The relevance of solving the technological problem of guaranteed inactivation of microflora by heating in liquid media and the preservation of their useful components, in particular, in wine materials, is substantiated. Traditional heat treatment with heating up to 70...75 °C leads to a deterioration in the properties of the medium due to the thermal decomposition of its useful components. Newer is the technology of heating by the energy of the microwave field in the working chamber. But its significant drawback is the formation of standing waves in the metal chamber, causing local zones of overheating in places of maxima and underheating in places of wave minima. The consequence of this is the deterioration of the chemical composition of products and unsatisfactory inactivation of microflora.

The elimination of these disadvantages of microwave processing of media is proposed to be carried out in a non-resonant chamber developed by the authors. Selective heating in the new chamber is produced by the energy of a uniform microwave field. At the same time, there are no local overheating and underheating of products. The technical implementation of a non-resonant type chamber involves the concentration of field energy in the volume of production, the conversion of the ballast field energy into thermal energy and its utilization.

The work includes theoretical substantiation and experimental confirmation of the advantages of the new technology compared to the traditional one. Selective heating of products in a non-resonant working chamber entails the possibility of reducing the temperature required for guaranteed inactivation of microflora by 25...30 °C. This helps to preserve the components of the product due to the absence of overheating and reduce energy costs. In addition, it provides: exclusion of harmful radiation from the working chamber; prevention of self-overheating of the generator and exclusion of the dependence of the energy efficiency of the chamber on the level of its loading with products

Keywords: heterogeneous medium, microwave heating, microflora inactivation, non-resonant chamber, uniform electromagnetic field

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DEVELOPMENT OF MICROWAVE TECHNOLOGY OF SELECTIVE HEATING THE COMPONENTS OF HETEROGENEOUS MEDIA

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1. Introduction

The development of the scientific direction of expanding the scope of application of the technology of microwave intensive heating of heterogeneous dielectric media contributes to the implementation of new promising applications of the action of an electromagnetic field, which are not always associated with the need for strong heating.

It is, for example, about the prospect of using the intended, that is, uniform over the volume of microwave heating when using other, new, promising technologies. These can be technologies such as the synthesis of chemically pure compounds, sterilization of media in a gentle thermal regime, sorption and decomposition of substances for their study, creation of plasma under the influence of an electromagnetic field, etc.

In addition, the development of science, the improvement of microwave heating systems require expanding the capabilities and improving the quality indicators of these systems through the integrated application of the scientific foundations of electrodynamics, materials science and thermodynamics.

The advantages of microwave heating over other heating methods are direct volumetric action, inertialessness, high intensity, controlled, flexible process control, environmentally friendly heating and independence from scarce energy sources.

These preferred advantages have previously contributed to the widespread use of microwave resonant systems, primarily in industrial production.

However, the higher potential benefits of such widespread heating systems are not currently being realized due to the imperfection of this conventional microwave heating technology in a resonant metal chamber.

Here is a typical list of imperfections of traditional microwave heating technology in a resonant-type working chamber:

– standing waves in the volume of a resonant-type chamber cause local overheating of dielectric materials in antinodes and undercooling at the nodes of a standing wave in this chamber;

– surface currents along the walls of the resonant chamaber contribute to harmful radiation from the chamber, often exceeding the permissible sanitary standards. These radiations lead to overheating of the mucous membranes and interfere with the operation of radio and electronic equipment;

– due to the mutual disorder of the natural resonant frequencies of the chamber and the magnetron generator at a low level of chamber loading, the energy efficiency of heating systems decreases by tens of percent;

– the microwave generator, under conditions of inconsistent load, does not generate the rated output power and overheats due to "standing" waves in the supply waveguide at a distance from the generator to the working chamber.

There are traditional technical solutions (the use of a rotation table in the chamber, a mechanism for rotating and lifting samples heated in the chamber, the use of a dissector that corrects the field pattern in the chamber). These solutions are focused on improving field uniformity. They affect the distribution of the field, which heats the processed medium in the chamber of the resonant system, however, they improve the integral heating uniformity, but do not eliminate local heating unevenness.

Such innovations contribute to an increase in the number of variants of local non-uniformity, the number of nodes and antinodes of the field per unit volume of the chamber and the processed medium, however, they do not neutralize the resonant properties of the system. Consequently, the listed disadvantages of resonant microwave heating chambers are practically not eliminated in chambers for both domestic and industrial purposes.

As a result, there is a need to develop theoretical prerequisites, principles for neutralizing the resonant properties of these systems, implement new functions and develop new promising microwave heating chambers for both industrial and domestic purposes.

That is why the new solution of the scientific and technological problem of guaranteed inactivation of microflora by selective heating of heterogeneous media and the preservation of useful components of these media emphasizes the relevance of the research topic.

2. Literature review and problem statement

In [1], the authors turn to fundamental research in order to theoretically comprehend the essence of the technology of microwave exposure to various dielectric media in various applications and using chambers of various designs. The process of powerful microwave heating of dielectric media in scientific, industrial and domestic conditions, together with traditional types of intense thermal effects on media, has been widely used for more than half a century. These publications are devoted to the problems of microwave processing of various products under conditions of intense heating.

Theoretical prerequisites for research in the direction of developing a technology for only thermal exposure to liquid media to inactivate microflora in them and improve product quality were developed quite a long time ago.

The work [2] laid the theoretical prerequisites for the development of technology for thermal heating of wine materials to inactivate microflora in them and improve product quality. The study is devoted to solving the technological problems of winemaking, primarily the microbiological stabilization of wine products by thermal heating, the development of materials and equipment for thermal inactivation of the microflora of wine materials.

However, now, in order to increase the biological stability of products, for example, wine materials (for a period of up to 12 months or more), thermal heating of products is more often carried out in a continuous flow at a temperature of 65 °C to 75 °C. Thermal treatment of wine materials to a high temperature is accompanied by a change in their chemical composition, the destruction of thermolabile, useful for humans, components of these materials occurs, darkening of color, change in smell and taste, and a "bread flavor" appears. The intensity of the changes depends on the composition of the product extract, the temperature level and the duration of its exposure when the wine materials are heated.

