 + 1.3 \cdot 10^{-13} \cdot Pₛₚ - 1901.14 \cdot \tau + 1.52 \cdot 10^{-17} \cdot Pₛₚ^2 - 2.33 \cdot 10^{-12} \cdot Pₛₚ \cdot \tau + 8986.93 \cdot \tau^2; \]

\[ W = -0.15 + 0.0002 \cdot Pₛₚ + 2.71 \cdot \tau - 7.45 \cdot 10^{-8} \cdot Pₛₚ^2 + 0.99 \cdot Pₛₚ \cdot \tau - 19.63 \cdot \tau^2; \]

\[ TMN = 3.32 + 63.02 \cdot \tau + 13.65 \cdot D - 162.54 \cdot \tau^2 - 238.32 \cdot \tau \cdot D + 21.22 \cdot D^2. \] (2)

Technical characteristics of a microwave installation containing a spherical resonator in a toroidal one are given in table 2.

| Parameters                              | Value |
|-----------------------------------------|-------|
| Total generator power, W/h             | 0.85  |
| Duration of exposure to microwave EMF, sec | 240   |
| Rotational speed of disk, rpm           | 500   |
| Heat temperature, °C                    | 64    |
| Capacity of the unit with one generator, kg/h | 12.28 |
| Specific energy costs, kW/kg            | 0.1   |

4. Conclusion

After analyzing the parameters of the developed microwave installations, it was found that the most optimal parameters will be an installation with a spherical resonator inside a toroidal one, which has a capacity of up to 40 kg/h when using 3 microwave generators. At the same time, the specific energy costs are 0.1 kWh/kg, and the microbiological parameters of the melted wax decrease from 0.7 to 0.2×10⁶ CFU/g, due to the high electric field strength. When implementing this installation in beekeeping, the annual economic effect will be 18,500 rubles.

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