Technical and economic aspects of designing a hybrid microwave electrotechnological installation for processing biological substrates and plant raw materials

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Abstract. The paper presents an algorithm for designing a hybrid microwave electrotechnological installation for processing biological substrates and plant material. The feasibility of designing a hybrid microwave electrotechnological installation is considered on the basis of comparative economic effects. A technical and economic optimization of the structure and parameters of a hybrid microwave electrotechnological installation for non-thermal processing of biological substrates and thermal processing of plant material was carried out. Purpose of the study: To conduct a feasibility study for the design of a hybrid microwave electrotechnological installation for processing biological substrates and plant raw materials. Methodology: The design and development of a hybrid microwave electrotechnological installation for thermal processing of plant material and non-thermal processing of biological substrates is based on the solution of a consistent boundary value problem of electrodynamics and heat and mass transfer. Results: The design algorithm and methodology for technical and economic calculation of a hybrid microwave electrotechnological installation for processing biological substrates and plant material are presented.

1 Introduction

Ultrahigh-frequency electrotechnological installations, using the energy of microwave electromagnetic oscillations, are capable of carrying out thermal microwave modification of plant material, as a result of which its properties and parameters change faster and more uniformly than when heat is transferred by thermal conductivity, convection, and thermal radiation [14].

In recent years, attention has been drawn to research and publications in the field of the use of microwave energy in various industries: microwave processing of lumber [8, 16], microwave drying of agricultural products [10, 12], disinfection of food products with microwave energy [13], microwave drying food products [9, 11], microwave drying of wood [1, 15], the effect of microwave radiation on the properties of polymers [5, 18],

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mathematical modeling of technological processes in a microwave electromagnetic field [7, 17], design of microwave electrical technological installations with working chambers hybrid type [15].

The combination of two technological processes in one hybrid microwave electrotechnological installation allows for simultaneous non-thermal modification of biological substrates and thermal modification of plant material.

When designing a hybrid microwave electrotechnological installation, questions arise about the use of one or another design element, one or another structure of the installation. It is proposed to make decisions on these questions based on the results of technical and economic calculations.

Ignoring the technical and economic aspect of designing a hybrid microwave electrotechnological installation may lead to the production, based on the design results, of an installation that does not meet the planned requirements for it, which is why the use of such an installation may be inappropriate. This, in turn, will lead to losses of time and money spent on the design and manufacture of a hybrid microwave electrotechnological installation for non-thermal processing of biological substrates and thermal processing of plant material.

Thus, practical consideration of technical and economic calculations at the design stage of a hybrid microwave electrotechnological installation increases the likelihood of satisfying its specified parameters and design features.

2 Materials and methods

With thermal microwave modification, the controlled parameter is temperature. To calculate it, you must use the heat conduction equation:

\[ \frac{\partial \theta}{\partial t} + v \nabla \theta = a_o \nabla^2 \theta + \frac{P_{\text{vol}}}{c_o \rho_o} \]

\[ \theta = T - T_0 \]

Where; \( T \) temperature of the processed material; \( T_0 \) – ambient temperature; \( v \) – speed of transportation of the processed material in the working chamber; \( a_o \) – thermal diffusivity coefficient of a biological substrate; \( c_o, \rho_o \) – specific heat capacity and density of biological substrate.

\[ P_{\text{vol}} = 0.5 \omega \varepsilon_0 c_t \tau / |E| \]

Where \( \omega \) – is the circular frequency; \( \varepsilon_0 \) – absolute dielectric constant; \( c_t, \tau \) – relative dielectric constant and dielectric loss tangent of the processed material; \( E \) – electric field strength of an electromagnetic wave.

