Mathematical Modelling of Engineering Problems
Vol. 10, No. 2, April, 2023, pp. 412-418
Journal homepage: http://iieta.org/journals/mmep

Application of Microwave Energy in Agriculture

Midhat Tuhvatullin[1*], Yuri Arkhangelsky[2], Rustam Aipov[2], Eduard Khasanov[3]

[1] Department of Power Supply and Automation of Technological Processes, Federal State Budgetary Educational Establishment of Higher Education "Bashkir State Agrarian University", Ufa 450001, Russian Federation
[2] Department of Electric Machines and Equipment, Federal State Budgetary Educational Establishment of Higher Education "Bashkir State Agrarian University", Ufa 450001, Russian Federation
[3] Department of Agricultural and Technological Machines, Federal State Budgetary Educational Establishment of Higher Education "Bashkir State Agrarian University", Ufa 450001, Russian Federation

Corresponding Author Email: midhat.tuhvatullin@mail.ru

https://doi.org/10.18280/mmep.100204

Received: 18 October 2022
Accepted: 12 February 2023

Keywords:
agriculture, hybrid type working chamber, microwave electroheat, microwave electromagnetic oscillations, microwave heating, non-thermal microwave modification

ABSTRACT

The purpose of this research is to modernize microwave dryers for drying agricultural products, where it is simultaneously possible to carry out thermal and non-thermal microwave modifications of objects. The paper considers microwave dryers for processing of both agricultural products (grain processing, pre-sowing seed treatment) and building materials (wood, polymer threads). The possibility of forming a new field based on the use of microwave electrotechnological installations on hybrid-type working chambers is shown, which will allow an agricultural producer to enter the commodity market not only with agricultural produce, but also with polymer materials with new properties obtained with non-thermal microwave modification in microwave electrotechnological installations with a hybrid-type chamber. As a result of the modernization of existing microwave electrotechnological installations, in which only thermal or non-thermal microwave modifications are carried out, and combining them into one microwave electrotechnological installation with a hybrid type chamber, in which thermal microwave processing of agricultural products, wood and non-thermal microwave processing of polymer materials will be carried out simultaneously, will significantly expand the possibilities of using microwave electrotechnology in agriculture.

1. INTRODUCTION

Agriculture provides the population with food, and therefore farm products are important for the domestic and global commodity markets. To ensure the successful functioning of agriculture, specialists of various spheres are involved. Farm products mostly are a dielectric material, for the processing of which it is possible to use microwave energy [1]. The classification of the fields of application of microwave energy in agriculture is shown in Figure 1.

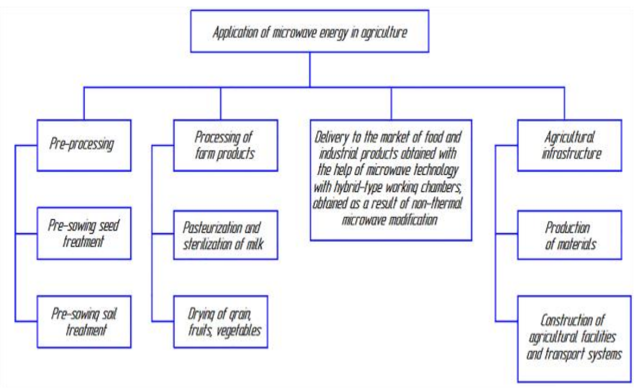

Figure 1. Classification of microwave energy application in agriculture

Technological processes of dielectric media processing, materials and products provide for changing the size, shape, improving the quality of the finished processing object, expanding its scope of application [2, 3]. In microwave electrotechnology, they talk about the modification of dielectrics, meaning physical, chemical and electrophysical modifications [4, 5]. Physical modification is a change in the physical properties of a dielectric by transforming its structure under the influence of physical influences [6].

The possibility and prospects of heating dielectric media, materials and products in an electromagnetic field are well known [7-9]. When polarized in an electromagnetic field, the dielectric absorbs the energy of electromagnetic vibrations and heats up from it. The power absorbed by the elementary volume of the dielectric, which is characterized by the dielectric capacitance and the tangent of the dielectric loss angle, the greater the higher the frequency and power of the microwave energy source [10-12].

The relative dielectric capacitance ε' and the angle of dielectric losses tg δ of dielectrics most often have maximum values in the range of ultrahigh frequencies (microwave). Thus, the so-called microwave dielectric heating (microwave heating) is the most promising [13-15].

