Запропонована технологія інтенсивного, енергоекономічного мікрохвильово-теплового масопереносу під час миття і сушіння аграрної та промислової продукції в мікрохвильовій нерезонансній камері з рівномірним полем нагріву. Камера оснащена вакуумним насосом і ультразвуковим генератором та функціонально зв'язана з випарником та конденсатором теплового насоса. Режиму біжучої хвилі в мікрохвильовій камері та інтенсивному випаруванню сприяють мікрохвильовий концентратор енергії поля в обсязі середовища та поглинаюче феритове покриття-перетворювач баластової енергії поля в теплову на перфораційній перегородці для продукції. Обгрунтовано напрям розвитку фізико-технічних основ мікрохвильово-теплової обробки середовищ, з метою миття продукції з застосуванням у вакуумній камері ультразвукового і мікрохвильового генераторів для інтенсифікації миття. Показана необхідність розвитку теорії і практики синтезу, виготовлення і застосування радіопоглинаючих матеріалів-перетворювачів енергії поля в теплову енергію. Запропоновано узгоджене комплексування модернізованої мікрохвильової та додаткової конвекційної технологій сушіння. Метою узгодження є отримання і використання синергетичного ефекту, а саме: економічного, інтенсивного та екологічно безпечного масопереносу вологи під час сушіння середовища, яке оброблюється.

Виявлено, що енергоекономічності процесу повного висушування в середині камери сприяють інтенсивне випарування вологи із продукції в рівномірному за обсягом електромагнітному полі та поточне осушення вологого повітря у випарнику теплового насоса. Сухе повітря подають в мікрохвильову камеру після його нагріву конденсатором теплового насосу. Це сприяє суттєво більш ефективному миттю-сушінню продукції на основі розвитку теорії і практики цього процесу. Застосування цього схемного рішення і раціональних параметрів режиму на практиці дозволяє вирішити суперечну проблему підвищення ефективності та екологічності процесів в побуту та в аграрному і промисловому виробництві

Ключові слова: мікрохвильово-тепловий масоперенос, нерезонансна мікрохвильова камера, покриття-перетворювач, тепловий насос

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DEVELOPMENT OF AN INTENSIVE MICROWAVE-THERMAL TREATMENT TECHNOLOGY FOR HETEROGENIC ENVIRONMENTS

B. Demianchuk
Doctor of Technical Sciences, Professor*
E-mail: bademyanchuk@ukr.net
N. Kolesnychenko
PhD*
E-mail: kolesnychenko.natalia@gmail.com
A. Ugol'nikov
PhD, Associate Professor*
E-mail: coalman6@ukr.net
A. Lapkin
Head of Laboratory
Department of Management and Marketing Maritime Business Institute
Odessa National Maritime University
Mechnikova str., 34, Odessa, Ukraine, 65029
E-mail: alpha666@te.net.ua
*Department of Technical Provision
Military Academy
Fontanska doroha str., 10, Odessa, Ukraine, 65009

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1. Introduction

The term 'intensive microwave-thermal treatment of heterogenic environments' means, first of all, a technologically complete, time-intensive process of washing and energy-efficient drying of products by consistently following steps such as:

1) environmentally friendly washing without harmful electromagnetic radiation from the chamber and without the use of detergents (chemicals);

2) complete drying, dehydration (in a microwave chamber without a centrifuge) of dispersed and continuous environments from sets, including food – fruits, vegetables; industrial products – fabrics, light clothing, etc.

It is a problem now to solve this task both with the help of the traditional microwave technology of processing these environments and particularly with the traditional technology of heating the environment with a heat pump. The problem remains even when each of these traditional drying technologies includes a centrifuge.

Microwave (traditional) processing of environments in open space causes radiation hazard for operators and adversely affects other electronic equipment. In a closed metal chamber, the traditional treatment does not ensure uniform heating of the environment throughout its volume. However, the conditions of traditional microwave action produce the following effects:

– uneven distribution of electromagnetic field energy in the chamber, which prevents a guaranteed manageable and controlled intensity of heating the environment; standing waves in the treated environment interfere with the coincidence of the gradients of temperature, pressure and moisture from the middle of the volume outside and make it impossible to implement the intense heating of the environment constituents;

– the inability to intensify the microwave heating of the environment without the risk of local overheating in places of maximums of the field in the space of the entire environment volume, which is repeated at an interval equal to half the wavelength of the field in the chamber;

– radiation from a traditional microwave chamber the walls of which have moving surface currents, so complex additional measures are needed to protect humans and electronic equipment;

– the existence of international standards for acceptable levels of background radiation of powerful microwave equipment, but compliance with the standards is unsatisfactory.

It is these physicotechnological effects and their theoretically and factually unresolved consequences that cause and emphasize the relevance of finding a technology of washing and drying products in everyday life, at farms and in industrial production.

2. Literature review and problem statement

In article [1], three methods of drying (hot air drying (HAD), microwave vacuum drying (MVD), and combined method (HAD+MVD)) are considered for drying mango pieces. The results showed the heterogeneity of drying mango pieces by HAD and MVD. The HAD-dried specimens had more moisture in the centre, but the MVD-dried ones showed the opposite result. Drying uniformity was improved when HAD and MVD had been combined.

This result confirms the need for combined methods and also the fundamental need for microwave drying in a chamber with a uniform electromagnetic field. This is what ensures both the quality and the intensity of the treatment processes without the risk of product damage.

Article [2] reviews microwave-based drying and dehydration technologies for industrial use. However, these methods are still more common in the field of experimentation. Microwave industrial drying has both advantages and disadvantages.

Indeed, the disadvantages of analogues consist in the lack of implementing the technological mode ‘moving wave’ in the traditional microwave drying equipment for intensive, high-quality and energy-efficient washing and drying of products.

