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Innovations in Technologies of Agricultural Raw Materials Processing

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Abstract: The study describes the installations designed to improve the energy efficiency of processing the fat-containing raw materials and to improve the quality of the finished product. The description is given for design of the installation with a supply of microwave energy for fat melting-containing raw materials as well as for the principle of its operation. The toroidal shielding enclosure of the installation comprises spherical perforated resonators inside which there are located the rapidly rotating stirring mechanisms.

Key words: Toroidal shielding enclosure, perforated spherical resonators, microwave generator, processing of agricultural, raw materials

INTRODUCTION

It is known that agricultural raw materials processing is energy-intensive, associated with the consumption of large amounts of electricity, steam and water. The heat treatment of a fat-containing raw material is used for fat melting. To remove fat from the fatty tissue, it is necessary to destroy the protein structure comprising fat, transfer it from an extracellular phase to free intracellular phase and then remove into an external environment. Currently, heat treatment is the most widely used technology for these purposes. There are used conductive and convective heat input methods by direct contact of raw materials with steam or heat is applied to the raw material through the wall from a heating medium. Edible raw fats and edible bone are treated for fat melting at 90°C (soft raw materials) and 100°C (bone). Duration of heat treatment of raw materials is determined by melting duration and conditioning for destruction of pathogenic microflora (Ivashov, 2001).

Intensification of the process on extraction and decontamination of fat from fat-containing materials and improvement of quality of fat and greaves are an urgent task. The quality of fat and greaves depends on the combined action of two factors: a maximum temperature and a duration of its affecting. The minimum duration of treatment is determined by the duration of fat melting and duration of raw conditioning to destroy pathogenic organisms at a given temperature of the process. Increase of temperature of medium above 120-130°C in processing fat-containing raw materials is undesirable since this leads to deterioration of the final product. In view of this the installation is designed for fat melting with the use of electromagnetic radiation energy (Ershova, 2014a; Novikov, 2015).

The aim of this work is intensification of the fat melting process by influence of ultrahigh frequency electromagnetic field on fat-containing raw materials ensuring improvement in the quality of a finished product with the lowest operating costs.

Object of research are technological systems and processes occurring during heat treatment of materials with using electromagnetic radiation energy, experimental prototypes and pre-production models of plants and their operative parts (cavity resonators with product input and output devices) in continuous mode and finished products.

Subject of the research is revealing the regularities of electromagnetic radiation exposure to the raw materials for the effective functioning of the installations in continuous mode.

Research methodology and methods. Research of process regularities was carried out on the basis of a scientific hypothesis about the behavior of electrodynamic systems with heat treatment of raw materials in continuous mode implemented in the MicroWave (MW) units with movable spherical resonators. With regard to the range of problems a complex of existing basic methods of research was used allowing to reveal the new design of the operative parts of

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microwave installations in the form of movable spherical resonator chambers located inside the shielding enclosure with below cutoff waveguides. The theory is based on the use of known locations of dielectric heating in microwave range, elements of the theory of microwave electrodynamic systems and propagation of electromagnetic waves inside cavity resonators. We used certified digital electrical measuring instruments and equipment in experimental researches to ensure sufficient accuracy of the results and also the standard method of estimating the reproducibility of effective operation modes of installations, numerical methods for solving problems arising upon the theoretical development of mathematical models for the processes of heat treatment of raw materials. Confirmation of regularities of raw material heating dynamics in movable resonators is achieved by a natural value of factors evaluation criteria in the process of testing of microwave installations in a production environment. When justifying the electro-technological processes and technical solutions we used a single system of interaction of the main installation components: a source of microwave radiation, a cavity resonator, below cutoff waveguides and slowing and shielding elements. We used in the researches a three-factor experiment active planning technique of type 23 and statistical treatment of research results using computer programs Microsoft Excel 10.0, statistic 5.0 and three-dimensional modeling of the embodiment of microwave installations in the program Compass-3D V15. The study substantiates the methods of calculation and design of resonant cavities including design features of installations with movable spherical resonators in microwave generators (Ershova, 2013).