Currently, domestic and foreign research in the field of the use of microwave energy in agriculture has become widespread: Microwave drying of corn [16], analysis of microwave drying methods of various rice varieties [17], the effect of microwave treatment on disinfection and stimulation of seed germination [18]; food industry: microwave sterilization of packaged foods [19], microwave sterilization of polymer packaging for food [20] microwave disinfection of food [21], construction: Microwave processing of nanomaterials [1], microwave processing of minerals [4], microwave absorption of multilayer structures based on graphene [22]; woodworking industry: microwave electrotechnological installation for drying rotating timber [12], microwave drying of bamboo in vacuum [5], the effect of microwave radiation on the humidity of various wood species [23]; chemical industry: development of composites with improved properties of absorption of microwave energy [24], production of polymers using the microwave method [25].

But the combination of thermal microwave modification (microwave grain processing, milk pasteurization, microwave wood drying) and non-thermal microwave modification of polymers (polymer filaments, fibres, viscous, bulk polymers, polysulfone films, epoxy resin and compounds) are presented in the research work for the first time.

The advantage of using microwave electrotechnological installations with hybrid type chambers in comparison with microwave electrotechnological installations in which these processes take place separately is an increase in commodity production, which does not lead to an increase in energy costs.

In this research work, the designs of microwave electrotechnological installations for technological purposes are spoken about, which can be used both in agriculture and the food and construction industries. The classification of the fields of application of microwave energy in agriculture is given, containing a new direction related to the use of microwave energy with hybrid type chambers. The working chamber of a hybrid type of microwave electrotechnological installation is a combination of two or more working chambers of non-thermal and thermal microwave modifications. It can produce simultaneously two or more types of products (grain, wood, polymer threads, vegetables, milk pasteurization). This gives significant advantages to this microwave installation with HTC, which microwave installation does not have, in which one type of product is processed.

The purpose of this research is to modernize existing microwave electrotechnological installations for drying farm products, in which, through the use of hybrid-type chambers, it is possible to increase the output of both farm, food and construction products.

In this regard, the following tasks were set:

- to analyze the fields of application of microwave energy in agriculture and give their classification.
- to analyze the designs of microwave electrotechnological installations used in agriculture.
- give examples of microwave electrotechnological installations with hybrid type chambers in which it is simultaneously possible to carry out drying of agricultural, food and construction products.

2. METHODS

When designing microwave electrotechnological installations for agricultural purposes, it is recommended to use the designs and methods of their calculation given for travelling wave cameras in works [9, 26, 27], for a beam-type chamber in works [11, 26, 28]. This information is given in the general context of the presentation of the scientific foundations of microwave electrotechnology.

The main problem of hybrid type chambers (HTC) is the dimensions [29]. They are significantly larger than those of other microwave electrotechnological installations. To a certain extent, this problem can be solved by using combined hybrid-type chambers, in which both microwave modifications are carried out in one chamber. A beam-type chamber (BTC) is most suitable for these purposes.

The calculation of modern HTS is carried out as it is proposed to do for non-thermal and thermal microwave BTC modifications. The modified objects can be moved using separate transport systems both parallel and perpendicular to each other. To simplify and reduce the cost of the design of hybrid-type chambers, it is necessary to limit the microwave electrotechnological installations with HTC on one camera, limiting the parameters that are available in this case for both processed objects.

The greatest difficulty is determining the parameters of the processed objects and their processing modes. So, for the design of microwave electrotechnological installations with hybrid type chambers, it is required to know not only what kind of dielectric and polymer will be processed in them, but also their shape, geometric dimensions, properties such as density, humidity, temperature, heat capacity, capacitance and the tangent of the dielectric loss angle, etc.

When designing and calculating microwave electrotechnological installations with hybrid type chambers, it is necessary to focus on the simplest layouts, the main attention should be paid to choosing the type and dimensions of the waveguide based on which technological blocks of thermal and non-thermal microwave modifications will be built, based on the geometry of objects that will be processed in the working chambers of these technological blocks.

To match the layers of processed dielectrics with a radiating horn (microwave generator), it is recommended to use a matching quarter-wave transformer. When calculating it using the theory of circuits, it is necessary to take into account all the layers that a flat electromagnetic wave radiated by a horn emitter passes through.

In the presented research work, the use of microwave electrotechnological installations with hybrid-type working chambers is limited to agricultural producers who will be able to carry out pre-thermal microwave processing of seeds and agricultural products, pasteurization of milk and non-thermal microwave processing of polymer materials simultaneously.

During the research, the following software was used: A modelling system for creating three-dimensional models and drawings COMPASS-3D v20.

3. RESULTS AND DISCUSSION

If one does not divide into heating and drying zones, it is quite difficult to control the technological process, and, consequently, to ensure the necessary quality of the final product with the necessary parameters.

At the same time, the following disadvantages can be distinguished during microwave drying in a chamber for thermal microwave modification: when heated, it is difficult to control the constant temperature and humidity of the processed material, the microwave effect on the processed product is uneven, with prolonged processing of one type of material, large energy costs arise.

The separation of heating and drying zones makes it possible to most carry out the heating procedure effectively in a microwave electromagnetic field and remove vapours at the evaporation stage (Figure 2).

