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Materials and Economic Aspects of Designing Microwave Electrical Installations

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ABSTRACT

Ultrahigh-frequency electro-technical installations are capable of performing thermal microwave modification of dielectric and non-thermal microwave modification of polymer materials and products, as a result of which new properties and parameters appear in the object processed in the working chamber of such an installation. When designing microwave electrical installations, it is necessary to consider the relationship between the dielectric parameters of the processed object and the parameters of the microwave electromagnetic field of the working chamber of the installation. The paper considers the influence of the parameters of the processed dielectrics on the synthesis of working chambers of microwave electrical installations and mathematical modelling of heat treatment in a microwave electromagnetic field, the structure and parameters of the installation on its economic efficiency. Consideration of the materials science and economic aspects of microwave electrical technology allows to accelerate and reduce the cost of design in microwave electrical technology.

1. INTRODUCTION

The processing of a dielectric in a microwave electromagnetic field has gained tremendous popularity at present. The process goes much faster than surface heat release, convection or thermal radiation due to volumetric heat release.

In recent years, attention has been drawn to research and publications in the application of microwave energy in agriculture. The works are devoted to increasing the efficiency of drying sawn timber by using a discrete arrangement of magnetrons and a mechanism for rotating sawn timber along its axis in the chamber space [1, 2], developing a microwave drying plant for agricultural products in farms [3].

The following works are devoted to investigations of thermal microwave modification for dielectric materials: development of various designs of working chambers with a standing wave [4], chambers with a travelling wave [5], and meander-type chambers [6, 7]; microwave drying of food products [4, 8]; microwave drying of sawn timber [9-12]; development of microwave electrical installations with hybrid chambers [13].

The microwave effect on polymer objects of inanimate nature shows a specific microwave effect on polymers. It can be called a non-thermal microwave modification (the properties of the processed polymer change within a few seconds of being in the microwave electromagnetic field, and the processed object practically does not heat up).

The research of non-thermal microwave modification to polymer materials is the subject of the following works: research of microwave drying of polymers [14-18]; research of nanostructured conducting polymers and composites [19, 20]; a construction of composites with improved characteristics of absorption of microwaves has been developed [21, 22]; studies of the influence of the electromagnetic characteristics of sodium chloride on temperature changes during drying in a microwave oven [23, 24]; mathematical modelling of technological processes in a microwave electromagnetic field [25, 26]; design of microwave electrical installations with hybrid type working chambers [27, 28].

This paper discusses the material science and economic aspects of designing microwave electrical installations, analyzes the influence of material parameters and properties of processed objects, economic parameters of microwave electrical installations on the decisions made during design.

Research Aim: Development of the foundations for the design of microwave electrical installations.

Research Objectives:

- To formulate the materials science and economic aspects of the design of microwave electrical installations;
- To show the influence of material science and economic parameters and characteristics of the element base and the entire electro-technical installation as a whole on the decisions made in the design of these installations.

2. METHODS

In microwave electrical technology, the material science aspect has not yet been considered in the design. The relations presented in this work, which solve the problem of synthesizing the working chamber of an electro-technical microwave installation, make it possible to calculate by calculation the influence of the accuracy of setting the parameters of the processed dielectric on the results of synthesis and mathematical modelling of the process of heat treatment of a dielectric material or product in a microwave electromagnetic field.

The synthesis of working chambers and mathematical modelling of technological processes of thermal microwave modification in a microwave electromagnetic field is carried out based on solutions to the joint boundary value problem of electrodynamics and heat and mass transfer.

The synthesis of working chambers of non-thermal microwave modification is carried out based on solving the boundary value problem of electrodynamics.

When choosing a layout option for microwave electrical installations, technical and economic calculations are used.

The calculating ratios of economic efficiency given in the work allow calculating the influence of the parameters of the installation and its elements on the decisions made regarding the design of the microwave installation.

The research object is the questions of a quantitative assessment of the influence of the materials science parameters of the processed dielectric and the selected structure and elements of the microwave electro-technical installation on the accuracy of the calculation of the working chamber the validity of economic decisions.