The work differs from others by methodological generalization of an electrodynamic system “microwave oscillator-cavity resonator-raw material” with different embodiments of the working chamber providing a continuous process of heat treatment and disinfection of raw materials due to repeated exposure of electromagnetic radiation with different wavelengths. Because of the design features of cavity resonators the installations have specifics in their work principles in the methods of designing components and electromagnetic radiation energy transfer elements from the source into raw materials as a whole. Structurally electromagnetic systems of microwave generators feature combining movable resonators and radiation chambers arranged in a toroidal waveguide. In the microwave technique such energy transfer method is an independent field of research. The process of heat treatment of agricultural raw materials described with a boundary problem solution of heat and mass transfer in the approximation of set parameters of the ultrahigh frequency electromagnetic field found in turn from the solution of the boundary electrodynamics problem within some interval of time with repeating the calculations for new time intervals to achieve the desired raw material temperature. Upon that it is possible to determine the process dynamics taking into account the changes in time of dielectric and thermal parameters of materials, to calculate the shape and size of a cavity resonator in accordance with the wavelength and critical dielectric field intensity and to determine the number of radiators and their arrangement in the work chamber (Ershova, 2014b).

The novelty of the research results consists in a systematic approach to the theoretical estimate of regularities of processes which take place in electrodynamic systems in the development of methods for influence of electromagnetic radiation on raw materials; in development of mathematical models which describe the processes of heat treatment of raw materials and in formulation of algorithms for matching structural and technological parameters with operating modes of the installation taking into account criteria of process assessment; in revealing the reserves for increasing in efficiency of the microwave installations equipped with movable cavity resonators for heat treatment of products in continuous mode; in the study of a heat exchange kinetics when the raw material is exposed to electromagnetic radiation in movable resonators; in development of a technique for engineering calculation of installation parameters for heat treatment of raw material using electromagnetic radiation.

Based on the existing electrophysical ways and technical means for processing fat-containing raw materials, we propose to carry out the heat treatment in a continuous mode combining energy of electromagnetic radiation and providing effective electric field intensity in the microwave range. What is more, pre-production samples with reasonable parameters and configuration of microwave generator cavity resonators, protected by patents for inventions are manufactured for heat treatment of fat-containing raw material.

MATERIALS AND METHODS

Physical, mechanical and dielectric properties of fat-containing raw materials: To justify the design and technological parameters and operating modes of the installation for heat treatment of fat-containing raw materials its physical, mechanical and dielectric properties were analyzed. The energy for protein denaturation at a change in temperature by 1°C for meat proteins during cooking is 0.84-1.26 kJ/(kg·K). The heat capacity of fat before melting is $(1.3\text{-}3)\times10^3$ J/(kg·K), after melting 2.6×10^3 J/(kg·K).

Table 1: Humidity of fatty tissues of animals

Kind of animal	Humidity (%)	Density (kg m^{-3})
Pork	0.25	915-961
Chickens	9.10	900
Cattle	0.20	915

The latent melting heat of fat is (121-151) 103 J/kg, water vaporization heat is (2480-2.27·T) 103 J/kg where T is the water evaporation temperature (°C).

Heat transfer coefficients at open steam condensation is 840-2780 W/(m^2·K) while at water heating -840-33300 W/(m^2·K); lowest coefficients at heating raw materials by air are (85 W/(m^2·K). Humidity of fatty tissues of animals is shown in Table 1.

The acid number of fats is not more than 1.2-3.5. The melting point of a beef fat is 42-52°C, lamb fat 46-55°C, pork fat -28-46°C. Refractive ratio of animal fats at 40°C is equal to 1.456-1.460.

It is known that the specific heat (J/kg) required to process fat-containing raw materials is necessary for initial heating, fat melting, denaturation of proteins, water evaporation and final heating but is independent of the power supply method (Ivashov, 2001). Duration for achievement of the necessary temperatures in the raw material mass is determined by the type of energy supply, intensity of the heat and mass transfer, the volume ratio, the surface area and mass of the raw materials and its physical parameters. To intensify the heat exchange is possible by raising temperature of the medium, changing the conditions of heat transfer by increasing the heat transfer surface at a constant weight of raw materials. Ambient temperature rise above 120-130°C while processing the fat-containing raw materials leads to deterioration of the melted fat. Grinding increases the heat exchange surface that intensifies heat exchange speeding up the internal heat transfer by thermal conduction. When producing bone meal, particles should have a size of 25-35 mm.

Existing equipment for fat melting operate in batch mode with a large volume, so duration of the heat treatment process is 4-5 h, this degrades the quality of fat and feed products. In view of the above-stated drawbacks and recommendations we offer to intensify the process of thermal extraction of fat with good quality by exposure of ultrahigh frequency electromagnetic field energy to shredded fat-containing raw materials.