Article [3] proposes intermittent microwave convective drying (IMCD) – an advanced technology that improves both energy efficiency and product quality during drying. IMCD simulation is essential for understanding the physics and refinement of the drying process and for optimizing the microwave power level and periodicity of the field during drying. In the study, a mathematical model for IMCD was developed and its adequacy was confirmed by experimental data. The model showed that the internal temperature of the material was higher than its surface in the IMCD and that the temperature was redistributed due to the intermittent microwave power. This can significantly improve product quality.

When using traditional microwave chambers, it is recommended to apply only a gentle mode of a standing wave action on the products, i. e. to increase the uniformity of heating only due to heat exchange. At the same time, it is better to use not ‘standing’ microwaves but an oven heated with firewood.

Article [4] presents an analysis of the energy efficiency of thermal systems, which is of practical importance for a number of reasons. The cycles and processes used in thermal systems exist in very different configurations, making it difficult to compare if particular models are required to analyse specific thermal systems. Thermal systems with low temperature differences between hot and cold sides also suffer from difficulties due to the uncertainty of the heat transfer point.

Such clear points are a consequence of the design features of thermal systems and should therefore be integrated into a global assessment. In the optimization of thermal systems, a detailed analysis of the entropy generation is suitable for detecting the performance losses caused by cycle components. In the analysis of plants, such logic is applied with the difference that the thermal system is then only a component, often industrially standardized, without considering the problem of time-intensive drying of products. The influence of the nonlinear boundary condition on the reversible thermal efficiency is given and the relation between the average real efficiency of the heat pump taking into account the linear and nonlinear boundary conditions is discussed. This is appropriate for a study that is devoted to the development of a technology for intensive microwave heat treatment of heterogenic environments. However, this article does not contain physicotechnical recommendations for the intensification and enhancement of the quality of the washing and drying process under the conditions of coordinated action of the microwave generator and the heat pump.

In [5], compositions of ferromagnetic $CoFe_2O_4$ nanoparticles and two conductive polymers (polyethylene dioxythiophene (PEDOT) and polypyrrole (PP)) are characterized. Both syntheses were carried out by polymerization of the monomers in the presence of dispersed magnetic $CoFe_2O_4$ nanoparticles at different mole ratios of the monomers. For PP composites, both the forced field and the applied field are required to maximize the decrease in magnetization with increasing polymer. The conductivity measurements indicate that for both types of composites, high polymer content leads to high electrical conductivity. These results indicate that the properties of the composite can be modulated by changing the polymer identity and the molar ratio of the monomers: $CoFe_2O_4$, which is important for the synthesis of radio absorbing materials as transformers of field energy into thermal energy.

The disadvantage of the technology is the lack of comparison of the results obtained with those required for practice.

In [6], the results of simulating the heat transfer process in inhomogeneous environments are presented with the assumption that part of the heat flux is dispersed in the air around the beam. The process of heat transfer in a solid material (beam) can be described by a partial differential equation of the whole order. However, in heterogenic environments, this can be described by a subdiffusion or hyperdiffusion equation, which results in a partial differential equation of the fractional order. Taking into account that part of the heat flow is sprayed into the surrounding environment, they further change the basic relation between heat flow and temperature, and in this case the heat transfer equation in the new form is obtained. This results in a transfer function that describes the relationship between the heat flux at the beginning of the beam and the temperature at a given distance.

No theoretical result of implementing the process of intensive mass transfer during the action on heterogenic environments has been described as provided.

In [7], the problem of extending the range of effective surface mass transfer coefficient is solved and the inhomogeneous distribution of first-order surface-reactive circular patches is considered. Analytical and boundary integral methods are used for calculations. An effective boundary condition of transport to the patches is obtained (up to the undiluted fraction of the patch section), depending on the local mass transfer coefficient (or reaction rate) and the shear rate. It is demonstrated that this boundary condition replaces the details of heterogenic surfaces at the normal effective sliding distance and is also determined for undiluted fractions of the patch area. The sliding distance depends on the shear rate; it also slightly depends on the reaction rate and the size of the patch. These effective boundary conditions can be used directly in large-scale physical simulations as long as local shear, reaction rate, and patch area fraction are known.

The mathematical methods presented in article [7] are important in the study of intensive microwave-thermal treatment of heterogenic environments, but they are not sufficient to simulate thermal analysis of the microwave-thermal process.

Article [8] presents trivial approaches to obtaining composites for protection against electromagnetic interference based on an epoxy base and carbon fibre. The Fe_3O_4 filler nanoparticles (NPs) were homogeneously dispersed in the epoxy matrix after surface modification using a silane coupling agent. The electromagnetic properties of interference shielding in combination with the complex permeability of composites were investigated in the range of 8.2–12.4 GHz. The total shielding efficiency (SET) increases with increasing loads of Fe_3O_4 NPs. The incorporation of Fe_3O_4 NPs into the composites increases the permeability, thus enhancing the ability to absorb electromagnetic waves. The increase in the SET, dominated by absorption losses, is explained by the enhanced magnetic losses and dielectric losses generated by Fe_3O_4 NPs and the multilayered construction of the composites. Microwave conductivity increases and penetration depth decreases with increasing loads of Fe_3O_4 NPs. For this study, it was important to analyse the processes of electromagnetic shielding with the complex permeability of composites.

However, the results obtained by the authors are trivial and have been known for more than one and a half decades, for example [10].

Study [9] proposes a method of correction of wave resistances of modified radio absorbing composites with heterogenic fillers in the form of a weighted mixture of ferrite and silicon carbide in a thermoplastic matrix. The method helps to ensure that there is no reflection of the field energy from the surface of the absorbing coating by matching the relative dielectric and magnetic permeabilities, which are normalized by the corresponding constant air. The method also contributes to providing the required significant level of linear absorption of the energy of the electromagnetic field by coating with a thickness not exceeding one millimetre. The advantage of using a polymer in the form of thermoelastoplastic consists in its moisture resistance and sufficient thermal resistance equal to more than 200 °C.