When designing modern microwave electrical technology installations, it is recommended to use the developed, published and tested method for solving the agreed boundary value problem of electrodynamics and heat and mass transfer. In microwave electrical technological installations of non-thermal microwave modification for mathematical modelling of the technological process, it is required to formulate a joint boundary-value problem of electrodynamics, strength and heat and mass transfer, and possibly other branches of physics. In the practice of designing installations for non-thermal microwave modification, in our opinion, it is possible not to carry out mathematical modelling of non-thermal microwave modification since it is carried out in a matter of seconds. When designing such installations, it is sufficient to know the required time of non-thermal microwave modification of the polymer, which should be determined experimentally at the design beginning.

The optimal profile of the waveguide is calculated for the average values in the operating temperature range for the experimental parameters ε_2' and $tg\delta_2$, that is, to solve the problem of synthesis of the working chamber, it is necessary to know the dependencies ε_2'(T) and $tg\delta_2$(T), where T is the temperature of the object being processed.

For mathematical modelling of microwave heat treatment of a dielectric, it is required to solve a consistent boundary-value problem of electrodynamics and heat and mass transfer:

$$\begin{gathered} rotH = j + \frac{\partial D}{\partial t};\ rot\mathrm{E} = -\frac{\partial B}{\partial t}; \\ divB = 0;\ divD = 0; \\ \frac{\partial \theta}{\partial t} + v\nabla\theta = k_{11}\nabla^2\theta + k_{12}\nabla^2 U + k_{13}\nabla^2 p + \frac{\mathrm{P}_{UD}}{\mathrm{c}_D\rho_D}; \\ \frac{\partial U}{\partial t} + v\nabla U = k_{21}\nabla^2\theta + k_{22}\nabla^2 U + k_{23}\nabla^2 p; \\ \frac{\partial p}{\partial t} + v\nabla p = k_{31}\nabla^2\theta + k_{32}\nabla^2 U + k_{33}\nabla^2 p \end{gathered} \quad (1)$$

where, H, E are the strengths of the magnetic and electric field of the electromagnetic wave; B, D are the magnetic and electric inductions of the electromagnetic field; j is the conduction current density; U is the specific moisture content of the processed object; p is the pressure of water vapour in the processed object; v is the speed of transportation of the processed object in the working chamber; k_{11}, k_{12}, ..., k_{33} are the heat and mass transfer coefficients; P_{UD} is the specific power absorbed by the processed object; c_D, ρ_D is the specific heat and density of the processed object.

$$\theta = T - T_0 \quad (2)$$

where, T and T_0 are the current and initial temperatures of the processed object.

It is required to know the dependencies $\rho(T, U, p)$ to solve Eq. (1), mathematical modeling of heat treatment of the processed object. The practice has shown that the dependencies $\varepsilon_2'(T,U)$ and $tg\delta_2(T, U)$ have the primary influence on the simulation results. The same profound influence is exerted by ε_2' and $tg\delta_2$ on the synthesis of the working chamber and mathematical modelling of heat treatment in the design of microwave electrical technological installations of thermal microwave modification with working chambers of the beam type or working chambers of the meander type.

It is important to note that approximate values are used in the calculations if in the design of a microwave electrical installation. Their temperature dependence is not taken into account. According to the results of these calculations, the working chamber may have parameters that are far from the specified ones. For this reason, it is advisable to preliminarily conduct material science studies of the material of the processed objects. Measurement issues of ε_2' and $tg\delta_2$ are described, for example, in works [4, 14].

As for the design of microwave electrical installations for non-thermal microwave modification of polymer objects, non-thermal microwave modification is most effective at optimal frequency values f_{opt}, strength E_{opt} in a given waveguide of the working chamber, and the time the polymer is in the electromagnetic field τ_{opt}. For polymer filaments, films and fibres, a given orientation in the electromagnetic field is required. The optimal value of these parameters of non-thermal microwave modification is different for different polymers; there is still no generally accepted physical nature of this phenomenon. Therefore, they should be determined experimentally before designing a microwave installation.