Dielectric characteristics of raw materials over a wide electromagnetic fields frequency range as a function of temperature, moisture and fat content were analyzed and presented in Fig. 1. High dielectric constant value at low frequencies and its sharp drop with increasing frequency are related with relaxation of charge and discharge process on a cell membrane. In the microwave range

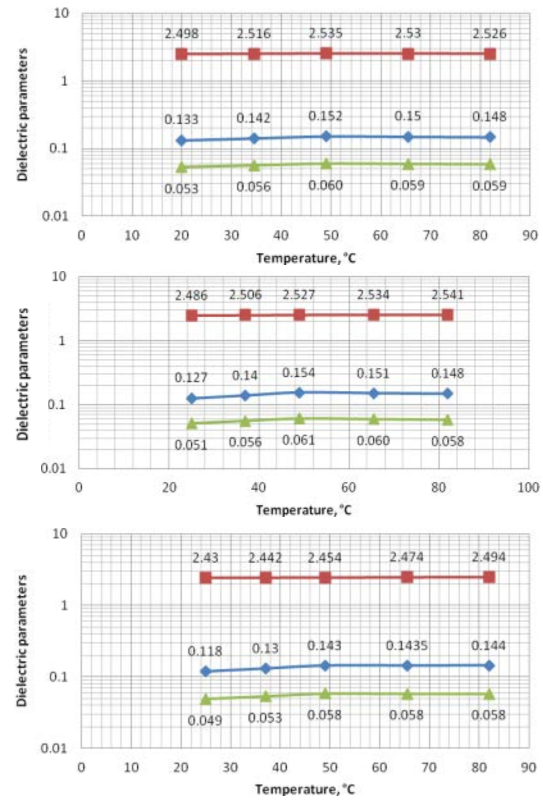

Fig. 1: The dielectric parameters of a fat-containing raw material: a) bacon; b) internal pork fat and c) lard

(433, 915 and 2400 MHz) dielectric properties of foods have been studied by A.M. Rogov. The main factors affecting the dielectric properties of materials are humidity and temperature what should be considered when selecting the heat treatment conditions. With the decrease in humidity the dielectric constant continuously reduces. In the temperature range from 20-45°C absorption coefficient increases as a result of redistribution of moisture. As the result of diffusion processes, intracellular fluid can freely penetrate cell walls and change liquid level in the capillaries formed by muscle cells and intercellular gaps. All of these features should be considered in justifying the penetration depth of microwave frequency electromagnetic energy in a raw material to achieve a uniform heat temperature distribution over the whole volume.

Given the patterns of fat accumulation and greaves weight change during heat treatment of fat-containing raw materials in microwave frequency electromagnetic field, we agree the processing duration with a generator specific power. We calculate the real productivity of the installation taking into account a power consumption of the microwave installation and duration of raw materials transportation inside the movable resonator chambers.

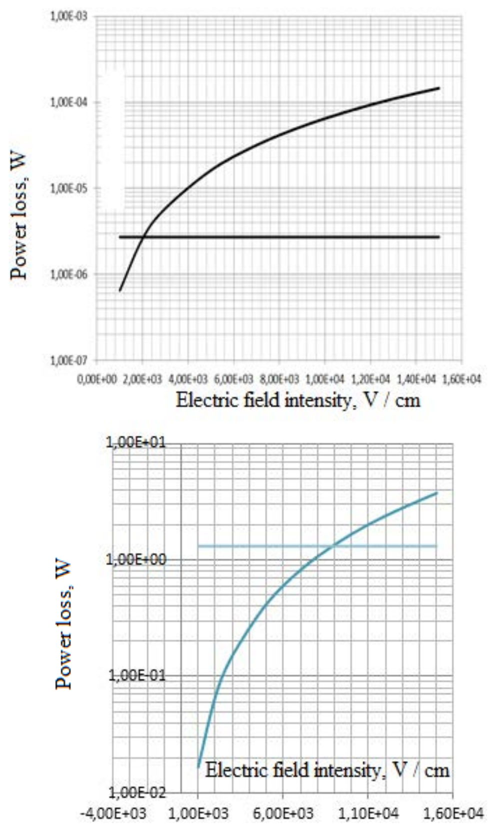

Fig. 2: Analysis of power losses for the dielectric heating of micro-organisms: a) water; b) fat) at different electric field intensities and heat losses power at cyclical fat temperature excess to 70°C

The results of calculations for power of dielectric losses at different electric field intensities and sizes of microbial colonies are shown in Fig. 2. For example, if the colony size is 50×10^{-6} m or more, ultrasonic cavitation can destroy the colonies structure to individual micro-organisms so that, to inhibit their development when exposing by an microwave frequency electromagnetic field with intensity more 2 kV cm^{-1}. If the electric field intensity is of 1 kV cm^{-1}, dielectric power losses (6.48×10^{-7} W) is lower than the heat power loss from the surface of microorganisms, so bacterial flora reducing would be insignificant.