In [3], the influence of an uneven in volume of production electromagnetic field on microflora cells in a traditional chamber of a resonant type is studied. It is noted that this significant heating of the product accelerates the coagulation of proteins and other colloids. Consequently, the problem of inactivation of the microflora of wine materials while maintaining their qualitative composition is relevant in modern biotechnology. Taking only some measures aimed at preserving the taste of products is not enough.

The publication [4] shows that using the traditional technology of microwave heating of various dielectric media in a metal chamber of a resonant type, it is impossible to get rid of the minima and maxima of the "standing" wave in the chamber, namely, uncontrolled local underheating and overheating of products. Therefore, it is impossible to guarantee the inactivation of the microflora in the composition of the product at the minimum heating and guarantee the absence of loss of product quality at the maximum. It is shown that the solution of this technological problem is possible by developing and using non-resonant chambers.

It is noted in [5] that sufficient inactivation is carried out in traditional chambers, but only due to the equalization of the temperature in the liquid due to heat transfer by heating it to the traditional 70 °C. It is noted that at this temperature it is difficult to ensure the safety of useful thermolabile components of liquid media. Therefore, it is proposed to implement a better inactivation of the microflora of liquid media in a flow through a chamber of a waveguide, but non-resonant type, where there is no standing wave.

In [6], the use of microwave radiation with a frequency of 915 MHz for pasteurization of packaged carrot cubes is studied. The experiments were carried out at a heating temperature of 90 °C in two modes, lasting 3 and 10 minutes. Comparison with the results of processing raw materials with hot water showed that in both cases equivalent microbial safety is achieved, but microwave significantly reduces the overall processing time and improves product uniformity. Computer analysis showed the inhomogeneity of the temperature field in the sample: a cold zone in the center and an increase in temperature when approaching the surface. The authors do not mention any attempts to reduce this unevenness and its impact on the quality of the product.

The article [7] discusses the use of microwave processing technology for pasteurization of tomato puree at a temperature of 96±2 °C in a semi-industrial continuous microwave oven. The studies were carried out at low radiation intensity for a longer time or high intensity for a shorter time. The results of the impact of irradiation on product quality were compared with the results of conventional heat treatment. It is noted that in all cases there is a decrease in the quality of the product, but high-intensity radiation (1900...3150 W) for a short time (150...180 s) gives better results and reduces processing time compared to the standard pasteurization process.

In the article [8], similar results were obtained. The authors used a combined pasteurization method, which consisted in preliminary microwave heating of grape juice and its subsequent heat treatment. According to the article, microwave heating of raw materials reduces the unevenness of the temperature field and pasteurization time and increases the quality of the final product. The study of the non-uniformity of the microwave radiation field as a result of the appearance of standing waves has not been carried out.

The article [9] also presents comparable results of high-pressure processing of green beans and their thermal pasteurization using microwaves. Such indicators as the number of Listeria innocua bacteria, chlorophyll content, vitamin C content, pH and others were controlled. Microwave pasteurization has been found to be more efficient in all respects than high pressure processing.

The work [10] is devoted to comparing the results of processing pesto sauce made from fresh beans using microwave and traditional thermal technologies. Quality control was carried out within 20 days after processing. It shows that in terms of microbial contamination, both methods give equally satisfactory results. In terms of preserving taste, nutritional value and presentation, the microwave oven surpasses traditional thermal pasteurization.

The authors of [11] conducted experimental studies of the effect of the pasteurization method on the quality of apple juice. Two technologies were used: conventional thermal and microwave. It was concluded that juice pasteurized using microwave technology has better taste and nutritional qualities and requires less time.

The article [12] considers the influence of composition, frequency and temperature on the properties of skimmed milk powder. Inhomogeneities of the temperature field were found, the magnitude of which depends on the shape of the milk container. The impact of heterogeneity on the quality of the final product has not been investigated.

In [13], attention is paid to the study of the non-uniformity of the temperature field in a sample that is subjected to microwave heating. Cuboid gellan gel samples were subjected to microwave irradiation in vertical and horizontal orientations. Experiments have shown that the vertical orientation of the sample contributes to a more complete absorption of microwave energy, while the horizontal orientation creates a more uniform temperature field. As a result, the vertical orientation of the sample contributes to greater energy efficiency, and the horizontal orientation improves the quality of processing and the shelf life of the finished product.

The article [14] considers the use of short-wave radio emission for the processing of various food products. It is noted that when using radio waves, there is no problem of wave interference, while when using microwave radiation, interference occurs, which leads to the appearance of cold and hot zones in the processed product.

A review of publications shows that the issues of the occurrence and neutralization of the harmful effects of standing waves in the volume of products loaded for microwave processing of the chamber are not reliably resolved in practice, both theoretically and in practice. The impact of this phenomenon on the quality and shelf life of products, as a rule, is not investigated.

The following multifaceted problem is currently unresolved, which it is expedient to formulate in the following form. It is advisable to take into account and use significant differences between the electrical parameters of useful components and microflora in a typical heterogeneous medium processed in a microwave field. For guaranteed preservation of useful components of products and guaranteed destruction of microflora, it is advisable to create a working microwave chamber without standing waves.

Improvement of the existing chambers of the resonant type is expedient, for example, on the basis of the implementation of their new functions, namely: the concentration of the field in the volume of production; conversion of ballast field energy; utilization of this energy

Next, it is necessary to evaluate theoretically and experimentally the effectiveness of the new microwave selective heating technology and compare it with known results, for example, heat treatment. In addition, it is advisable to compare the energy and environmental characteristics of non-resonant and resonant chambers.