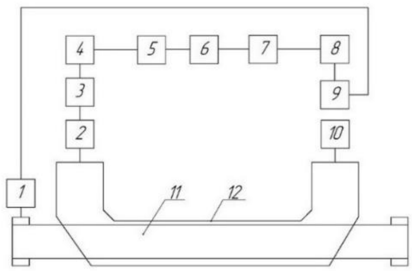

Figure 1. Installation for microwave modification of objects: 1 - electric drive; 2 - reflected power meters; 3 - meter of incoming power; 4 - turns; 5 - variable attenuator; 6 - ferrite valve; 7 - microwave generator; 8 - power supply for the microwave generator; 9 - control unit; 10 - passed power meter; 11 - transport system; 12 - working chamber

It requires special equipment (Figure 1). It is desirable, of course, in this case, to have a broadband microwave generator.

The setup shown in Figure 1 makes it possible to study the effect on the samples of the processed polymer of different tension, processing time, frequency within the operating range of the rectangular waveguide used in the setup. Still, for studies of the non-thermal microwave modification on a broader frequency range, a similar setup probably required a different cross-section and a different broadband microwave generator in the range.

3. STUDY RESULTS

After electronics mastered the microwave range of electromagnetic oscillations, interest in the use of microwave energy was first shown by specialists in the field of food technologies and physicians and biologists who were interested in the results of microwave exposure to humans, animals and microorganisms. And already, the first results of these studies showed their dependence on the structure, properties and parameters of dielectrics processed in the microwave electromagnetic field, the presence of a specific non-thermal microwave modifying effect on polymers and biopolymers.

Experience in the design of microwave electrical installations indicates that the development of a specific microwave electrical installation experimentally takes longer and is more expensive than a design using calculation methods. But the calculated ratios include the parameters of the material of the processed object. In synthesizing the working chamber of a microwave electrical installation, this is especially clearly seen if the calculation is carried out using an equivalent circuit of a transmission line partially filled with a dielectric being processed, on which the working chamber is built. So, for example, if the transmission line is a rectangular waveguide with a flat layer of the processed dielectric on the expansive wall of the waveguide (Figure 2), then the equivalent circuit of such a waveguide has the form shown in Figure 3.

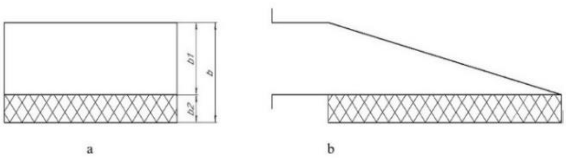

Figure 2. Rectangular waveguide partially filled with a machined dielectric: a - cross-section; b - longitudinal section

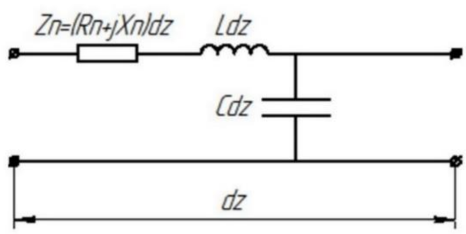

Figure 3. Equivalent diagram of a rectangular waveguide with a layer of the processed dielectric on the expansive walls of the waveguide

The linear parameters of this equivalent circuit are:

$$R_n = \frac{60\pi^2 R_F}{a\left[1-\left(\frac{\lambda}{2a}\right)^2\right]\sqrt{\varepsilon_2'\sqrt{1+tg^2\delta_2}}}$$

$$X_n = \frac{60\pi^2 R_X}{a\left[1-\left(\frac{\lambda}{2a}\right)^2\right]\sqrt{\varepsilon_2'\sqrt{1+tg^2\delta_2}}}$$

$$\mathrm{C} = \frac{a}{60\pi^2 c b_1}\left[1-\left(\frac{\lambda}{2a}\right)^2\right] \tag{3}$$

$$L = \frac{60\pi^2 b_1}{ca}$$

where, λ is the wavelength of the microwave generator; a is the width of the expansive wall of the waveguide; b_2 is the thickness of the processed dielectric layer; b_1 is the thickness of the air layer above the dielectric being processed; t_c is the light speed; ε_2' and $tg\delta_2$ are the dielectric parameters of the processed dielectric.