In [10], a method is proposed for magnetite production along with the technology of thermochemical synthesis of disperse ferrite oxides of transition metals of the Fe_3O_4 system with a molecular structure of a spinel of an inverted type (Patent No. 75749 of Ukraine of 15 May 2006). The study analyses physical mechanisms during the implementation of technologies that influence the results of synthesis and practical application of a substance with the desired electrophysical properties. It is in this paper that recommendations are provided for the practical application of this filler in the composite coating to ensure uniform field volume in the microwave heating chamber and to reduce interference radiation from the chamber. Ways to provide the benefits of this compound are also recommended when practically used as a filler for the polymer matrix of any radio absorbent coatings. In particular, one of the recommendations is to harmonize the wave resistances of dielectric environments at the boundary of the air-environment interface. For this purpose, it is advisable to measure accurately the parameters that make up the complex permeability of environments with electromagnetic losses. This is necessary for purposeful parameter correction in order, first, to provide a reflection of the field energy close to zero. Secondly, it is necessary to ensure a linear absorption of the energy of the electromagnetic wave at the level of 12...15 dB/mm when the coating is applied to a metal surface. It is these electromagnetic field energy absorbers that form the basis for the construction of a coating for a perforation partition in a microwave-thermal machine that implements the technological process proposed in the article.

In [11], a physicotechnical solution was found to increase the thermal stability of the coating and the absorption coefficient of the energy of the electromagnetic field in the thin layer of the coating-transformer, without loss of its mechanical power. The thermo-elastoplastic base of this coating by vibration treatment is polymerized and contains a chemically bound polymer and oxide molecules. This solution makes it possible to activate the process of washing and drying without the risk of damaging the products at places of maximums of the standing wave field. It also prevents mechanical damage to the product when it is supplied into the ambient air chamber after being washed in a vacuum microwave non-resonant chamber.

A significant gain in saving energy consumption by mass transfer during product drying (approximately 3...4 times) is the combined volumetric effect of the electromagnetic field and the heat pump in the evaporator and condenser. This coordinated process is implemented by means of a blower fan due to the selection (in the environment of the evaporator) of moisture from the air of the microwave chamber. Further, dry air is heated in the vicinity of the condenser of the heat pump in the area of thermal activation of the process of mass transfer of moisture. The extraction of warm air from the condenser of the heat pump and the supply of it to the chamber of consistent drying, i. e. in the area of microwave-thermal drying, are carried out with the help of another fan.

The unresolved issues in this information source are, firstly, the justification of the requirements for the physicotechnical parameters of the microwave equipment while achieving the goal of microwave-thermal transfer. Secondly, the levels of temperature parameters during the implementation of the mode of operation of the heat pump equipment, which is consistent with the level of microwave heating of the environment, namely, the air at the inlet of the heat pump, remain undefined.

Common to most publications is the unresolved part of the problem not only in determining the parameters of heat and mass transfer. An unanswered question is the overall level of energy efficiency and environmental safety for the widespread distribution at home and in the production process of non-resonant microwave-thermal treatment of heterogenic environments.

3. The aim and objectives of the study

The aim of the research is to substantiate the physical and technical mechanisms and process parameters that contribute to the implementation of technological bases of microwave-thermal, energy-efficient, intensive and environmentally safe treatment of heterogenic environments.

To achieve this aim, the following objectives were set and done:

– to justify the feasible option of functional elements of equipment to implement a technology for automated, high-quality, microwave-thermal, economic, intensive, and environmentally safe treatment of heterogenic environments, i. e. washing and drying products of different types, and to determine the technical means to implementation in the microwave chamber and intensely use of chemical detergents, without overheating and underheating of products as well as without harmful radiation of the field from the chamber;

– to determine the required parameters of the surface coating with electrically conductive absorber in the form of magnetite in order to coordinate the wave resistance of the air and the absorbing coating;

– to determine the means for economical and complete removal of moisture from the environment during its complete drying without a centrifuge.

4. Substantiation of the feasible variant of the functional elements of microwave-thermal equipment

Technological equipment for washing and drying is necessary for qualitative and energy-efficient processing of any products, for example, fruits, vegetables, medicinal plants, fabric, as well as thermal insulation materials in industrial, field and domestic conditions. It must perform the functions of washing with water of any initial temperature and without the use of detergents. The drying of the product should be complete, in the chamber after washing, without the use of a centrifuge.

In order to achieve the required technical result, it is advisable to equip the microwave-thermal equipment with the following: a metal housing; a chamber with a gateway and a seal and with a horizontal perforated partition; and a vacuum unit therein. The unit must dilute the air to 0.30...0.50 MPa and be connected through the valve to the upper part of the chamber by an ultrasonic oscillator at a frequency of 25...30 kHz, located in the middle of the chamber.

In addition, it is advisable to provide the equipment with electrically operated shut-off valves for water supply to and discharge from the chamber as well as for pumping and supplying air; an emitter of electromagnetic waves; and a microwave generator at 2.4...2.5 GHz. The generator output must be connected to the emitter input; a transparent quartz gateway with a seal in the side wall of the upper part of the chamber, which is rigidly connected to the output opening of the emitter of electromagnetic waves.

The electromagnetic wave emitter shall include a wavefront correction lens such that the dimensions of the emitter overlap are inversely proportional to the dimensions of the horizontal perforated partition for products. This will contribute to the concentration of field energy in the angular sector, the cross-sectional dimensions of which in the picture plane are consistent with the cross-sectional dimensions of the volume of products loaded onto the horizontal perforated partition.

On this partition, it is advisable to place a thermoelastoplastic ferrite coating-transformer of ballast electromagnetic energy into thermal.

It is advisable to connect the power supply and control unit to the vacuum unit, to the microwave generator, to the ultrasonic radiator and to the shut-off electrically operated valves.

It is advisable to equip the microwave and thermal equipment not only with the microwave activation area of the washing and drying but also with the area of thermal activation of the drying process as a part of a series of the compressor, the condenser, the throttle, and the evaporator.