During thermal microwave modification, the processed material is heated not only due to polarization, but also due to conductivity. From a macroscopic point of view, these heat releases are indistinguishable from each other, and therefore are presented in the form:

\[ \varepsilon = \varepsilon' - j \varepsilon'' = \varepsilon' (1 - j \tau \delta) \]
Where $\varepsilon'_a, \varepsilon''_a$ – is the real and imaginary parts of the absolute dielectric constant of the processed medium; $\sigma$ – specific conductivity of the medium; $\omega$ – circular frequency.

\[
\varepsilon'_a = \frac{\varepsilon''_a}{\varepsilon_0} \quad (5)
\]

\[
\varepsilon''_a = \frac{\varepsilon'_a \sigma}{\varepsilon_0 \omega} \quad (6)
\]

The time it takes to heat the processed material to a given temperature depends on the value of $P_{\text{yd}}$. The greater $P_{\text{yd}}$ is, the shorter this time is, and, in turn, the greater the frequency of electromagnetic oscillations $f$ and the electromagnetic field strength $E$ in the working chamber, the greater $P_{\text{yd}}$ is.

The value of $E$ is found by solving Maxwell’s equations for a certain design of the working chamber, that is, for the corresponding boundary conditions [4]:

\[
\begin{align*}
\text{rot} H &= \frac{\partial D}{\partial t} ; \\
\text{rot} E &= \frac{\partial B}{\partial t} ; \\
\text{div} B &= 0 ; \\
\text{div} D &= 0 ,
\end{align*} \quad (11)
\]

Where $E, H$ – is the electric and magnetic intensity of the electromagnetic wave (case $j = 0$ – absence of conduction current);

\[
D = \varepsilon E \quad (12)
\]

\[
B = \mu H \ (\mu = 1) \quad (13)
\]

The prospects for the use of thermal microwave modification of biological substrates and plant material are stimulated by a number of reasons:

- Intensification of the technological process of heat treatment due to volumetric heating.
High quality of the technological process of heat treatment both due to greater uniformity of heating and due to the absence of contamination of the treated object during the heating process.

Precision control of the technological process of heat treatment due to the possibility of precise dosing of the value supplied to the working chamber of microwave power.

Reducing the harmful impact on the environment and improving working conditions for service personnel.

It should be noted that electricity is most promising for industrial heating.

3 Research results

Technical and economic calculations at the design stage make it possible to determine the optimal structure and parameters of a hybrid microwave electrotechnological installation for processing biological substrates and plant material.

The following indicators are used for technical and economic calculations:

- **Integral effect or net present value:**
  \[
  \mathcal{E}_T = \sum_{t=0}^{T} \sum_{j=1}^{n} (H_j, H_j) + H_j + S_j + M_j - 3_t \left[ (1 + E)^{-t} + \Phi_t (1 + E)^{-t} \right]
  \] (14)

  Where \( H_j, H_j \) is the quantity and price of a unit of the j-th product produced by the installation at the t-th calculation step; \( n \) — number of types of products on the calculation horizon \( T \); \( H_j \) — cost assessment of the accompanying effect in the production sector at the t-th step; \( S_j \) — cost assessment of the social effect at the t-th step; \( M_j \) — residual value of fixed assets of production infrastructure excluded from operation at the t-th step; \( 3_t \) — operating costs of the installation, including taxes and payments at the t-step; \( E \) — discount rate; \( \Phi_t \) — residual value of fixed assets at the time of \( T \), or:
  \[
  \mathcal{E}_T = \sum_{t=0}^{T} (R_t - 3_t)(1 + E)^{-t}
  \] (15)

  Where \( R_t \) — is the result achieved at the t-th calculation step; \( 3_t \) — costs incurred at the t-th calculation step; \( R_t - 3_t \) — the effect achieved at the t-th calculation step.

- **Profitability index:**
  \[
  H_\Phi = \frac{1}{K} \sum_{t=0}^{T} (R_t - 3_t^*)(1 + E)^{-t}
  \] (16)

  Where \( 3_t^* \) — are the costs at the t-th step of the calculation without taking into account capital investments; \( K = \sum_{t=0}^{T} K_t (1 + E)^{-t} \) — the amount of discounted capital investments;

- **Internal rate of return (discount rate \( E_{BH} \), at which the magnitude of the reduced effects is equal to the reduced capital investments).**
Payback period \( \tau_{\text{co}} \) (period measured in months, quarters or years, starting from which initial investments and other costs associated with the development and implementation of technological equipment are paid off by the total result of operation).