3. The aim and objectives of research

The aim of research is to develop a microwave technology for selective heating of medium components that differ in electrical conductivity and permittivity parameters based on the creation of a non-resonant type working chamber. This will allow guaranteed inactivation of the microflora of colloidal liquids at a lower (by 30 °C) temperature and guarantee the preservation of useful substances in the liquid.

Objectives, the implementation of which ensures the achievement of the aim:

– to determine the factors of action of microwave radiation on the components of a heterogeneous colloidal medium during its heating;

– to build a model of self-adjusting microwave equipment of a non-resonant type with an electromagnetic field uniform in volume;

– to construct a functional diagram of self-adjusting microwave equipment of a non-resonant type with an electromagnetic field uniform in volume in the working chamber;

– to determine the environmental, energy and technological characteristics of the process of microwave selective heating of the components of heterogeneous media.

4. Materials and methods of research

The object of research is the technological process of heating dielectric heterogeneous media in the volume of a metal working chamber using the energy of an electromagnetic field.

The hypothesis of research is the possibility of implementing the intended selective heating of a heterogeneous medium, namely, achieving guaranteed inactivation of microflora in the composition of products with simultaneous guaranteed preservation of product components useful to humans. For this it is necessary:

– take into account the peculiarities of the action of electromagnetic fields on the components of the medium, in particular, more intense heating over time of those components that have greater electrical conductivity and dielectric constant;

– change the structure of the field in the chamber in order to eliminate "standing" waves in the chamber by changing the design of existing working chambers.

This will facilitate the operation of the magnetron generator in the "traveling" wave mode and provide better process characteristics, namely: environmental friendliness, energy efficiency and equipment reliability.

The research assumes that the polymer shell and membrane of the cytoplasm of microflora cells, in contrast to its cytoplasm itself, are always, firstly, radio-transparent, and secondly, have a low level of thermal conductivity. That is why these features contribute: firstly, to the penetration of the field into the electrically conductive cytoplasm and its powerful heating; secondly, they interfere with heat exchange between the cytoplasm and products, which will lead to selective heating.

The simplification adopted in research is that the converter, that is, the absorber, of the ballast field energy into thermal energy, which, along with the field concentrator in the product volume, is required to obtain a "traveling" wave in the chamber, has a high level (10 dB/mm) field transmission coefficient in the energy absorber.

When performing the research, both computational-theoretical and experimental methods were used. Calculation methods were used to substantiate the assertion of a more intense inactivation of microflora in a liquid medium in a non-resonant microwave chamber compared to a traditional thermal one. The experimental part of the study consisted in the development, design and creation of laboratory equipment for microwave heating of various types of prototypes in modernized non-resonant chambers.

The following were chosen as prototypes: for chambers of cyclic action – distilled water in a fluoroplastic standard vessel; for chambers of action of the field on a liquid medium in a stream – wine material in a tubular quartz chamber. It is these samples that have the lowest level (10–14 S/m) of the specific electrical conductivity of the container, which prevents edge overheating of the product. They have sufficiently studied properties, retain the results of processing and are widely used in practice.

The results of the experiments were compared with the results of heating the same media samples in a traditional resonant chamber.

Tests of the created sample for the purpose of acceptance into operation were carried out, according to the Order of the Ministry of Agrarian Industry of Ukraine, at the state enterprise "Odesawineprom", Odesa, Ukraine.

5. Results of studies of the process of microwave heating of heterogeneous media

5. 1. Determination of factors of action of a microwave field during heating of heterogeneous colloidal media

To quantify the results of microwave selective heating using a uniformly intense field in a medium, the following factor must be taken into account.

Let's denote by P_C the power density of the field that transforms into a thermal field in the material of microbial cells. Accordingly, the specific power density dissipating in the medium will be denoted by P_M

Then, at an arbitrary point of the volume of wine material in a non-resonant chamber without standing waves, these values of power density are equal to

$$P_C = \sigma_C \cdot E_C^2, \tag{1}$$

$$P_M = \sigma_M \cdot E_M^2, \tag{2}$$

where σ – specific electrical conductivity of the components of a heterogeneous medium (for example, cells and wine material), Sm/m;

E – electrical intensity of the electromagnetic field, V/m.

The thermoelectrodynamic balance equations for the components of a mixture of microflora cells and liquid products in the treated medium, respectively, have the form

$$\sigma_C \cdot E_C^2 = c_C \cdot \rho_C \cdot \frac{\Delta\theta_C}{\Delta t},\ \ \sigma_M \cdot E_M^2 = c_M \cdot \rho_M \cdot \frac{\Delta\theta_M}{\Delta t}, \tag{3}$$

where c – specific heat capacity of each component of the medium, J/kg•K;

ρ – mass density of each of the components, kg/m³;

$\Delta\theta_M$, $\Delta\theta_C$ – increase in the temperature of the liquid products of the medium being processed and microflora cells due to their heating under the influence of electromagnetic oscillations, K;

Δt – duration of the exposure time (or pulse) of electromagnetic radiation, s.

Based on the equality of the electric field inductions in the components of the medium being processed, according to the laws of field theory, the equality is always true

$$\varepsilon_C \cdot E_C = \varepsilon_M \cdot E_M, \tag{4}$$

where ε – parameter (permittivity) that characterizes the degree of polarizability of a medium component under the action of an electromagnetic field.

It can be assumed that under the conditions of a short-pulse electromagnetic field, there is no heat exchange between the processed components of the medium. Then equations (3), (4) allow to find the indicator *Fo*, which is the ratio of the expected temperature increase in the material of microorganism cells to the temperature increase in wine materials over time Δt. This temperature ratio has the form

$$Fo = \frac{\Delta\theta_C}{\Delta\theta_M} = \frac{\sigma_C}{c_C \cdot \rho_C \cdot \varepsilon_C^2} : \frac{\sigma_M}{c_M \cdot \rho_M \cdot \varepsilon_M^2}, \tag{5}$$

where *Fo* – microwave heating selectivity parameter, which characterizes the level of increase in the efficiency of microwave pasteurization in a microwave chamber of a new design with an electromagnetic field of uniform intensity in the volume of the medium.