The dependencies F_R and F_X from $\frac{b_1}{\lambda}\sqrt{\varepsilon_2'\sqrt{1+tg^2\delta_2}}$ and $tg\delta_2$ are shown in Figure 4.

A travelling-wave working chamber with a waveguide profile built on such a transmission line:

$$b(z) = b_2 + \frac{a_1\sqrt{1-\left(\frac{\lambda}{2a}\right)^2}}{60\pi^2}\left[-\frac{\Lambda}{4\pi}X_{PR} + \sqrt{\left(\frac{\Lambda}{4\pi}\mathrm{X}_{PR}\right)^2 + (R_{PR}Z)^2}\right] \tag{4}$$

where, R_{PR}, X_{PR} are the values R_n and X_n taken as calculated for the selected length of the layer of the processed object, has a uniform absorption of microwave power along the length of the processed dielectric. That is, uniform heat treatment and ideal matching with the microwave generator; that is, the efficiency of the working chamber for the use of microwave energy (excluding thermal losses) equals 100%. (R_{PR}-R_t, X_{PR}-X_t).

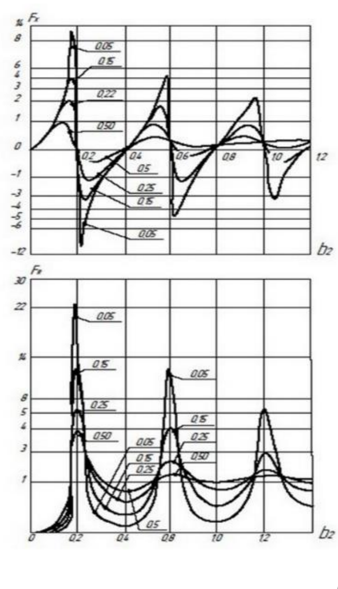

Figure 4. Dependencies F_R and F_X from $\frac{b_1}{\lambda}\sqrt{\varepsilon_2'\sqrt{1+tg^2\delta_2}}$ and $tg\delta_2$

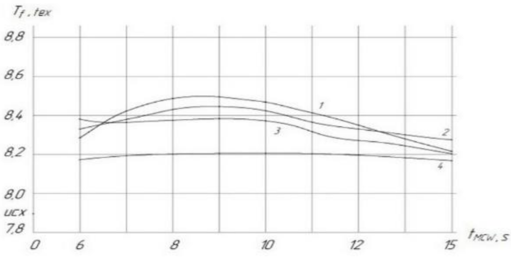

Figure 5. Linear density dependence T_f of polycaproamide threads on the microwave exposure time t_{MCW} at microwave power: 1 - 100 W; 2 - 125 W; 3 - 150 W; 4 -200 W: (initial - polycaproamide thread without microwave exposure)

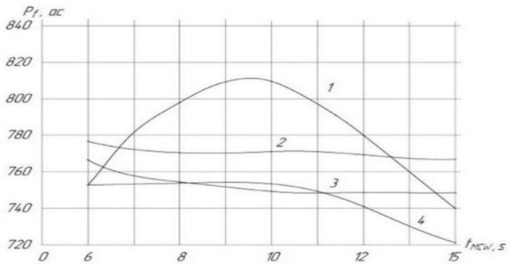

Figure 6. Dependence of the breaking load P_f of polycaproamide filaments on the microwave time t_{MCW} exposure at microwave power: 1 - 100 W; 2 - 125 W; 3 - 150 W; 4-200 W: (initial - polycaproamide thread without microwave exposure)

The results of non-thermal microwave modification of polycaproamide filaments are shown in Figures 5 and 6.

The results of designing a microwave electrical installation are influenced not only by ε_2' the material of the processed object but also by the material's structure.