The developed installations for thermal treatment of fat-containing raw materials: Six installations for fat melting have been developed with features of their working chambers configuration. Newly developed designs of resonator chambers of microwave installations ensure maximum quality factor and provide continuous raw material processing without complex systems for radiation limiting through a shielding enclosure and with low-power magnetrons. The heating of raw materials located in a suspended state and the short duration of treatment create the conditions for rational use of microwave frequency electromagnetic field energy upon provision for high fat quality.

Four installations contain spherical resonators. Three installations have the resonators formed from two hemispheres and two of them are equipped with a perforated hemispheres rigidly fixed to periphery of a twirled disk (Fig. 3 and 4).

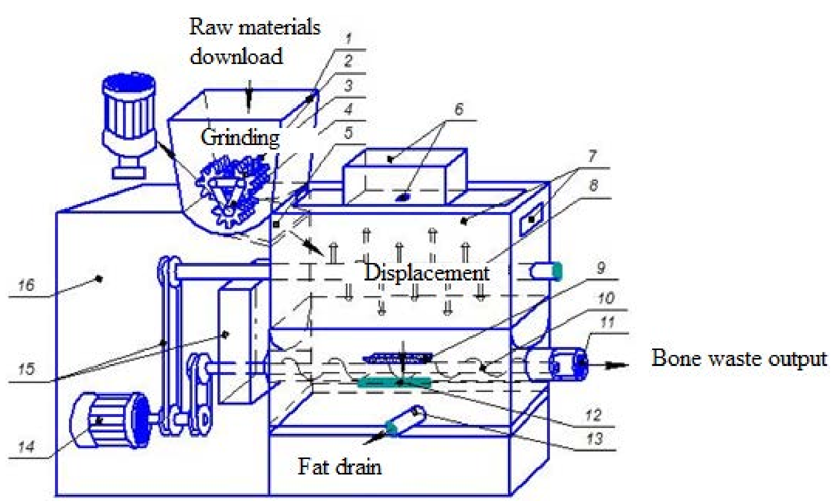

Fig. 3: Installation for heat treatment of fat-containing raw materials; 1: loading capacity; 2: roller grinding mechanism; 3: set of starwheels with an electric motor; 4: the electric motor with gear mechanism; 5: tray; 6: microwave generator; 7: resonator chamber; 8: stirring mechanism drive; 9: discharge auger enclosure window; 10: discharge auger; 11: die; 12: filter; 13: receiver tank; 14: electric motor; 15: belt drive and gearbox; 16: shielding enclosure

RESULTS AND DISCUSSION

The first installation: The installation was designed for heat treatment of fat-containing raw material and consists of four main modules. The first module provides grinding a fat-containing raw material by a roll grinder. The second module is used for a heat treatment of raw materials inside the resonator chamber by the energy of a microwave electromagnetic field. The third module allows for filtering of melted fat and forming bone waste through the discharge auger and the die. The fourth module integrates electric motors and gearboxes.

When a raw material enters between the rollers, it is ground and further moves into the resonator chamber where an endogenous heating of the crushed material occurs. Thus for uniform heating of raw material throughout its volume it is necessary preliminarily to enable stirring mechanism and the discharge auger. The raw material heated up to the fat melting temperature passes into the discharge auger. Further, bone wastes are extruded through the die and melted fat flows through the filter into the receiver tank. The resonator chamber is inside the shielding enclosure. The installation operates continuously providing parallel grinding of raw materials, their heating, fat melting, injection and extrusion of bone waste. Screws of the discharge auger and the die allow further grinding the bone waste with end product in the form of bone meal with adjustable size of grains. Features of the designed installation allow grinding processes to perform for fat-containing raw materials and fat melting due to dielectric heating, and separation into two fractions such as bone meal and melted fat. Quality of a finished product depends on combined action of two factors: temperature of the endogenous heating and microwave frequency electromagnetic field exposure dose.

The second unit (patent No. 2 550 423 and application No. 2015102660/13) runs in batch mode, transportation of dosed raw materials is carried out in the perforated hemispherical movable parts 4 of cavity resonators located in a toroidal shielding enclosure 2 (Fig. 4).