From expressions (1), (2) and (4) it is possible to determine the ratio of volumetric power densities of the microwave field, which is converted into heat in microflora cells and in processed products. This ratio depends only on the values of the electrical conductivity of the components and the values of their permittivity. A quantitative assessment of the level of this ratio, for example, for wine materials, has the value

$$\frac{P_C}{P_M} = \frac{\sigma_C}{\sigma_M} \cdot \frac{\varepsilon_M^2}{\varepsilon_C^2} = 2.5. \tag{6}$$

A quantitative assessment of the level of the ratio of the temperature increase $\Delta\theta_C$, which can be created in the material of microbial cells, to the temperature increase $\Delta\theta_M$, for example, in the processed wine material according to (3) taking into account (6), gives the value

$$\frac{\Delta\theta_C}{\Delta\theta_M}=\frac{\sigma_C\varepsilon_M^2}{\sigma_M\varepsilon_C^2}\cdot\frac{c_M\rho_M}{c_C\rho_C}=2.3. \qquad (7)$$

It must be emphasized once again that such relationships are valid only when an electromagnetic field uniform in volume is created in the working chamber.

In a chamber with a uniformly distributed field, the following main factors of effective bactericidal microwave action of the field on the processed components of the medium always operate:

– almost instantaneous penetration of an electromagnetic wave deep into the processed product in its entire volume;

– free penetration of the field through the polymeric (radiotransparent for microwave radiation) membrane of microflora cells;

– more intense heating of the cell cytoplasm compared to the medium of the wine material due to significant differences in their levels of specific electrical conductivity;

– low thermal conductivity of the membrane, which prevents free heat exchange between the more heated cytoplasm of the microflora cell and the less heated liquid medium being processed. This leads to an increase in the temperature difference between the cell cytoplasm and the treated medium;

– simultaneous and equal influence of the field energy on all microorganisms without exception in the processed medium under the conditions of the field, evenly distributed in the volume of the medium.

In a chamber of traditional design, due to the appearance of a standing wave in the minima of the electromagnetic field, the inactivation of microflora is not guaranteed, and in the maxima of the field, uncontrolled overheating of the processed products is possible.

Under the conditions of exposure of the processed products to a field that is precisely controlled in intensity, it should also be noted that the effect of microwave radiation on the components of the heterogeneous medium being processed is not destructive, but only thermal.

To substantiate the assertion that the only thermal effect of the microwave field is expedient to compare the energies of microwave, infrared and ultraviolet quanta with the binding energy of molecules. The results of comparative estimates of the energy of the wave quantum of the indicated ranges and the binding energy of the molecules of the processed product are shown in Fig. 1.

It has been established that:

1) the energy of a microwave radiation quantum with a wavelength of λ=12.2 cm is 43,000 times less than the binding energy of less heat-resistant molecules of the wine material medium. In this case, only the thermal effect of the field is possible, that is, the destruction of the molecules of the processed medium or the appearance of new chemical compounds during the processing of wine materials is impossible;

2) the energy of the radiation quantum of infrared waves is 1400 times less than the binding energy of the least heat-resistant molecules of the wine material medium. In this case, only the thermal effect of the field is also possible, and the destruction of the molecules of the medium undergoing processing also does not occur;

3) the energy of a quantum of ultraviolet radiation (in the bactericidal part of this wave range) is comparable to the binding energy of the molecules of the medium. In this case, the destruction of the molecules of the processed medium is possible, therefore, the use of this radiation for the purpose of pasteurization is unacceptable.

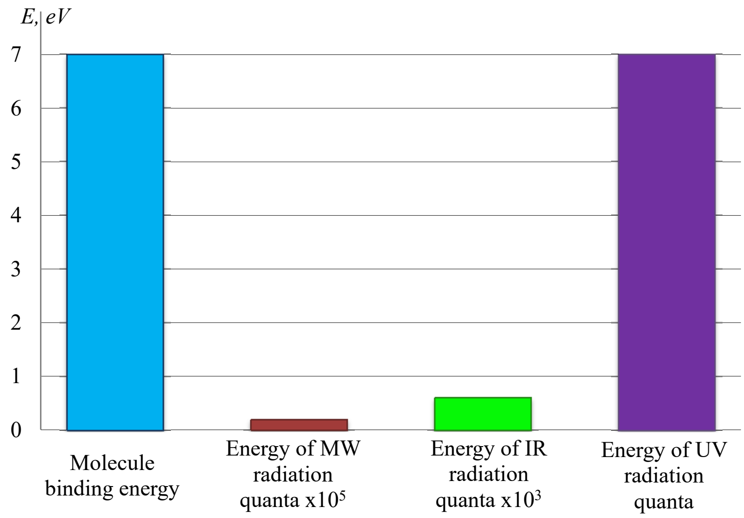

Fig. 1. Comparative estimates of the binding energy of the molecules of the processed medium and the energy of field quanta of different ranges of electromagnetic waves

5. 2. Functional diagram of equipment with a microwave field uniform in terms of product volume

These factors were the basis for the creation of equipment using microwave waves (with a wavelength allowed for industrial use equal to 12.2 cm). Two devices were created: a laboratory version of a cyclic operation and a pilot version of an device for processing products in a stream. In this equipment, the effect of the electromagnetic field is uniform in volume.

The functional diagram of the new microwave equipment, which is, in fact, self-adjusting, is shown in Fig. 2 [4].

In Fig. 2: r_o – longitudinal size of the heated medium; r – depth of penetration of the electromagnetic field into the medium; s_0 – cross-sectional area of the treated medium; s – cross-sectional area of the field beam in the medium.

The created experimental-industrial version of the device of low productivity assumes microwave processing of wine material in a stream. The scheme of the upgraded device of cyclic action is provided in Fig. 3.