For example, liquid and bulk dielectrics are conveniently processed in working chambers around irregular waveguide with a cylindrical transport channel on the waveguide axis (Figure 7).

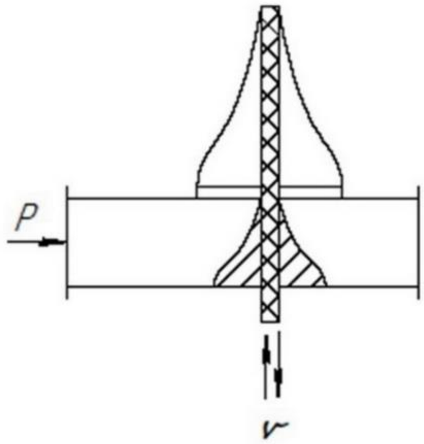

Figure 7. Working chamber with a travelling wave on an irregular circular waveguide

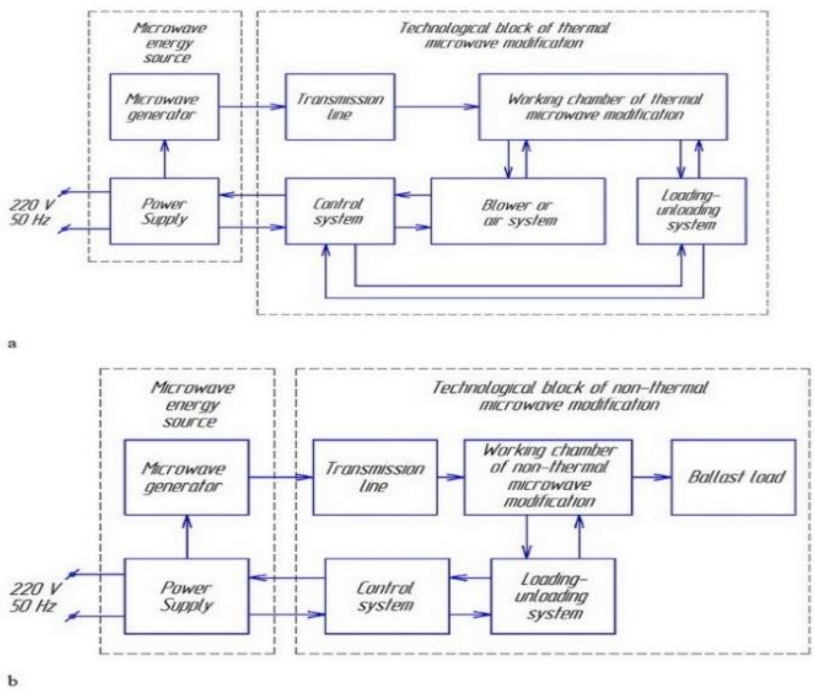

Figure 8. Block diagram of a microwave electrical installation with a hybrid-type working chamber: a - technological unit of thermal microwave modification; b - technological block of non-thermal microwave modification

The previous makes it possible to formulate the material science aspect of designing microwave electrical installations for thermal and non-thermal microwave modifications:

- the results of solving the problem of synthesis and mathematical modelling of the technological process of an electro-technical microwave installation are decisively influenced by the parameters of the object being processed when heated; these are primarily dependencies $\varepsilon_2'(T)$ $tg\delta_2(T)$ and when drying $\varepsilon_2'(T, U)$ and $tg\delta_2(T, U)$;

- before designing a microwave electrical technological installation of a thermal microwave modification, it is necessary to determine the dependencies $\varepsilon_2'(T)$ and $tg\delta_2(T)$ or $\varepsilon_2'(T, U)$ and $tg\delta_2(T, U)$ the sensitivity of the solution to the problem of synthesis and mathematical modelling and the accuracy of setting these dependencies in the calculations during the design is established, and therefore the use of approximate dependencies ε_2' and $tg\delta_2$ in the design and usually leads to the need for experimental revision the designed working chamber;

- systematic mathematical studies of non-thermal microwave modification of polymers should be continued to build a physical picture of this technological process and construct its mathematical model. Still, microwave electro-technical installations of non-thermal microwave modification implement non-thermal microwave modification, as a rule, not in the optimal model.