It is advisable to separate the two areas by a vertical partition with ventilation gateways, in which a fan of humid air injection to the evaporator and a fan of extraction of dry warm air from the condenser of the heat pump must be installed.

It is also advisable to connect the power supply and control unit to the fans and the compressor.

Thermoelastoplastic ferrite coating-transformer of ballast electromagnetic energy into thermal energy is located in the microwave activation area of washing and drying on the horizontal perforated partition. This coating is advantageous to perform polymerization filled with a dispersed magnetic electrically conductive filler in the form of transition metal oxide in the form of a ferrite-ferrite spinel compound.

Both washing and drying with the help of constant and uniform microwave heating of wet products are carried out intensively and energy-efficiently in the chamber. This is due to the volumetric heating of a damp product by an electromagnetic field without uncontrolled local overheating and overheating of the product due to the absence of ‘standing’ waves in the chamber.

This type of field is caused by the absence of waves reflected from the perforated partition in the chamber due to the use of a thermoelastoplastic ferrite coating-transformer of ballast electromagnetic energy into thermal energy. This coating is polymerisation-filled and contains a disperse magnetic conductive filler, a transition metal oxide, in the form of a compound $Fe_3O_4=(Fe)^{2+}(Fe_2)^{3+}(O_4)^{2-}$ with a molecular structure of a spinel of the inverted type.

This dispersed magnetic conductive filler has a specific electrical conductivity equal to $10^3...10^4$ S/m, i. e. it has a level in excess of known similar fillers of seven or more orders of magnitude.

The essence of the construction and operation of the microwave-thermal equipment, which was developed by the authors, is explained in more detail by means of Fig. 1, which schematically shows the general construction of this equipment.

The housing 1 structure. The housing 1 contains a chamber 2 with a gateway 3 with a seal and with a horizontal perforated partition 4 located therein. A vacuum unit 5 in the form of a vacuum pump is connected to the upper part of the volume of the chamber 2 in order to prevent direct contact of the vacuum channel with the water for washing products. An ultrasonic emitter 6 is located inside the chamber 2 so that it is always below the minimum water level for washing products, using a cavitation effect on the frequency of mechanical oscillations, which is equal to 20–30 kHz.

Shut-off valves 7–10 are located at the inlet (outlet) of the chamber 2 and provide: 7 – water supply to the chamber 2; 8 – discharge of water after washing products; 9 – pumping the air from the chamber 2 with the help of the unit 5 in order to reduce the energy consumption of the ultrasonic generator in the aquatic environment during washing; 10 – air release and supply.

The supply of atmospheric air to the chamber 2 after the end of the stage of washing products and the opening of the valve 8 for water discharge provide the function of drying in the first stage.

The emitter of electromagnetic waves 11 is rigidly connected by its input to the output of the microwave generator 12, and by its output – to the radiotransparent quartz gateway 13, which has a seal in the side wall of the chamber 2.

A thermoelastoplastic ferrite coating-transformer 16 of ballast electromagnetic energy into thermal energy is located on a horizontal perforated partition 4. The emitter of electromagnetic waves contains a lens 14 of the wavefront correction.

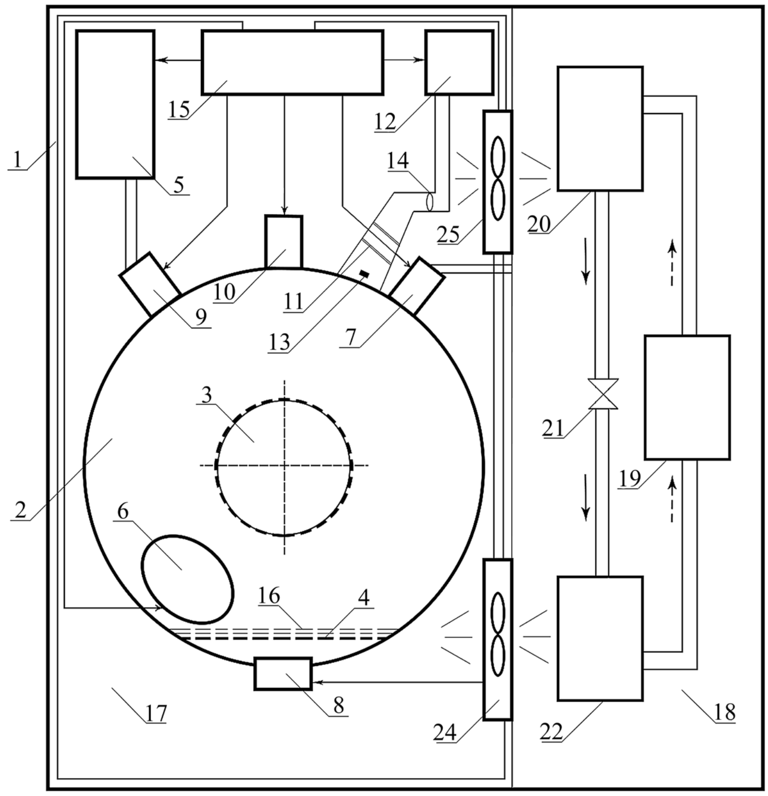

Fig. 1. The design scheme of the microwave-thermal equipment:
1 — housing; 2 — chamber; 3 — gateway; 4 — perforated partition;
5 — vacuum unit; 6 — ultrasonic emitter;
7, 8, 9, and 10 — shut-off valves (water supply, water discharge, air pumping, and air outlet);
11 — emitter; 12 — microwave generator; 13 — quartz gateway;
14 — lens of wavefront correction; 15 — power supply and control unit;
16 — coating-transformer of ballast electromagnetic energy;
17 — area of washing and drying activation;
18 — area of thermal drying activation; 19 — compressor; 20 — capacitor;
21 — throttle valve; 22 — evaporator; 23 — vertical partition;
24 and 25 — fans for air supply and release

The dimensions of the radiator overlap are inversely proportional to the dimensions of the horizontal perforated partition 4. This will contribute to the concentration of energy in the angular sector, the cross-sectional dimensions of which are consistent with the cross-sectional dimensions of the perforated partition 4.