In Fig. 3: 1 – working chamber; 2 – concentrator of electromagnetic energy; 3 – waveguide; 4 – magnetron generator; 5 – fan; 6 – heterogeneous medium; 7 – composite converter of field energy into thermal energy; 8 – plates for utilization of ballast energy; 9 – light signal indicator and control unit.

In this equipment, new functions of microwave equipment for inactivation of the microflora of wine materials were implemented:

– concentration of energy in the volume of the processed medium;

– conversion of electromagnetic ballast energy into thermal energy using ceramic tiles and ferrite filler of a metakaolin base;

– utilization of ballast thermal energy by blowing copper plates in metakaolin;

– ensuring electromagnetic safety and energy efficiency of the process using a non-resonant microwave chamber.

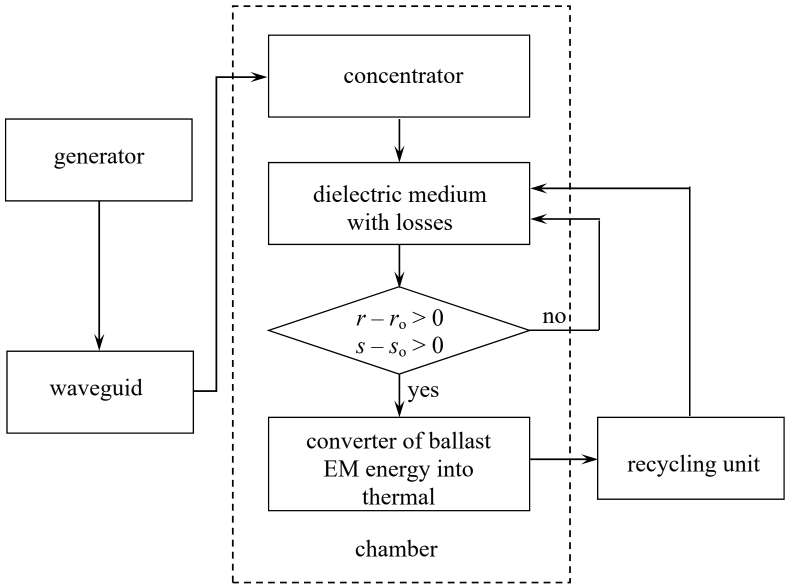

Fig. 2. Functional diagram of a non-resonant device for selective microwave heating of heterogeneous media

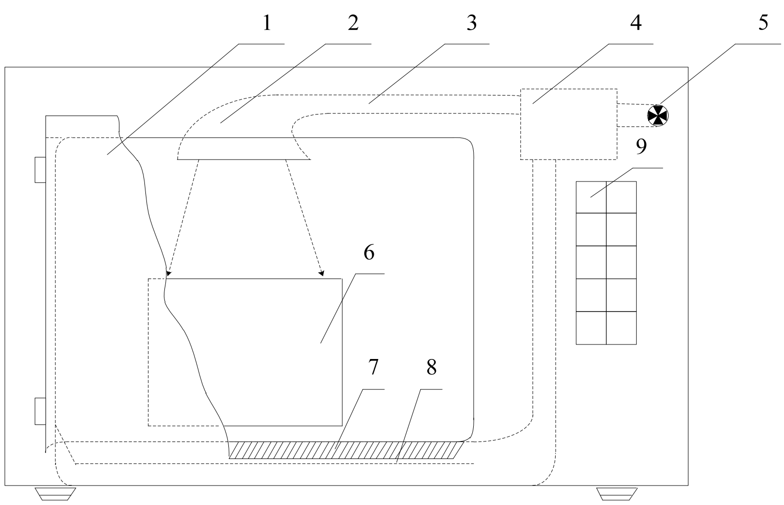

Fig. 3. Modernized cyclic chamber for microwave selective heating of heterogeneous media

5. 3. Determination of environmental, energy and technological characteristics of the process of microwave selective heating of components of heterogeneous media

The radiation power flux density from such a chamber to the environment is much lower than the level established in accordance with sanitary standards [4]. It is important to emphasize that the level of power flux density p_s (μW/cm^2) of radiation from non-modernized chambers from the mass m (loading of chambers) exceeded the sanitary allowable standards by 5...10 times.

Fig. 4 shows the experimental values of the level of power flux density p_s (μW/cm^2) from the upgraded chambers on the mass m of the load of microwave heating chambers, normalized by the nominal level of the mass m_0 of their load. These density levels are obtained as a result of testing the upgraded chambers and measuring the electromagnetic field radiation flux density from the upgraded working chamber. The microwave chambers studied before and after the upgrade belong to the indicated manufacturers of this equipment.

The measurement of harmful radiation levels, namely the power flux density, that is, the Umov-Poynting vector module, was made in the neighborhood of a viewing window and slots in the loading locks of modernized standard cyclic chambers.

The results, depending on the level of the mass of distilled water, normalized by its nominal level, obtained at a distance from the chamber body equal to 50 mm, using a standardized P-20 power flow device.

From those shown in Fig. 4 results of measuring harmful radiation from non-resonant chambers, it follows that these levels are close to zero, that is, they satisfy even the most stringent requirements of the countries of the world.

Experimental studies carried out by the authors of the work also show that the energy efficiency of modernized chambers of cyclic action exceeds the efficiency of similar non-modernized chambers by 15...30 %.

These results are obtained by careful measurements and comparison of the results of heating standard samples of distilled water in microwave chambers from four manufacturers around the world: Japan; Italy; Korea; Ukraine.

The measurement results were determined by experimentally determining the ratio of the energy level lost to heat the sample in the chamber to the energy level measured by the counter. Through this meter, power was always supplied to the microwave chamber. This was repeated many times at different levels of chamber loading before and after the modernization of these chambers.