Further, when designing an electro-technical microwave installation, making decisions on various highly controversial issues is necessary. Examples of such situations:

- some serial materials for technological purposes have an efficiency less than attainable; an increase in efficiency will increase the energy efficiency of a microwave electrical installation but will reduce economic efficiency due to an increase in the price of a magnetron;
- to reduce the price of a microwave electro-technical installation of a thermal microwave modification, the power supply unit of a microwave generator is sometimes assembled without a rectifier so that the microwave energy source operates in a pulsed mode, which reduces the performance of the installation;
- in the working chamber of the beam type, it is recommended to use a quarter-wave matching transformer to match the processed object with the microwave generator, but this will increase the price of the installation;
- to reduce the cost of an installation with a beam-type working chamber, it is possible to abandon the use of a horn emitter, but reflections from such a chamber will increase, that is, its energy efficiency will decrease;
- A microwave electro-technical installation with a hybrid-type working chamber (Figure 8) simultaneously produces two types of products, one of which is a dielectric that has undergone a thermal microwave modification.

The second is a polymer that has undergone a non-thermal microwave modification. Still, if you increase the power of the microwave generator, use a power divider, it is possible to obtain two modified different polymers and two modified different dielectrics in one installation. Still, the installation owner will have the task of selling these products on the product market.

These and other questions of designing microwave electrical installations can be answered using economic calculations in the design of these installations. For this, a comparative economic effect should be used (comparison of economic efficiency (net discounted income) of the compared options, calculated over the same time or interval).

$$\Delta E_{\Sigma} = E_{\Sigma 2} - E_{\Sigma 1} \tag{5}$$

where, $E_{\Sigma 1}, E_{\Sigma 2}$ is the net present value of the options being compared.

$$E_{\Sigma 1,2} = P_{1,2} - Z_{1,2} \tag{6}$$

where, $P_{1,2}$ is the profit of the compared options; $Z_{1,2}$ are the costs of the compared options on an interval of one year.

If $E_{\Sigma} > 0$, then it is advisable to accept the second option, and if $E_{\Sigma} < 0$, then the first option should be accepted.

If we see:

$$E_{\Sigma} = E_{\Sigma CONST} - E_{\Sigma VAR} \tag{7}$$

where, $E_{\Sigma CONST}$ is the constant part E_{Σ}; $E_{\Sigma VAR}$ is the variable part.

Then you can find the global minimum $E_{\Sigma VAR}$, that is $E_{\Sigma VAR.MIN}$, from the ratio:

$$\frac{\partial E_{\Sigma VAR}}{\partial x_1} = 0; \frac{\partial E_{\Sigma VAR}}{\partial x_2} = 0; \frac{\partial E_{\Sigma VAR}}{\partial x_n} = 0 \tag{8}$$

We obtain conditions under which:

$$E_{\Sigma MAX} = E_{\Sigma CONST} - E_{\Sigma VAR.MIN} \tag{9}$$

And from these conditions, it is possible to find the parameters of the microwave energy source of the microwave electrical installation, as well as the microwave power, the frequency of the microwave energy source, productivity, that is, the number of installations operating in parallel to ensure a given production volume. In (8) x_1, x_2, ..., x_n are independent variables $Э_{\Sigma}$.

It should be noted that when designing microwave electrical technological installations of non-thermal microwave modification, it is not required to solve the system of Eq. (8). The parameters of the microwave energy source in these installations are set to ensure the technological process of non-thermal microwave modification of a polymer object, at optimal values of tension, frequency, and time modifications τ_{opt}.

It is not necessary to solve the Eq. (8) for the same reason when designing a microwave electro-technical installation with a hybrid-type working chamber. Still, suppose this installation is designed to use a powerful microwave energy source and a microwave power divider in order to increase the volume and range of products. In that case, the practicality of such a solution must be verified using relation (5).