The power and control unit 15 is connected to the vacuum unit 5, to the microwave generator 12, to the ultrasonic emitter 6, and to the electrically controlled shut-off valves 7–10.

In addition, the microwave-thermal machine further comprises: an area 17 of microwave activation for washing and drying of products and an area 18 of thermal activation of the drying process in a series of connected elements such as the compressor 19, the condenser 20, the throttle valve 21, and the evaporator 22.

The areas are separated by a vertical partition 23 with ventilation gateways. Into the floodgates of the vertical partition 23 there is a fan 24 for pumping wet air into the evaporator 22 and a fan 25 for extracting warm air from the condenser 20.

The power supply and control unit 15 is also connected to the fans 24, 25 and the compressor 19. The thermoelastoplastic ferrite coating-transformer 16 of the ballast electromagnetic energy into thermal energy, which is located on the horizontal perforated partition 4, is polymerization-filled and contains a disperse magnet.

The rapid mass transfer, according to the technology implemented by microwave-thermal equipment, results in the natural coordination of the directions (from the middle of the samples to be dried and outside) of the gradients of the three physical parameters of products such as moisture, temperature, and vapour pressure.

This effect is achieved only in the absence of standing waves in the chamber, first of all, due to the thermoplastic ferrite coating-transformer 16, which is applied to the horizontal perforated partition 4.

The coating absorbs the ballast electromagnetic energy of the field the level of which is substantially increased during the drying step, because the coating converter 16 is polymerization-filled. The converter contains a concentrated dispersed magnetic conductive filler, a transition metal oxide, in the form of the compound $Fe_3O_4=(Fe)^{2+}(Fe_2)^{3+}(O_4)^{2-}$ with a molecular structure of a spinel of the inverted type.

This filler provides comparable relative dielectric and magnetic permeability and high electrical conductivity of the coating-transformer. These are the necessary and sufficient conditions for the non-reflecting absorption of the ballast energy of the electromagnetic field in the chamber 2, even at the stage of final drying of the product. At this stage, the product contains a small amount of moisture, so it becomes more transparent. This factor requires the transition to the stage of convection drying with dry and warm air from the condenser from the area of the heat engine.

It is important to emphasize that the process of intensive, i. e. accelerated, economical, environmentally sterile, uniform and complete drying of products, especially, for example, fruits and vegetables, is underway; it implies complete drying without a centrifuge. All this is especially useful in practice in production, at farms and at home, because it has been an unresolved problem.

It should be emphasized that the temperature of microwave heating of the wet polymeric environment during drying with the help of a traditional chamber with a standing wave in the electromagnetic field maximums can reach 260 °C and more. This corresponds to the temperature of the local uncontrolled ignition and destruction of the product. Therefore, the use of various well-known equipment for this purpose, because of the uncontrolled process of microwave heating and local overheating, is quite dangerous.

When using traditional drying technology, this requires a gentle drying mode, i. e. too long drying with low generator power. Active drying with a high power microwave generator is too risky.

The process of efficient high-quality washing and complete drying of products by the technology offered begins and ends in the middle of the chamber 2, i. e. without the need to carry it out in the open space.

Thus, at the final stage of mass transfer during the drying of practically radiotransparent products with the help of new technology, the ferrite coating-transformer 16 of ballast energy of the field begins to function. This prevents the waves reflected from the horizontal perforated partition 4, protecting the product from overheating. Meanwhile, the operation of the heat engine unit provides effective and energy-efficient convection mass transfer for complete drying.

The unit then switches off the generator, the compressor and the fans, using the pre-set washing and drying mode. After deflection of the gateway 3 in view of the increase, dry products are used to accommodate long-term reliable storage.

We will make sure that the new microwave and thermal equipment components are as reliable and as necessary as possible.

The implementation of the advantages of the washing and drying process with the help of a set of essential structural features in the proposed microwave-heat machine requires new properties of the elements of this machine.

First, it is necessary to prevent reflection of the electromagnetic field energy from the surface of the thermoelastoplastic ferrite coating-transformer 16 of the ballast electromagnetic energy into thermal, which is applied to the horizontal perforated partition 4 of the chamber 2.

Secondly, the technology requires intensive damping of the ballast electromagnetic field energy in this coating. These requirements are satisfied by the coating converter 16 with an electrically conductive ferrite filler for a polymeric thermoplastic base with comparable relative levels of dielectric and magnetic permeability. These levels of permeability must be normalized by the relevant electromagnetic constants of the air.

These properties are only achieved through a ferrite magnetic filler with a semiconductor electrical conductivity of $10^3...10^4$ S/m. These requirements need further justification.

5. Determination of required surface coating parameters in a microwave chamber with a conductive absorber

To substantiate the required quantitative values of the reflection coefficient and the passage coefficient of a single-layer absorbent coating, let us define the electrodynamic parameters of some dielectric environment. This environment is isotropic with electromagnetic losses, i. e. it has extraneous currents.

The electromagnetic field in this environment depends on the path length *z* of the traveling wave propagating beyond the air-to-cover boundary and after the first drying step of the processed product. The field also depends on the complex values of the dielectric and magnetic permeabilities, i. e. on the parameters characterizing the reflecting and absorbing properties.

An important requirement for the absorbent material is to ensure, in a wide range of frequencies, the minimum reflection of the electromagnetic wave from the boundary of the air-to-cover section.

The factual solution of the problem of comparing the wave resistances of the environments of the air and the boundary coating material poses significant technical difficulties.

No less difficult it is to solve the problem of significant attenuation of the field energy in the coating environment, which converts the energy of the electromagnetic field into thermal energy.

Let us first determine the necessary conditions for the coordination of the wave resistance of the air environment and the absorbing coating 16, i. e. the environment with the loss of field energy.