The design algorithm for a hybrid microwave electrotechnological installation for processing biological substrates and plant material is shown in Figure 1.

When designing a hybrid microwave electrotechnological installation, the following indicators must be determined and calculated:

- Feasibility of design.
- Parameters and processing mode.
- The optimal number of hybrid microwave electrical technological installations, ensuring maximum profit over the interval of a year of operation.
- Dimensions of the working chamber for thermal microwave modification of the processed plant material.
- Electric drive, if the working chamber of the thermal microwave modification operates in the methodical mode.
- Mathematical modeling of the technological process in the working chamber of thermal microwave modification.
- Dimensions of the working chamber for non-thermal microwave modification of the processed biological substrate.
- Electric drive, if the working chamber of the non-thermal microwave modification operates in the methodical mode.
- Mathematical modeling of the technological process in the working chamber of non-thermal microwave modification.
- Economic effect of the final version of the hybrid microwave electrotechnological installation.

The design ends with the preparation of technical specifications for the construction of a hybrid microwave electrotechnological installation.

When choosing the initial version of a hybrid microwave electrotechnological installation, one should focus on the simplest layouts; the main attention at this stage should be paid to the choice of the type and dimensions of the waveguide, on the basis of which the technological blocks of the hybrid microwave electrotechnological installation will be built, based on the geometry of the objects that will be processed in the working chambers of these technological blocks, for example, biological substrates and plant material.

The greatest difficulty is in determining the parameters of the processed objects and their processing modes. Thus, to design a hybrid microwave electrical technological installation, you need to know not only what kind of biological substrate will be processed, but also with what productivity, with what geometric dimensions, you need to know the relative dielectric constant \( \varepsilon' \), the dielectric loss tangent \( \tan \delta \), the dependence of these parameters on temperature and humidity (moisture content), the specific heat capacity \( c \) and density \( p \) of the treated substrate.

Non-thermal microwave modification of biological substrates has been studied less than thermal microwave modification of plant material. There is often no information about at what value of the electromagnetic field strength \( E \) in the working chamber of the non-thermal microwave modification of a biological substrate, changes in its structure and parameters properly occur. There is no information on how long there should be a non-thermal microwave modification at frequency \( f \) and at electromagnetic field strength \( E \).
Fig. 1. Algorithm for designing a hybrid microwave electrotechnological installation for processing biological substrates and plant material.
At the design stage, the question of the feasibility of using a hybrid microwave electrotechnological installation should be answered. This can be done by comparing a hybrid microwave electrotechnological installation with any alternative installations that produce non-thermal and thermal modification of biological substrates and plant material. But there is not yet an alternative to an installation that carries out non-thermal treatment of biological substrates outside the microwave electromagnetic field, so a hybrid microwave electrotechnological installation can be compared with a microwave electrotechnological installation for non-thermal influence on a biological substrate. And this is the first option for resolving the issue of the feasibility of using a hybrid microwave electrotechnological installation.

Secondly, a hybrid microwave electrotechnological installation can be compared with a microwave electrotechnological installation for thermal effects on plant material.

Thirdly, a hybrid microwave electrotechnological installation can be compared with two microwave electrotechnological installations, one of which carries out only non-thermal microwave modification, and the other - thermal microwave modification. The comparison parameter in a market economy should be economic efficiency (net present value); the decision on the advisability of using a hybrid microwave electrotechnological installation is made based on the results of calculations of comparative economic effects

\[ \Delta \mathcal{E}_{\text{r-H}} = \mathcal{E}_{\text{r}} - \mathcal{E}_{\text{H}}; \]
\[ \Delta \mathcal{E}_{\text{r-T}} = \mathcal{E}_{\text{r}} - \mathcal{E}_{\text{T}}; \]
\[ \Delta \mathcal{E}_{\text{r-H+T}} = \mathcal{E}_{\text{r}} - \mathcal{E}_{\text{H}} - \mathcal{E}_{\text{T}}. \]