It must be said that, in our opinion, economic calculations in the design of microwave electrical installations are not used as often as they should be. Therefore, it is helpful to formulate the economic aspect of designing microwave electrical installations:

-when designing microwave electrical installations, situations often arise when it is necessary to make this or that decision, for which there are no technical grounds;

- in the absence of technical grounds for deciding on one or another element of the installation, a variant of the technological process for the layout of a microwave electro-technical installation, one should be guided by the result of comparing the economic effects of the compared options for the upcoming decision;
- the conditions for achieving the maximum profit from the operation of the designed microwave electro-technical installation allow choosing the optimal parameters of the microwave energy source of the installation, at which this profit is maximum.

Like all electrical technology as a whole, microwave electrical technology is, as they say, at the junction of scientific and technological and socio-economic areas. Therefore, the design of microwave electrical technology installations will be the more successful, the more successful the cooperation of electro-technologists with materials scientists, economists and sociologists. Sociologists will determine the consequences of a decision made, which will improve the technical characteristics of the installation and an increase in prices for both the installation and the manufactured products to maintain or increase the economic efficiency of the installation.

In this case, it would be appropriate to talk about the social aspect of designing a microwave electro-technical installation, but this issue is already in the competence of sociologists.

4. COMPARISON

The feasibility study of the decisions made in microwave electrical technology in one or another fragment is considered in the works of the Saratov school of microwave electrical technology. In this paper, economic aspects are considered in unity with materials science issues for the first time. Such a systematic approach provides a complete and objective consideration of interrelated issues in the design of microwave electrical installations.

In the design of microwave electrical installations, materials science and economic aspects play a significant (central) role. Let us compare the two lines of the behaviour of the installation designer: these aspects are ignored or taken into account. In the first case, the technical calculations of unreliable values of the processed object's material science parameters will first lead to the need for experimental refinement of the working chamber of the electrotechnical microwave installation. It will lead to additional costs of time and money for the development of the installation.

Suppose we do not compare the cost-effective options for the decisions made in relation to the application of certain technical and structural solutions. In that case, the manufactured installation may not meet the standard requirements, and its use may be simply inappropriate.

Practical consideration in the design of microwave electrical technology installations of material science and economic aspects increases the likelihood of satisfying the specified parameters of the microwave electrical installation, manufactured based on the results of solving problems of synthesis, mathematical modelling and design of such an installation.

5. CONCLUSIONS

The information presented in work on the design of working chambers with a travelling wave for microwave electrical installations implementing thermal microwave modification of dielectrics indicates the decisive influence of dielectric parameters and material of the processed object on the solution of the problem of synthesis of a chamber coordinated with the microwave generator and uniformly heating the modified dielectric and on the results mathematical modelling of the process of heat treatment of the processed object in this working chamber.

When designing a microwave electrical installation for a non-thermal microwave modification of a polymer, due to the lack of a mathematical model of any technological process of microwave exposure to a polymer object of processing, it is not possible to carry out reliable mathematical modelling of the technological process, by calculation to determine the optimal values, and, so that to achieve maximum economic efficiency during the operation of such a facility, an experimental study of the conditions for an effective non-thermal microwave modification is required.

When designing microwave electrical installations, questions regularly arise about using one or another structural element, one or another structure of the installation. It is proposed to make decisions on these issues based on the results of economic calculations, and this makes the economic aspect of designing a microwave electrical installation relevant.

Ignoring the material science and economic aspects of the design of an electrotechnical microwave installation can lead to the manufacture of an installation based on the design results that do not meet the planned requirements, which may make the use of such an installation inappropriate. It will lead to a loss of time and money spent on designing and manufacturing a microwave electrical installation of a non-thermal, thermal microwave modification or an installation with a hybrid-type working chamber.

6. PRACTICAL APPLICATION OF RESEARCH RESULTS

Practical consideration in the design of microwave electrical technology installations of material science and economic aspects increases the likelihood of satisfying the specified parameters of the microwave electrical installation, manufactured based on solving synthesis problems, mathematical modelling and design of such an installation.

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