The method of measuring parameters of distilled water treatment in the mode of cyclic action is determined on the basis of a typical algorithm for cyclic processes of heating the product in a container. The water heating temperature in the chamber was measured using an alcohol thermometer TU 25-11-899 1986, when its entire lower part was immersed in water. The energy E_s, spent on heating the medium, and the partial (for one heating) efficiency, K, taking into account the total energy E consumed, were calculated by the formulas:

$$E_s = c \cdot \rho \cdot v \cdot \Delta\theta; \; K = E_s / E$$

where c – specific heat capacity of distilled water, J/kg K;

ρ – mass density of distilled water, kg/m≥;

Δθ – increase in the temperature of the liquid product of the medium compared to the temperature before the start of heating, K.

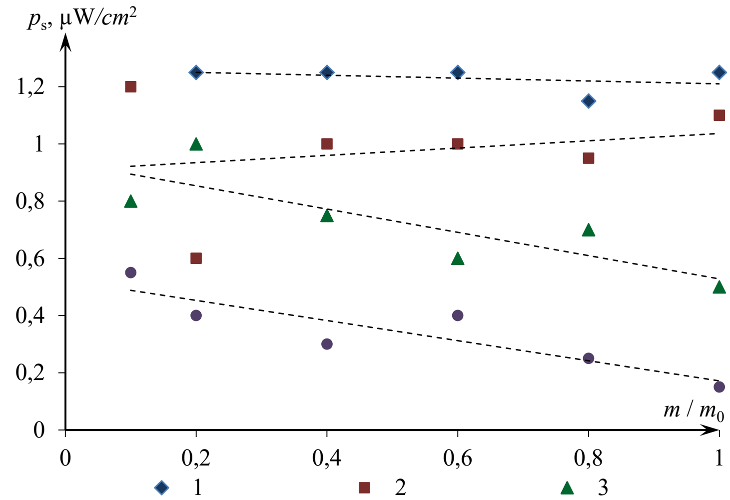

Fig. 4. Experimental values of the power density of the radiation flux from the modernized standard chambers of different manufacturers at different degrees of loading of the microwave chamber:
1 — KOR-6105 (Korea); 2 — Dniprianka-1 (Ukraine);
3 — SMC E70-TFA (Japan); 4 — Delonghi (Italy)

The increase in efficiency, Δ*K*, taking into account the results of averaging over all *n* heatings of different load levels for one microwave chamber of a particular manufacturer, was determined by the resulting formula

$$\Delta K=\Sigma_i\{[(E_s/E)_{im}-(E_s/E)_{inm}]/(E_s/E)_{inm}\}/n.$$

It is this value of the increase in efficiency for a camera from different manufacturers that fluctuated during studies at the level from +0.15 to +0.30. Individual measurements showed, especially at low load levels, even +0.40. This is explained by the fact that at low loading levels, the location of the spectrum of its resonant frequencies does not coincide with the location of the frequency spectrum of the magnetron generator. Therefore, its signals do not enter the chamber, are reflected from the entrance to the chamber, create a "standing" wave in the supply waveguide and overheat the generator itself. While for a non-resonant chamber this effect is never observed.

The authors also created and patented a microwave selective heating device for the purpose of microbial stabilization of liquid media in a flow [5]. The functional diagram of the device with a uniform field in the volume of the waveguide working chamber is shown in Fig. 5.

The diagram (Fig. 5) shows: 1 – recuperation unit; 2 – hydraulic switching unit; 3 – product filling unit; 4 – product draining unit; 5 – stabilization process control unit; 6 – unit for generating supply voltages; 7 – unit for generating electromagnetic oscillations; 8 - wave-shaped chamber with a tubular dielectric channel; 9 – absorber of ballast electromagnetic energy with a utilization channel; 10 – eat exchanger with a liquid channel for additional heating of the product and a product channel; 11 – product supply pump; 12 – product level regulator; 13 – generator liquid cooling pump.

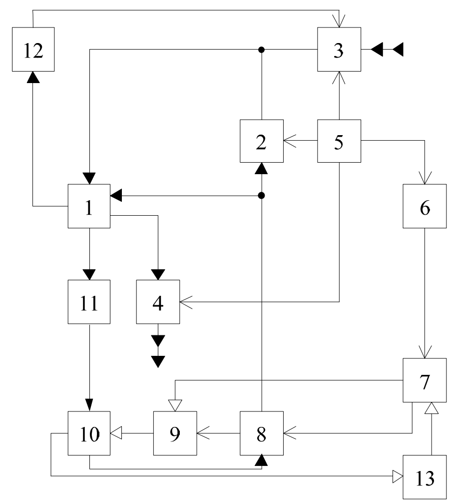

Fig. 5. Functional diagram of a microwave device, for selective heating of liquid media in a stream in order to stabilize them

The shaded arrows (Fig. 5) indicate the channels for supplying the product processed for the purpose of microbial stabilization, the unshaded arrows indicate the channels for supplying the liquid heat carrier, which takes thermal energy from the generator (unit 7) and absorber (9) and transfers it to the product in the heat exchanger (10). Ordinary arrows indicate the channels for supplying: electrical control signals; supply voltage; electromagnetic field.

A pilot version of this device, the device, is shown in Fig. 6. This device is designed for microbial stabilization of wine materials in the flow.