Where \( \Delta \mathcal{E}_{\text{r-H}} \) – is the comparative economic effect when comparing a hybrid microwave electrotechnological installation and a microwave electrotechnological installation of non-thermal modification; \( \Delta \mathcal{E}_{\text{r-T}} \) – comparative economic effect when comparing a hybrid microwave electrotechnological installation and a microwave electrotechnological installation of thermal modification; \( \Delta \mathcal{E}_{\text{r-H+T}} \) – comparative economic effect when comparing a hybrid microwave electrotechnological installation and a microwave electrotechnological installation of non-thermal microwave modification, as well as a microwave electrotechnological installation of thermal modification; \( \mathcal{E}_{\text{r}} \) – net profit of a hybrid microwave electrotechnological installation; \( \mathcal{E}_{\text{H}} \) – net profit of a microwave electrotechnological installation of non-thermal modification; \( \mathcal{E}_{\text{T}} \) – net profit of a microwave electrotechnological installation of thermal modification.
\[ \mathcal{E}_\sum \gamma = \{(\Pi_t - \Pi_h - C_{CT}) \cdot (1 - \gamma_{hi}) - (C_{\text{EMET}} + C_{\text{EMBT}} + C_{\text{EBT}}) \cdot (1 - \gamma_h) - C_{\text{CMET}}(1 - \gamma_h - \gamma_{hi}) - (K_{\text{INP}} + K_T + K_{\text{TPP}} + K_{TB}) \left[ 1 + i_k + \gamma_{hm} + (\gamma_{ch} + \gamma_A)(1 - \gamma_h) \right] \} (1 - \gamma_s) \]

Where \( \Pi_t, \Pi_h \) – is the annual productivity of the microwave electrotechnological installation of thermal and non-thermal modification; \( \Pi_t, \Pi_h \) – unit prices for microwave electrotechnological installations of thermal and non-thermal modification; \( C_{CT}, C_{CH} \) – costs of raw materials for microwave electrotechnological installations, thermal and non-thermal modification; \( C_{\text{EMET}}, C_{\text{EMCH}}, C_{\text{EBT}} \) – costs of electricity consumed by the energy source in a hybrid microwave electrotechnological installation, in a microwave electrotechnological installation of non-thermal and thermal modifications; \( C_{\text{CMET}}, C_{\text{CMH}}, C_{\text{CBT}} \) – water costs in a hybrid microwave electrotechnological installation, in a microwave electrotechnological installation of non-thermal and thermal modifications; \( K_{\text{INP}}, K_{\text{INM}}, K_{\text{ITG}} \) – investments in a source of microwave energy in a hybrid microwave electrotechnological installation, in a microwave electrotechnological installation of non-thermal and thermal modifications; \( K_h, K_t \) – investments in working chambers in a microwave electrotechnological installation of non-thermal and thermal modifications; \( K_{\text{INP}}, K_{\text{TPP}} \) – investments in microwave electric drives for electrotechnological installations of non-thermal and thermal modifications; \( K_{TB}, K_{TB} \) – investments in the water supply system of a hybrid microwave electrotechnological installation, microwave electrotechnological installation of non-thermal and thermal modifications; \( \gamma_h, \gamma_{hi} \) – coefficients taking into account taxes on profits and value added; \( \gamma_{hi} \) – coefficient taking into account salary accruals; \( i_k \) – bank interest; \( \gamma_{hm} \) – coefficient taking into account property tax; \( \gamma_{ch} \) – coefficient taking into account deductions for spare parts (reservation); \( \gamma_s \) – coefficient taking into account the payment of dividends.