Optimal (at the minimum reflection coefficient from the composite surface) ratios between the dielectric and magnetic permeability values and the corresponding conductivity values of the composite are required. The optimum values are determined by solving the complex equation system with respect to the composite characteristics after determining this reflection coefficient.

During the fall of a flat homogeneous electromagnetic wave by the normal (this is the most unfavourable case) to the interface, the complex amplitudes of the intensity vectors of incident, reflected and transmitted waves are as follows:

$$\dot{\vec{E}}_m^0 = \vec{x}_0 \dot{\mathbf{A}} e^{-jK_0 z}, \quad \dot{\vec{H}}_m^0 = \vec{y}_0 \frac{\dot{\mathbf{A}}}{W_0} e^{-jK_0 z}, \quad (z<0);$$

$$\dot{\vec{E}}_m^- = \vec{x}_0 \dot{\mathbf{B}} e^{-jK_0 z}, \quad \dot{\vec{H}}_m^- = -\vec{y}_0 \frac{\dot{\mathbf{B}}}{W_0} e^{jK_0 z}, \quad (z<0); \tag{1}$$

$$\dot{\vec{E}}_m^+ = \vec{x}_0 \dot{\mathbf{C}} e^{-jKz}, \quad \dot{\vec{H}}_m^+ = \vec{y}_0 \frac{\dot{\mathbf{C}}}{W} e^{-jKz}, \quad (z>0),$$

where $\dot{W}_0$ and $\dot{W}$ are the wave supports of the air and the composite; K_0 and K are the wave numbers for these environments.

For the coefficients of the wave reflection ρ and wave passage τ into the environment in the form

$$\dot{\rho}=\frac{\dot{E}_m^-(0)}{\dot{E}_m^0(0)},\quad \dot{\tau}=\frac{\dot{E}_m^+(0)}{\dot{E}_m^0(0)},$$

in accordance with (1) and taking into account the continuity of the tangential components of the stress vectors at the interface, i. e. according to the system

$$\begin{cases}\dot{E}_{m1\tau}=\dot{E}_{m2\tau}\\ \dot{H}_{m1\tau}=\dot{H}_{m2\tau}\end{cases}\Rightarrow\begin{cases}\dot{E}_{m\tau}^0+\dot{E}_{m\tau}^-=\dot{E}_{m\tau}^+\\ \dot{H}_{m\tau}^0+\dot{H}_{m\tau}^-=\dot{H}_{m\tau}^+\end{cases}\quad(2)$$

a system of equations is obtained, the solution of which gives the dependence of the reflection coefficient and the passage coefficient on the parameters of the composite in the form

$$\rho=\frac{\dot{W}-\dot{W}_0}{\dot{W}+\dot{W}_0},\quad \tau=\frac{2\dot{W}}{\dot{W}+\dot{W}_0}.\quad(3)$$

It follows from (3) that with $\dot{W}=\dot{W}_0$ (the environments are consistent) the reflection coefficient is zero and the coefficient of the field's passage from the air to the environment is one, which corresponds to the complete transition of the field energy from one environment to another.

Let us determine the conditions of harmonization of the wave resistances of the environment through the parameters of the composite and air. For air environment, the wave resistance is the following:

$$\dot{W}_0\approx\sqrt{\frac{\dot{\mu}_0}{\dot{\varepsilon}_0}}=\sqrt{\frac{4\pi\cdot10^{-7}}{\frac{1}{36\pi}\cdot10^{-9}}}=120\pi,\quad(4)$$

where $\dot{\mu}_0$, $\dot{\varepsilon}_0$ are the magnetic and dielectric constants of the vacuum (and also the air).

For an environment with losses, the wave resistance is

$$\dot{W}=\sqrt{\frac{\dot{\mu}}{\dot{\varepsilon}}}\approx\sqrt{\frac{\mu'-i\mu''}{\varepsilon'-i\varepsilon''}},\quad(5)$$

$$\mu'=\mu_0\mu,\ \varepsilon'=\varepsilon_0\varepsilon,\ \mu''=\frac{\sigma_{\text{i}}}{\omega},\ \varepsilon''=\frac{\sigma_{\text{y}}}{\omega};$$

$$\mu_0=4\pi\cdot10^{-7}\ \text{H/m},\ \varepsilon_0=\frac{10^{-9}}{36\pi}\ \text{F/m},\quad(6)$$

where $\dot{\mu}$, $\dot{\varepsilon}$ are the absolute magnetic and dielectric constants of the composite permeability; μ, ε relative magnetic and dielectric constant of the composite; σ_{i}, $\sigma_{\text{ỳ}}$ are the magnetic parameter of field losses and specific conductivity of the composite.

In accordance with the conditions of harmonization of environmental resistances in the form of a complex equation $\dot{W}=\dot{W}_0$, according to (4) and (5), we obtain a system of equations:

$$\begin{cases}\arctan\left(\frac{\sigma^M}{\omega\mu_0\mu}\right)=\arctan\left(\frac{\sigma^E}{\omega\mu_0\mu}\right),\\ \mu^2+\frac{\left(\sigma^M\right)^2}{\omega^2\mu_0^2}=\varepsilon^2+\frac{\left(\sigma^E\right)^2}{\omega^2\varepsilon_0^2}.\end{cases}\quad(7)$$

The solution of system (7) as to σ^M/μ_0 and ε gives the desired correlation between the parameters of the composite, which ensures a minimum (almost zero) reflection. The required parameters are as follows:

$$\varepsilon=\mu;\quad \sigma^M/\mu_0=\sigma^E/\varepsilon_0.\quad(8)$$

These conditions are essential for the practical implementation of the tasks due to:

1) a significant reduction of the reflected wave energy of the field from the environment-coverage with losses;

2) attenuation of the intensity of the field inside the coating environment, subject to the admissible values of the thickness of the coating-transformer of the energy of the field into thermal energy.