Bottom perforated hemispheres are charged with fat-containing raw material through the loading hatch. Raw material is filled with washing liquid through the feed tube and washing liquid amount in the area of piezoelectric elements 11 should be sufficient to immerse the raw material into it. After filling in all perforated hemispheres with raw materials, energy sources of microwave electromagnetic radiation and ultrasonic generators should be turned on. When the movable perforated hemisphere is joined with the stationary hemisphere 3, the raw material is exposed to microwave frequency electromagnetic field influence. If the perforated hemisphere is plunged into the liquid, the raw material is subjected to ultrasonic vibrations. The shielding enclosure combines the functions of a ring waveguide and an ultrasonic generator tank. The third installation (application No. 2014150840/20) combines diffraction movable spherical resonators in a circular waveguide of rectangular cross section (Fig. 5). During exposure of microwave electromagnetic field to a raw material, electromagnetic waves through the perforations in the hemispheres 9 and through the gap between the hemispheres of the resonator chamber propagate outside the cavity resonator, i.e., inside the toroidal waveguide with rectangular cross-section 16 formed in the annular space between the shielding enclosure 1 and the cylinder 15. Upon that a traveling wave flow in the waveguide 16 is absorbed with the raw material located in the lower perforated area 9. Melted fat and fragmented greaves are discharged through perforation of the hemisphere and rotor disk 2 where they are stored in the pan 10.

The fourth installation (application No. 20151117451) for fat melting contains stationary arranged diffraction

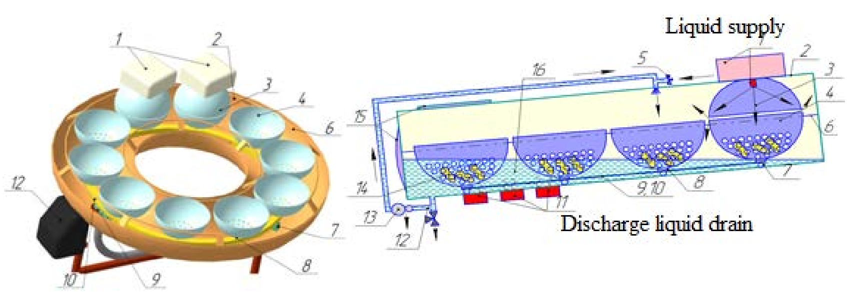

Fig. 4: Installation with ultrasonic and microwave generators for treatment of fat-containing raw materials (spatial and schematic picture); 1: microwave generator with magnetron; 2: circular waveguide; 3: stationary hemisphere of the cavity resonator; 4: movable perforated hemisphere cavity; 5: liquid supply pipe; 6: directing bezel; 7: rollers; 8: articulation; 9, 10: driving sprocket with gear ring; 11: piezoelectric elements of the ultrasonic generator; 12: branch pipe to drain the waste liquid; 13: circulation pump with filter; 14: fat-containing raw material; 15: door for unloading and loading a raw material; 16: washing fluid

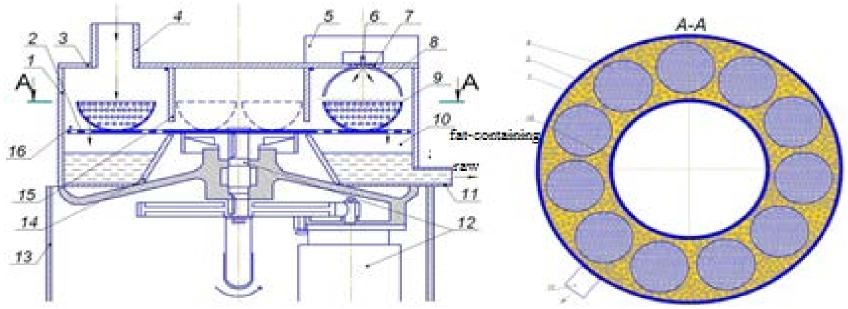

Fig. 5: Installation for heat treatment of fat-containing raw materials in a microwave frequency electromagnetic field; 1: shielding cylindrical enclosure; 2: perforated disc rotor; 3: shielding enclosure cover with window; 4: suction intake; 5: microwave generating units; 6: MW radiator; 7: dielectric sleeve; 8: upper (stationary) hemispheres of resonator chambers; 9: lower (movable) perforated hemispheres of resonator chambers; 10: pan; 11: outlet; 12: electric motor with gear mechanisms; 13: bed; 14: truncated cone; 15: cylinder; 16: toroidal shielding enclosure