If the comparative economic effect calculated according to (18) taking into account (19) is positive, the return on investment period should be calculated

\[ \tau_{BIH} = \frac{K}{\mathcal{E}_\sum \gamma} \]

Where \( \tau_{BIH} \) – is the time of return on investment made in the project of a hybrid microwave electrotechnological installation; \( \mathcal{E}_\sum \gamma, \mathcal{E}_\sum \gamma \) – net present value (profit, economic efficiency) over the one-year interval obtained during the operation of a hybrid microwave electrotechnological installation; \( K \) – total investments in a hybrid microwave electrotechnological installation.

\[ \tau_{BIH} \leq \tau_{BIH} \]

Where \( \tau_{BIH} \) – is the specified (selected) return on investment period expressed in years.

If the condition is met, then the development and implementation (application) of a hybrid microwave electrotechnological installation is advisable.
If the comparative economic effects calculated by (18) taking into account (19) are negative, then the development and use of a hybrid microwave electrical technological installation with the given initial data of the problem is impractical.

Note that you can try to adjust the initial data of the project so that its implementation is still feasible.

When carrying out calculations regarding the feasibility of designing a hybrid microwave electrotechnological installation, it will be necessary to collect information about the economic parameters (characteristics) of the elements participating in the project (microwave generator, its power source, working chambers, prices of electricity, water, electric drives, etc.). Design experience shows that this is not easy to do; moreover, the determination of feasibility is carried out at a stage when the technical and economic optimization of the installation has not yet been carried out, therefore the result of calculating the feasibility of a hybrid microwave electrotechnological installation is to a certain extent indicative.

When performing technical and economic optimization of a hybrid microwave electrotechnological installation, the net present value (integral effect, economic efficiency) defined by relation (18) should be used as the objective function.

Let's imagine \( \varnothing \) as follows:

\[
\varnothing = \varnothing_{\text{const}} - \varnothing_{\text{var}}
\]  

(22)

Where \( \varnothing_{\text{const}} \), \( \varnothing_{\text{var}} \) is the constant and variable parts \( \varnothing \).

Then finding \( \varnothing_{\text{max}} \) is reduced to finding the conditions under which \( \varnothing_{\text{var}, \text{min}} \), so that the structure and parameters of a hybrid microwave electrotechnological installation that has maximum economic efficiency are determined.

Technical and economic optimization of a hybrid microwave electrotechnological installation comes down to solving a system of equations where is the constant and variable parts.

\[
\frac{\partial \varnothing_{\text{var}}}{\partial x_1} = 0; \\
\frac{\partial \varnothing_{\text{var}}}{\partial x_2} = 0; \\
\frac{\partial \varnothing_{\text{var}}}{\partial x_n} = 0,
\]

(23)

Where \( \varnothing_{\text{var}} \) is determined using relations (18) and (19);

\( x_1, x_2, \ldots, x_n \) — independent parameters on which depends \( \varnothing_{\text{var}} \), that is, the global minimum of dependence is determined \( \varnothing_{\text{var}, \text{min}} = \varnothing_{\text{var}}(x_1, x_2, \ldots, x_n) \).

\( \varnothing_{\text{var}} \) also depends on standard and dependent parameters. The standard parameters when calculating \( \varnothing_{\text{var}} \) do not vary; in all cases they remain specified. Dependent parameters in calculations must be determined through independent parameters. Independent parameters in problems of technical and economic optimization of a hybrid
microwave electrical technological installation are usually the number of microwave generators $M$ in one installation, microwave power $P$ and frequency $f$ (wavelength $\lambda$) of the microwave generator [2, 6], and if $M$ and $P$ are included in the expression $\mathcal{E}_{\sum_{\text{var}}}$ in explicitly, then there is no $f$. As a first approximation, we can assume that [3].

$$V \approx \lambda^3; \quad S \approx (3-6)\lambda^2$$  \hspace{1cm} (24)

Where $V$ and $S$ are the volume and surface of the heated biological substrate.

In conditions of free prices during technical and economic calculations, such dependent parameters of the problem as prices for installation elements pose a big problem. Analytical dependences of these parameters on other parameters, strictly speaking, are impossible, but it is possible to imagine these prices in such a dependence on the independent parameter $P$.

$$\Pi = aP^2 + bP + c$$  \hspace{1cm} (25)

Where $a$, $b$, $c$ are constants [2].