To solve the first problem, it suffices to ensure that condition (8) is satisfied. However, to solve the second problem when the absorbent material is deposited, for example, on a metal surface, it is necessary to meet both the conditions of (8) and the conditions of (8) in the form of the inequality:

$$\tan\delta_E=\tan\delta_M>>1,\quad(9)$$

where $\delta_E=\sigma_E/(\omega\varepsilon_0\varepsilon)$, $\delta_M=\sigma_M/(\omega\mu_0\mu)$.

These requirements make it possible to provide the necessary high level of linear absorption of the field energy and a small level of reflection of the field energy from the absorbing coating, even if it is deposited on a metal substrate.

Indeed, the coefficient of energy loss of the field in the thickness of the absorbing environment whose parameters are agreed, according to (1), (7), (8), is equal to

$$K''=\frac{\omega}{2c}\sqrt{\varepsilon\cdot\mu}\left(\frac{\sigma_E}{\omega\varepsilon_0\varepsilon}+\frac{\sigma_M}{\omega\mu_0\mu}\right)=$$
$$=120\pi\sigma\ \text{Om/(Om}\cdot\text{m)}.\quad(10)$$

Therefore, in order to provide significant linear attenuation of the field in a consistent environment with losses of the field energy, at a thickness of the material layer, for example, z=2 mm, it is necessary to have a specific conductivity of the environment having the order of several Siemens per meter.

Provided that the specific electrical conductivity of this synthesized filler is generally equal to $\sigma_E=10^3...10^4$ S/m or more, obtaining the required specific electrical conductivity of the finished coating 16 at the level of 5 S/m is easy. Therefore, indeed, at σ_E=5 S/m, taking into account (10), we find the required dimensionless measure of the field damping in the coating, which is equal to

$$K''z=120\pi\cdot\sigma_E\cdot z=3.77.\quad(11)$$

Double passing of a wave through a covering 2 mm thick causes its energy to be reduced 2,500 times.

A similar level of the degree of attenuation of the field energy in the finished absorbent coating can be achieved only with the help of fillers in the form of ferrite-ferrite spinel of the inverted type.

Such filler materials are magnetic semiconductors with comparable levels of relative dielectric and magnetic permeability. This complies with the requirements for the coating parameters obtained according to (8)–(10).

The calculations emphasize the real ability to meet these requirements. These fillers have a low level of activation energy and thus high sensitivity and a wide allowable dynamic range of change in the intensity of electromagnetic field inputs on the absorbing coating.

In addition, the technology of thermochemical synthesis of fillers of this type, such as Fe_3O_4, $NiCO_2O_4$ etc., does not require scarce raw materials, scarce thermochemical reaction catalysts and does not require sophisticated equipment and time consuming.

Let us consider the essence of thermochemical synthesis of the filler and the polymerization filling of the absorbent coating.

The thermochemical synthesis of the filler is aimed at providing the required complete level of inversion of the obtained oxide compound with the structure of ferrite-ferrite spinel. In this case, trivalent iron cations should occupy part of the octahedral positions of its elementary molecular cell, and the rest of these positions must be occupied by divalent iron cations.

The proportionality of the ionic radii of these cations provides a high degree of inversion of this compound, which is a condition for giving it the desired semiconductor and magnetic properties.

The small ionic radii of the divalent and trivalent iron cations contribute to the high mobility of charge carriers when they diffuse from a cation to a cation, thereby causing an unusually low level of activation energy of the charge carriers. This energy is equal to tenths and even hundredths of electronvolts.

The low level of magnetic viscosity (inertia) of this material is manifested in the small value of its relaxation time. That is, the material has a small time to change the orientation of the magnetic spin-spin and spin-orbital moments under the action of the electromagnetic field energy that enters the surface of the absorbing coating.

The technology of obtaining the filler is sintering within one hour (implementation of the reduction reaction) of a mixture of simple Fe_2O_3 oxide with reactive carbon in the presence of oxygen.

Such technology has advantages over the known (for example, the method of chemical deposition of salts of metals or hydroxides of these metals) not only in the quality of the material obtained. In addition, the new technology contributes to the reproducibility and stability of the required high electrical conductivity, comparable normalized magnetic and dielectric permittivity, and the synthesis time, according to the proposed technology, is one hour.

On the contrary, the time consumed according to traditional technology, i. e. under the application of the deposition method, the total time of deposition, washing, filtration, drying and grinding of the finished filler, takes a week.

The vibrating treatment of the filler prior to the filling operation of the thermoplastic coating contributes to the effect of chemical bonding between molecules of a polymeric binder of organic nature and molecules of a ferrite oxide filler with a spinel structure of the inverted type.

The polymerization filling of the polymer environment with electrically conductive ferrite oxide thus contributes to the high concentration of the absorber in the polymer matrix. Consequently, this contributes to achieving the desired high level of absorption of the field energy without losing the mechanical strength of the absorbing coating after its hardening.

6. Determination of means for economical and complete removal of moisture without a centrifuge from the environment during its complete drying

The process is implemented by the parameters of the components of the unit of thermal intensification of the process of heat and mass transfer of the compressor 15, the throttle 21, the evaporator 22, and the condenser 20 in the heat pump of the microwave-thermal equipment. These parameters are not fundamentally different from the typical parameters of any heat pump.

The required power of the compressor, the technical characteristics of the throttle, the evaporator, and the condenser in accordance with the technological mode of a specific technological process provide the implementation of the functions:

– removal of moisture from the air by getting it on the cooler of the heat pump chamber;

– additional heating in the environment of the condenser (heat pump) in order to further intensify the process of drying the environment at the final stage, when the environment has lost most of the moisture and becomes practically transparent to the electromagnetic wave.

The implementation of the set of these functions is fundamentally necessary. It contributes, first, to energy conservation at an important, final stage of processing a heterogenic environment; secondly, they ensure the implementation of a high level of energy efficiency of the process in accordance with the Carnot cycle.

Depending on the specific required parameters of the mode of heat and mass transfer in the second stage of processing the environment, i. e. at the stage of drying, the values of the temperature of the evaporator T_1 and the condenser T_2 is set taking into account the desired process performance.