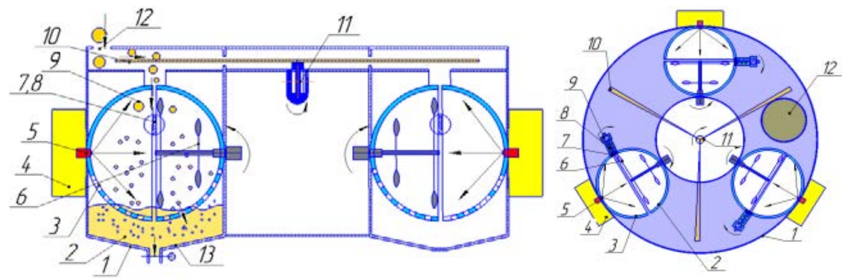

Fig. 6: Installation for fat melting; 1: shielding enclosure; 2: first perforated hemisphere, 3: second perforated hemisphere; 4: microwave generator unit; 5: magnetron radiator; 6: agitating mechanism with electric motor; 7: grinding mechanism (knives and grills); 8: discharge auger; 9: suction intake; 10, 11: scrapers with the electric motor for moving raw materials; 12: second torus with rectangular cross section and loading hatch; 13: storage trough with a drain pipe and valve

spherical resonators but each sphere provides mixing mechanisms inside it also performing a dissector function. Spherical resonators are arranged in an annular shielding enclosure having rectangular cross-section (Fig. 6).

The fifth installation (application No. 2015119370) for separation of melted fat from a fat-containing raw material comprises a number of generators with one coaxial resonator. The outer perforated cylinder (drum) is rotational (Fig. 7). Continuous process is provided by the perforated drum with a rotor and an auger. Ground fat-containing bones are continuously charged into a cylindrical perforated drum-resonator 3 through an annular gap. Due to the centrifugal force melted fat and greaves particles of a certain size are extracted through the drum 3 perforations and thrown to the perforated walls of the rotor 2. Melted fat through perforation of the rotor 2 flushes to the pipe 14 and is withdrawn. Greaves pressed to the perforated surface of the rotor 2 moves up by the turns of the auger 4 and is discharged into the pocket 1.

The sixth installation for fat melting (application No. 2015116255) contains many perforated spherical resonators connected with each other through the holes in the common side wall of the cylinder. If to excite a spherical cavity resonator, the microwave energy through a hole in the side wall enters into the inner part of the cylinder and then to the adjacent sphere where there is no radiator (Fig. 8).

The purpose of such a resonator chamber design is to promote the best interaction of ultrahigh frequency fields with electron streams. An electron stream passes through the holes in the closely spaced walls of the resonator and therefore excites the electromagnetic oscillations in it. Small distances between the bases of the cylinder 2 allows the time of electron movement in the cavity resonator to reduce that is the main condition for generation and amplification of microwave oscillations excited by electromagnetic fields. Electric field is concentrated mainly in the cylindrical part of the resonator.

Working process: Shredded fat mass enters the space between the two disks, the space in between them is agreed with the wavelength. Dissector provides a centrifugal field in the cylindrical part of the resonator chamber 2. Rapidly rotating dielectric vane feeder 6 directs particles of raw materials to the spherical part 3 of the resonator chamber. Due to the centrifugal force ground particles are moved to the cylinder periphery and through windows on its side surface fall into the spherical parts of the resonator chamber 3. Under the influence of microwave frequency electromagnetic field fat melts during its mixing; greaves are degraded to smaller particles that pass through the spheres 3 perforation. The radiation flux through perforations of the spheres and lattice 7 holes of the grinding mechanism will be locked in melted fat. The melted fat mass enters the accumulation tank and is pumped by the pump 12 through the discharge pipe. High intensity of heat exchange inside the installation is achieved by combining the raw material grinding processes in suspended condition while providing a centrifugal field with the use of the dissector and uniform heating in microwave frequency electromagnetic field. The specific energy value released in elementary volumes of the cylindrical resonator chamber 2 may vary in 10-15 time. Dielectric feeder vanes simultaneously perform dissecting function contributing to equalization of the electromagnetic field in a cylindrical volume of the resonator chamber. By providing a high microwave electric field intensity the fat/greaves mixture is completely disinfected and the product quality remains high.

Model prototypes of installations for the heat treatment of agricultural raw materials using electromagnetic energy radiation are shown in Fig. 9. Specifications of basic installations are shown in Table 2.