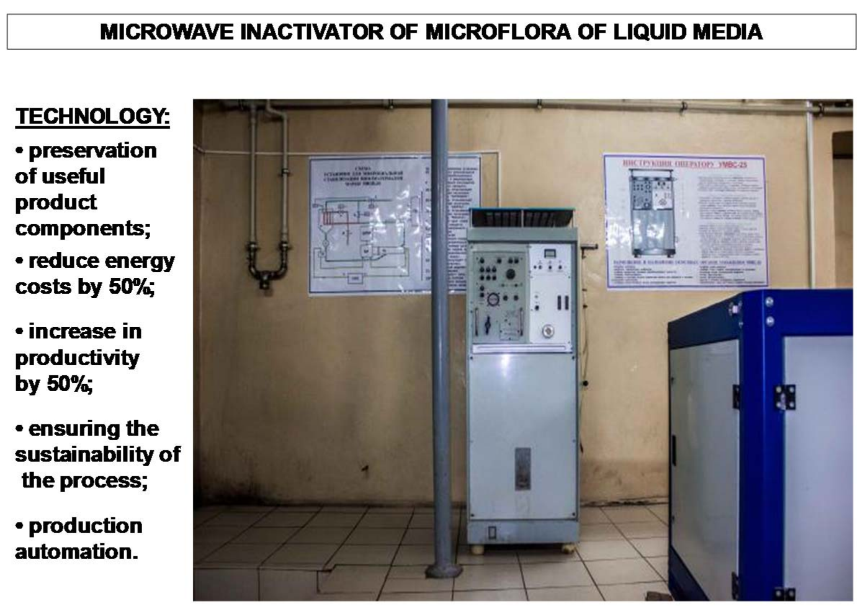

Fig. 6. Microwave device for inactivation of the microflora of wine materials in a stream [5]

The operation of the device starts on the signals of the control unit (5). The signals are initially sent to the product filling unit (3), the supply voltage generation unit (6) and the hydraulic switching unit (2). The product is fed through the filling unit (3) to the recovery unit (1). After the volume of the recuperating unit (1) is filled, the product level regulator (12) stops the product supply through the filling unit (3). The product supply pump (11) pumps the product first in a closed circle: from the first outlet of the recuperating unit (1) through the heat exchanger (10), the dielectric tubular channel of the waveguide chamber (8) and the unit (2) to the first inlet of the recuperation unit (1). At present, the liquid cooling pump (13) of the generator pumps the liquid in a closed circle: the cooling channel of the generator unit (7), the utilization channel as part of the electromagnetic energy absorber (9), the liquid channel for additional heating of the heat exchanger product (10), the pump (13). Powerful electromagnetic energy is supplied to the waveguide chamber (8) with a tubular dielectric channel to the unit generator (7), which heats the product in the tubular dielectric channel and destroys the microflora of the product. The unused part of the electromagnetic energy enters the absorber (9), turns into heat, which is transferred through the liquid channel of the heat exchanger (10) to the product in another channel of the heat exchanger (10), for additional heating of the product.

After heating the product with the help of repeated electromagnetic action in the waveguide chamber (8) and in the heat exchanger (10) to a temperature pre-set in the control unit (5) by the stabilization process, this unit (5) sends a signal to close the hydraulic switching unit (2) and open drain unit (4) of the finished product. The finished product is cooled in the recuperating unit (1) using the cold product inlet flow through the product filling unit (3).

The set of essential features of the device provides the advantages of the invention over the prototype. The increase in the quality of stabilization of the product, first of all, is due to the absence of edge overheating of the product along the waveguide of the chamber (8), in comparison with the prototype. This waveguide is filled with a wine material-energy converter. A "travelling" wave propagates in the chamber waveguide (8) (without the maxima and minima of the "standing" wave). The point is that the chamber waveguide (8) is loaded on a special absorber (9) of the ballast field energy. Thus, the absence of field reflection from the closed end of the chamber waveguide (8) eliminates the interference of the incident wave with the reflection, and the absence of overheating and underheating of the product is achieved.

An increase in the energy efficiency of the device ensures the presence of a closed liquid system consisting of: a pump (13), a cooling channel of the generator unit (7); the disposal channel in the absorber (9) and the liquid channel of the heat exchanger (10). The latter has a product channel. In this case, the absorber (9) of ballast electromagnetic energy is, for example, a composite based on modified metakaolin with a ferrite filler. The absorber (9) covers a metal plate from the inside, which is rigidly fixed at the end of the waveguide. In addition, a tubular metal liquid cooling channel is rigidly fixed to the plate.

An increase in the manufacturability of the device implementation is ensured by using a chamber (8) in the form of a linear rectangular waveguide with a tubular dielectric channel also of a linear type, for example, in the form of a quartz glass tube penetrating the waveguide along at an angle of 160–170 degrees to its wide walls, in their middle part.

According to experimental measurements and calculations obtained quantitative estimates of the advantages of the present invention. It is not only about the absence of destruction of the useful components of the product. The energy efficiency increase of this device is 50 %.

In the process of experimental work and state tests, the dependence of the degree of microflora inactivation on the processing temperature is studied. The results of research and comparison with the results of traditional heat treatment for two samples of wine products are presented in Fig. 7, 8.

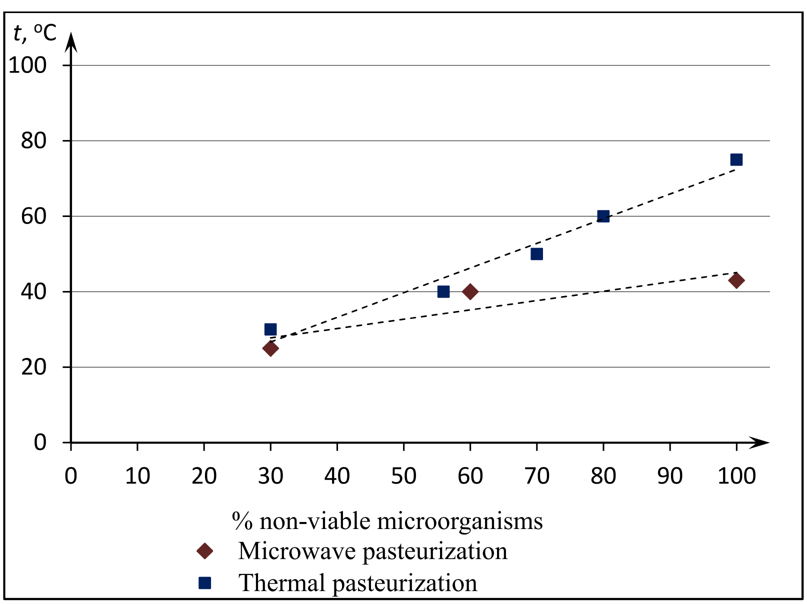

Fig. 7. The percentage of non-viable microorganisms during thermal and selective heating of wine "Table Red No. 1" at different temperatures