A similar method for calculating optimal parameters and selecting the optimal structure of a hybrid microwave electrical technological installation is used in the design of microwave electrical technological installations of thermal modification [2], and it is shown that by analyzing the structure of $\mathcal{E}_{\sum_{\text{var}}}$, in relation (22), it is possible to find the conditions for achieving $\mathcal{E}_{\sum_{\text{max}}}$, that is, to optimize the hybrid microwave electrical installation without resorting to solving the system of equations (23).

Of course, optimization of a hybrid microwave electrotechnological installation has its own characteristics. Thus, if non-thermal microwave modification is permissible at any intensity $E$ in the working chamber of non-thermal microwave modification, then optimization can be carried out using the given method. If the non-thermal microwave modification can be performed only at a given value $E_3$ in the working chamber of the non-thermal microwave modification, then the power of the microwave generator (microwave energy source) is selected taking into account the cross-section of the waveguide in the working chamber of the non-thermal microwave modification such that in this waveguide $E = E_3$.

The frequency of the microwave energy source is selected from those permitted for use in microwave electrical technology, at which the effect of non-thermal microwave modification takes place. The length of the homogeneous waveguide of the working chamber is selected such that the voltage at its input is $E_3 + \Delta E_3$, and at the output $E_3 - \Delta E_3$, that is:

$$E_3 - \Delta E_3 = (E_3 + \Delta E_3)e^{-2\alpha l}$$  \hspace{1cm} (26)

Where $\Delta E_3$ is the permissible deviation of the relative stresses $E$ from $E_3$; $l$ — length of the working section of the working chamber of non-thermal microwave modification; $\alpha$ — attenuation coefficient of an electromagnetic wave propagating in the working chamber.
4 Practical application of research results

When performing technical and economic optimization of a hybrid microwave electrotechnological installation, there is a specific task. When operating such an installation, the manufacturer receives two different products. Of course, he is interested in a plant that produces two types of products that are equally necessary for the manufacturer. Let's say both products are further used in the production of a third type of product, which the manufacturer supplies to the commodity market. In this case, when designing such a hybrid microwave electrotechnological installation, the performance of technological blocks of non-thermal and thermal microwave modifications should be coordinated. The fact is that the length $l$ of the working chamber of a non-thermal microwave modification, calculated from relation (11), is very large, and, as a consequence, the productivity of the working chamber of a non-thermal microwave modification will most likely be greater than required. In this case, the manufacturer has a choice: he can make the non-thermal microwave modification significantly less than $l$ in the working chamber or not do this, in which case he will have at his disposal some of the material that has undergone non-thermal microwave modification, which he can send to the commodity market regardless of the product working chamber of thermal microwave modification.

5 Conclusion

Relation (24) allows you to determine the maximum volume of the biological substrate being processed and, knowing the time required for non-thermal modification, you can calculate the productivity of the working chamber of non-thermal microwave modification.

With non-thermal microwave modification, there is little and no significant change in the microwave power over the length; all of it from the working chamber of the non-thermal microwave modification enters the working chamber of the thermal microwave modification. If, using the synthesis of the working chamber of a thermal microwave modification, this chamber is designed to be perfectly matched to the transmission line, then the plant material is evenly heated. Knowing the power and volume of plant material in this chamber, you can easily calculate the productivity of the working chamber of the thermal microwave modification.

Knowing the productivity of both technological units, it is possible to determine how many parallel hybrid microwave electrical technological installations will be required to ensure the annual production volume. Since there may be several such installations, we should not talk about a hybrid microwave electrotechnological installation, but about microwave equipment for creating a hybrid microwave electrotechnological installation.

The impact on $\Sigma$ of various modifying changes in the layout of a hybrid microwave electrotechnological installation and the feasibility of these changes should be calculated by calculating the comparative economic effect.

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