Research and experimental validation of the system-integrated approach to ensure the quality and safety of products treated in the ultrahigh frequency

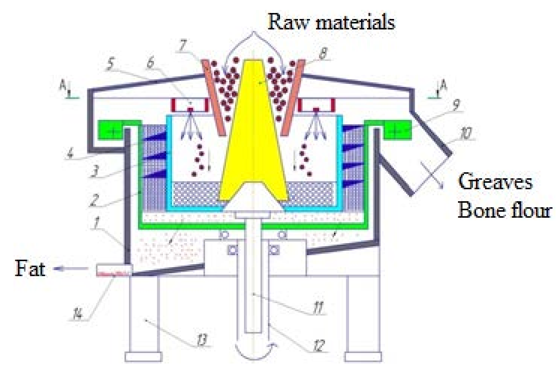

Fig. 7: Design of the microwave installation for separation of molten fat from fat containing raw materials; 1: cylinder-shaped shielding enclosure; 2: perforated cylindrical rotor; 3: cylindrical drum; 4: auger; 5: shielding enclosure cover; 6: MW generator unit with the magnetron radiator; 7: charging capacity; 8: conical radiation limiter; 9: scrapers; 10: product discharge pipe; 11: rotor, drum and auger shaft; 12: hollow shaft of the rotor; 13 mounting rack

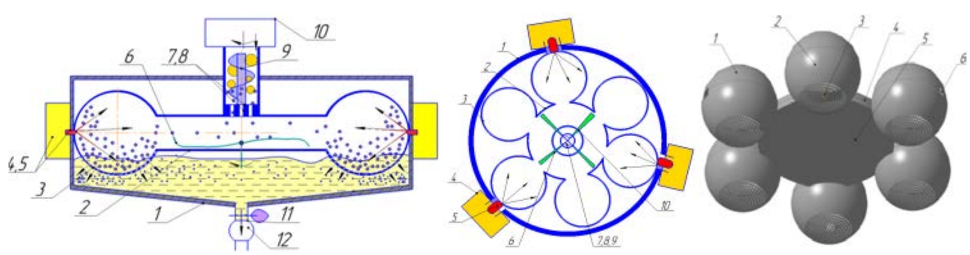

Fig. 8: Installation for fat melting; 1: cylinder-shaped shielding enclosure with a conical bottom; 2: cylindrical part of the resonator chamber; 3: spherical part of the resonator chamber; 4: MW generator unit; 5: magnetron radiator; 6: teflon vane feeder with electric motor (dissector); 7, 8: grinding mechanism; 9: discharge auger; 10: receiver tank; 11: branch pipe with a valve; 12: pump for discharging a molten fat mass

Table 2: Specifications of the developed installations

For treatment of fat-containing raw materials	Values	For heat treatment of fat with an expired storage time productivity (kg/h)	Values
Frequency of the ultrasonic generator (kHz)	45-60	Productivity (kg/h)	25…30
Ultrasonic generator power (kW)	43	Grinder power (kW)	0.13
Microwave generator power (kW	0.73	Centrifuge drive power (kW)	0.62
Motor power (kW)	2.4	Centrifuge drive speed (rev/min)	1460
Total installation power (kW)	0.6	Power consumption of the microwave generator (kW)	1.2
Specific energy consumption (kWh/kg)	3.73	Power consumption of the installation (kW)	1.95
	0.075-0.083	Specific energy consumption (kWh/kg)	0.065-0.078
		Overall dimensions (m)	0.8×0.7×1

Fig. 9: Basic models of installations for heat treatment of fat-containing raw materials using electromagnetic radiation energy: a) Microwave and ultrasonic unit for fat-containing raw materials processing; b) Microwave installation for thermal treatment of fat-containing raw materials and c) Microwave installation for thermal treatment of fat