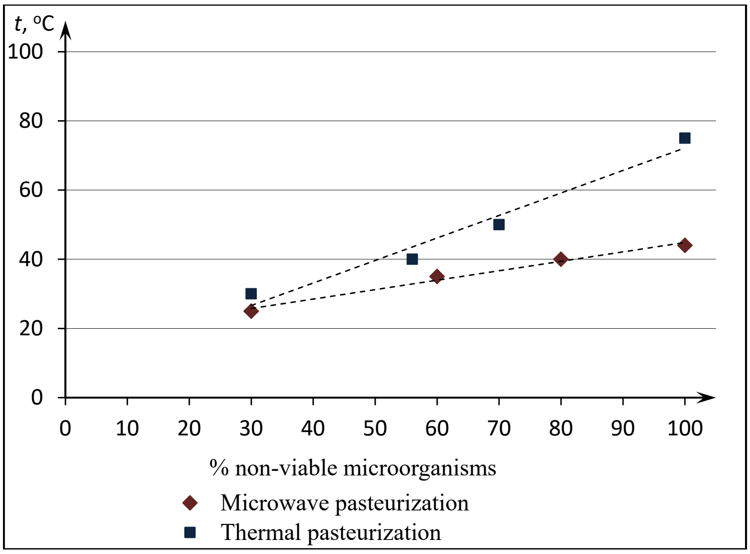

Fig. 8. The percentage of non-viable microorganisms during thermal and selective heating of wine "Table Red No. 2" at different temperatures

The values of the percentage of non-viable microorganisms from the temperature of the required heating in the new device clearly shown in Fig. 7, 8 demonstrate that one hundred percent inactivation of the microflora is achieved at a noticeably lower (by 30 °C) temperature of selective heating than with thermal or traditional microwave heating.

6. Discussion of the results of the development of technology for microwave selective heating of heterogeneous media

The main result of this study is the achievement of a synergistic effect of eliminating most of the disadvantages of traditional heating of heterogeneous media in resonant chambers, while upgrading the existing traditional microwave equipment, by building a non-resonant chamber.

The complex application of the scientific foundations of electrodynamics, materials science and thermodynamics made it possible to create a chamber with an electromagnetic field of a traveling wave, with uniform heating and new properties.

Successful implementation of selective heating of liquid products, such as wine materials, the microflora of which must be guaranteed to be destroyed, and useful components to be preserved, has been developed, created, theoretically substantiated and experimentally evaluated during factory tests [4].

The new technological equipment allows the improvement of the well-known pasteurization technology. The development of electrodynamics, microelectrodynamics and thermal physics makes it possible to reduce by 30 % the temperature of heating the medium by an electromagnetic field of the microwave range uniform over the volume of the chamber.

These new properties of the electromagnetic field thus make it possible to simultaneously create favorable conditions for the inactivation of microflora, for example, in any liquid illustrated by the example of wine materials.

Thus, it is about a mechanism for solving the controversial problem of guaranteed inactivation of microflora while maintaining the potentially high quality of liquid products: wine materials, milk, juices, beer, processed in an electromagnetic field uniform throughout the volume of the chamber.

The main factors that ensure the achievement of a set of new beneficial results of the application of selective microwave heating technology are:

– almost instantaneous penetration of an electromagnetic wave deep into the product and a volumetric, simultaneous and selective effect of the field energy on all microorganisms and the medium, which differ in the magnitude of electromagnetic parameters;

– free penetration of the field through the shell of the microflora cell, through the polymeric (radio-transparent for the microwave wave) membrane of the cytoplasm of the microflora cells;

– more intense heating of the cell cytoplasm than the drinks medium, since the cytoplasm is an aqueous solution of salts and microelements. The cytoplasm is much more intense (50 times compared to the cell membrane and 10 times compared to the medium) absorbs the energy of electromagnetic waves;

– low thermal conductivity of the polymer cell membrane, which prevents heat exchange between the cell cytoplasm and the treated medium;

– lowering the required temperature for processing the medium during microwave processing in an electromagnetic field uniform in volume prevents the destruction of its useful biologically active components, which contributes to the preservation of potentially high qualities of the processed products;

– combination of these factors leads in the following way: firstly, at least to a guaranteed inactivation of the microflora of wine materials at a lower temperature, and as a maximum – to rupture of the cell membrane, as is always observed under a microscope. Secondly, low temperatures, sufficient for guaranteed inactivation of microflora, eliminate the need to heat drinks to the traditional temperature (65...75) °C.

The model of beverage stabilization created by the authors can be further developed, for example, for pasteurization of various types of products: beer, juices, milk, etc. Now it is used for microbial stabilization of wine materials, it has passed state tests, has been put into operation and is used in the «Odesawineprom» enterprise for microwave stabilization of elite wines.

7. Conclusions

1. Selective heating of a dielectric heterogeneous medium in the form of products in a working chamber with an electromagnetic field uniform in volume leads to guaranteed inactivation of the microflora and preservation of the components of this product useful for humans.

2. New constructive units of the working chamber, namely: field energy concentrator, field ballast energy converter, this energy utilizer allow improving the technical characteristics of microwave product processing equipment. These include:

– value of harmful radiation from the working chamber at a level close to zero;

– efficiency of the cameras, exceeding the known ones by 15 ... 30 percent;

– independence of this coefficient from the level of loading of the working chamber.

3. Comparison of the results of experimental studies of the technology of microwave selective heating of dielectric media, obtained after the development and testing of new

equipment for cyclic operation and the action of a liquid flow, confirm the expected results of theoretical studies. The discrepancy between the theoretical and experimental results does not exceed a few percent.

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