For example, the condenser 20 of this area of the heat pump requires a temperature of T_1=340 K, and in the evaporator 22 the temperature is involved at the level of T_2=255 K, so a typical energy conversion factor with the help of a heat pump consisting of the compressor, the capacitor 20, the throttle valve 21, and the evaporator 22 is

$$\xi = \frac{T_1}{T_1 - T_2} = 4. \qquad (12)$$

During the microwave-drying process, an acceptable level of extraction of moisture from the air by the evaporator 22 is carried out by means of the blower 24 and an acceptable level of heat transfer to the dry air from the condenser 20 by the fan 25.

According to (12), the efficiency of intensification of mass transfer shows that 4 kW of thermal power for every 1 kW of power will be supplied to the chamber 2 (to accelerate the processes in the microwave-thermal machine). Power is expended on the operation of the compressor 15 in the unit 18 for heat intensification of the drying process.

7. Discussion of the research results of the new technology of intensive microwave-thermal treatment of heterogenic environments

Achieving the desired results for the synthesis of ferrite-ferrite oxide by thermochemical sintering in a minetype furnace by means of a catalyst requires compliance with the technological requirements of its synthesis. Providing conditions for their fulfilment contributes to the efficient production of a heat-resistant (up to 800 °C) highly dispersible filler (with a conductivity exceeding 10^3 S/m, with a particle size of ≤1 μm) with comparable values of dielectric and magnetic permeability.

It is these properties of the filler that provide the required levels of absorption (of the field energy) by covering the perforated horizontal partition of the chamber to ensure the intensive and high-quality processing of heterogenic environments of various purposes such as linen, fabrics, thermal insulation materials, and agricultural products.

The high level of energy absorption of the electromagnetic field is ensured even with a sufficiently thin (1–2 mm) coating for the chamber, which provides intense and high-quality heat and mass transfer during the processing of heterogenic environments.

The polymerization filling of the binder base of an organic thermosetting polymer based on thermoplastic elastomer is successfully implemented in a metal reactor of a vibrating machine with metal layers of different diameters.

Mechanical-chemical fusion of ferrite oxide particles with ferrite-ferrite oxide particles contributes to a significant increase in the concentration of ferrite filler without losing the mechanical strength of the coating for the chamber of the microwave-thermal machine during the processing of products.

The consistent drying of products with the combined operation of microwave heating equipment environments and energy-efficient 'heat pump' contributes to the triple effect:

– firstly, it intensifies the labour-intensive process of complete removal from the heterogenic process environment, free and bound moisture;

– secondly, it contributes to a reduction of more than 4 times the energy consumption for drying the products in the chamber 2 without a centrifuge;

– thirdly, it reduces by several times the time consumption for the implementation of the process of washing and drying products in a microwave-thermal machine.

Thus, the technology contributes to a more productive, economical, environmentally friendly process of intensive processing of various heterogenic environments that need high-tech implementation.

The implementation of intensive mass transfer technology, i. e. high-quality washing and drying during microwave-thermal treatment of heterogenic environments of a wide range of practical purposes, requires further efforts.

First of all, building a microwave-thermal machine that aims to apply new technological advances to the processing of any product requires new design solutions, new equipment and original materials.

Secondly, processing, i. e. washing and drying to a given level, the environment of a particular type requires careful theoretical substantiation and experimental testing of optimal parameters of the temperature-thermal regime of the microwave-thermal machine.

Thirdly, during the development and implementation of a microwave-thermal technology, careful efforts are also important to ensure (at the design stage) the quality of products to be processed by the technology being offered, as well as the constant quality control of the products at the stage of working out the parameters of the technological mode of intensive processing.

8. Conclusion

1. The efficiency of intensive and high-quality processing of heterogenic environments is increased only by performing all technological operations proposed and based on different physical principles, namely:

– vacuation of the chamber to treat the environment, in order to reduce the damping of energy of ultrasonic vibrations during the washing of products;

– ultrasonic treatment of the environment in order to intensify the process of washing the components of the environment due to the cavitation effect;

– microwave uniform heating in the volume of the environment and water in order to facilitate quality controlled washing without detergents, in case of significant pollution of the environment;

– application of atmospheric pressure energy for the initial economic extraction of dirty water and free moisture from the treated environment;

– neutralization of the resonant properties of the chamber in order to intensify the drying process; first of all, the removal of bound moisture;

– application of the process of extracting moisture from the air by getting it on the cooler of the heat pump chamber for the purpose of final drying of the products;

– additional heating of the air around the condenser of the heat pump in order to intensify the drying process of the environment; this is necessary at the final stage when the environment has lost most of the moisture and becomes practically transparent to the electromagnetic wave at the outlet of the concentrator.

2. The appropriate equipment for the implementation of technology for automated, high-quality, microwave-thermal, intensive, and environmentally friendly treatment of heterogenic environments, i. e. washing and drying of products, is the coordinated use of a microwave heater and a heat pump. This facilitates the technological process of complete removal of moisture from the environment during the stage of drying without a centrifuge.

3. The implementation of the process of intensive and safe washing without the use of chemical detergents, without overheating and underheating of products, as well as without harmful radiation of the field from the chamber, is ensured by a set of new units. These include: a vacuum pump, an ultrasonic generator, a unit of concentration of energy in the volume of the environment, and thermoplastic coating of a horizontal perforated partition in the chamber.

4. The required parameters of ferrite non-reflective coating with electrically conductive magnetite absorber to fill the thermoplastic elastoplastic are as follows: the same relative dielectric and magnetic permeability; the same values of the corresponding conductances, which are normalized by the corresponding air permeabilities; and the commensurate levels of the corresponding tangential angles of field loss in excess of one.

The proposed technology can reduce the energy cost of processing heterogenic products by more than four to five times and the energy consumption of washing and drying thermal insulation environments by eight to ten times.

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