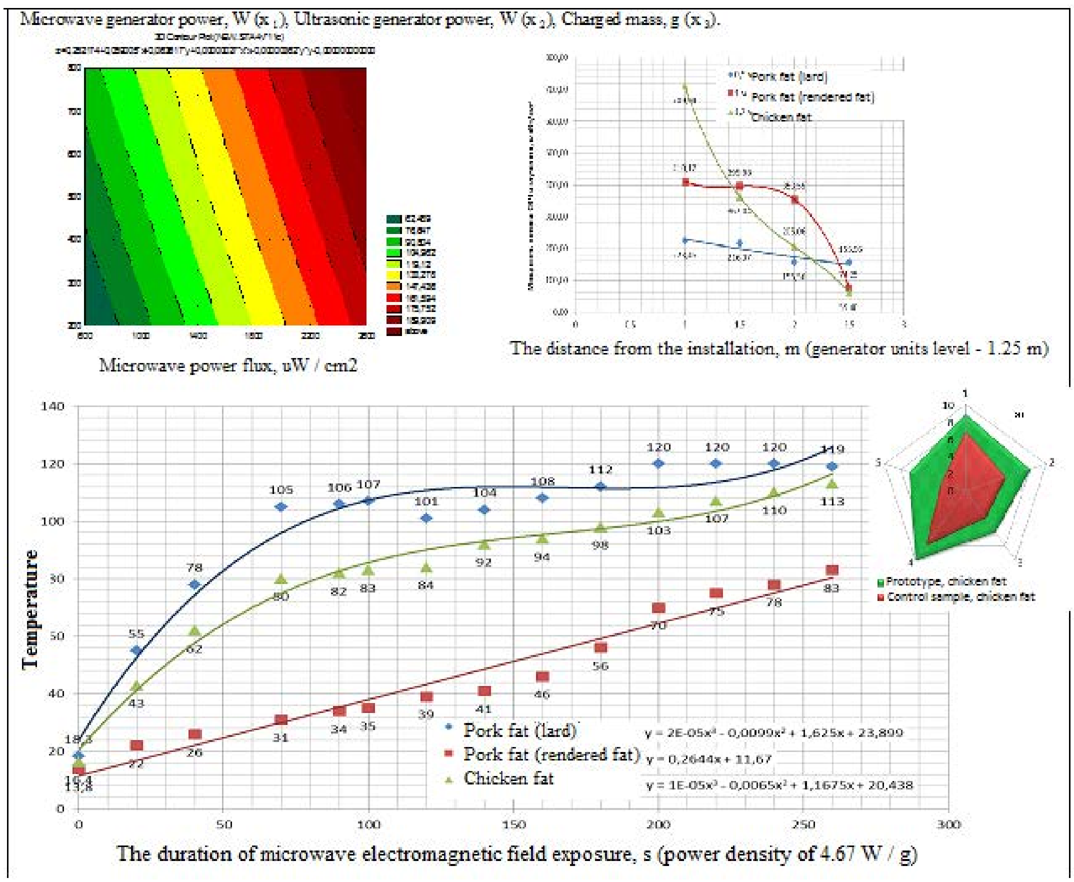

Fig. 10: Dynamics of fat-containing raw material heating in the working chamber of the microwave installation, two-dimensional cross sections in isolines of the three-factor energy consumption model (kW·h/kg) for heat treatment of raw materials, the heat flux distribution pattern over the product surface, the microwave radiation power flux around the installation

electromagnetic field: Research and experimental validation of the system-integrated approach to ensure the quality and safety of products treated in the ultrahigh frequency electromagnetic field includes the research results for the dynamics of fat-containing raw material heating depending on the configuration of resonator chambers; degree of lowering the total microbial number for products; organoleptic characteristics of the product;

flux power and radiant exposure of microwave radiation around the designed installations; empirical expressions of main criteria for the models to justify the key parameters of heat treatment processes for f various agricultural raw materials (Fig. 10).

Technical and economic assessment: We have considered effectiveness of research and efficiency of application of the developed installations in processing of fat-containing raw materials. The annual economic effect of application of MW installation for heat treatment of raw materials with capacity of 50 kg h^{-1} is 353 thousand rubles per year.

CONCLUSION

We have grounded electromagnetic characteristics (electric field intensity and the quality factor), the geometry and dimensions of the cavity resonator and the electrical parameters of a raw material. Loaded Q factor and volumes of the resonator chambers ensuring the effective value of an electric field for disinfection of a raw material during the heat treatment are agreed. Raw material kinetics regularities upon heating in the microwave installation with spherical movable perforated resonator chambers having rational design and process parameters are determined.

A non-traditional approach to heat treatment and disinfection of fat-containing raw materials comprising the repeated exposure of microwave frequency electromagnetic field in installations with the new embodiment of operative parts is proposed.

A complex of structural and technological parameters and operating modes of installations with electromagnetic radiation sources to ensure product quality improvement at reduction of operating costs confirmed by the results of their functioning in a production environment is substantiated.

Many installations were manufactured and tested in a production environment for the purpose of heat treatment and disinfection of fat-containing raw materials with the use of electromagnetic radiation sources that reduce operating costs and improve product quality. As a result of testing the installations under production conditions it was showed a reduction in specific energy consumption for heat treatment of raw materials to 30%; product quality was improved by 6-9 points and the total product microbial number reduced by two orders of magnitude. The annual economic effect of application of each individual installation with electromagnetic radiation sources for heat treatment and decontamination of agricultural raw materials will be 100-400 thousand rubles.

The expediency and prospects of the use of electromagnetic radiation energy in different wavelengths for technologies on thermal treatment and disinfection of raw materials for increased safety products is proved and reserves which increase the efficiency of electrodynamic systems are identified.

Prospects for further research into the topic. The development of microwave installations with combined resonator and radiation chambers arranged inside a circular waveguide for heat treatment of raw materials with the control and monitoring system under repeated exposure of microwave frequency electromagnetic field will lead to creation of a large number of new energy-saving technologies.

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