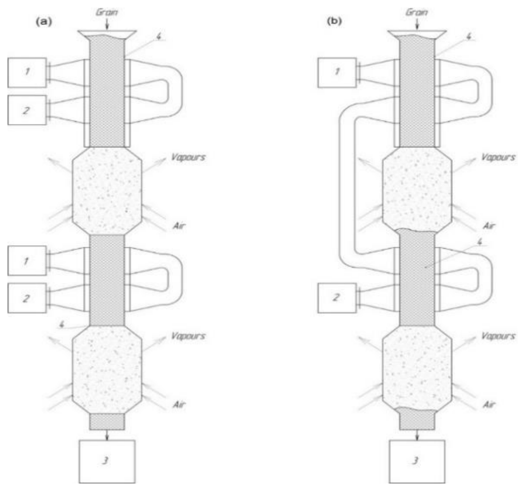

Figure 2. Vertical microwave grain dryers: (a) - on several microwave generators; (b) - on one microwave generator; 1 - microwave generator; 2 - ballast load; 3 - grain hopper; 4 - beam type chambers

The advantage of the presented designs of microwave dryers is their work in a methodical mode since there is no time spent on loading and unloading the processed object. Biological processes of the processed material are activated as a result of a short-term stay in the microwave electromagnetic field, uniform distribution of heat and moisture in the seed stream is ensured. Pathogens of seed diseases are destroyed both on the surface and inside the seeds.

The calculation of different types of microwave dryers has its characteristics, the scientific basis for calculating the microwave electrotechnological installation on the BTC is given in research [10].

Figure 3 shows the design of vertical-horizontal microwave grain dryers. In these microwave dryers, the heating zone is assembled on a vertical BTC, and the drying zone is located horizontally. A system with a transport line and an electric drive is used to move grain in the drying zone. This increases the cost of the microwave dryer but reduces the height of the microwave dryer. When choosing the option of a microwave dryer, comparative technical and economic calculations should be carried out to determine the economic efficiency of these installations.

Fruits, vegetables and grain can be dried in horizontal microwave dryers (Figure 4). In this case, farm products are placed in the transport system on a radio-transparent horizontal sheet along with the microwave dryer, passing through the heating and drying zones, the number of which is calculated taking into account the required productivity, the dielectric parameters of the processed object and the parameters of the microwave generator.

As for pre-sowing seed treatment, we are talking about pre-sowing heating of seeds, which increases their germination. Such processing can be carried out in radio-transparent packages in household microwave ovens. The furnaces are switched on for the time required to heat the package with seeds to the set temperature. With significant volumes of seeds, their heating can be carried out in the heating zone of the microwave grain dryer.

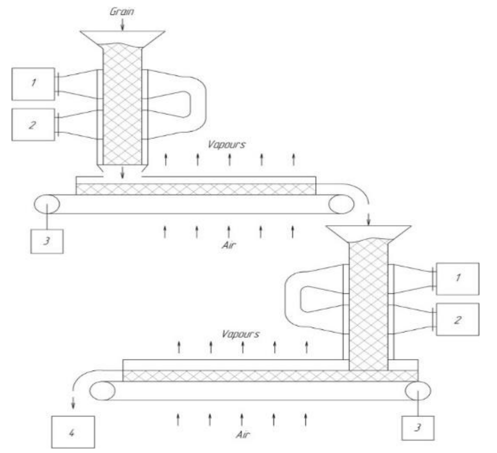

Figure 3. Vertical-horizontal microwave grain dryer: 1 - microwave generator; 2 - ballast load; 3 - electric drive; 4 - grain receiving hopper

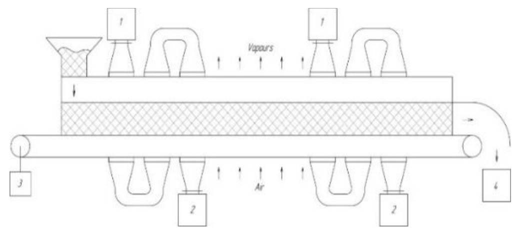

Figure 4. Horizontal microwave grain dryer: 1 - microwave generator; 2 - ballast load; 3 - electric drive; 4 - hopper for processed grain

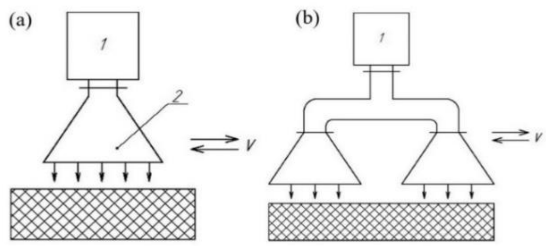

Figure 5. Microwave electrothermal installation for pre-sowing soil treatment: (a) with one horn emitter; (b) with several horn emitters

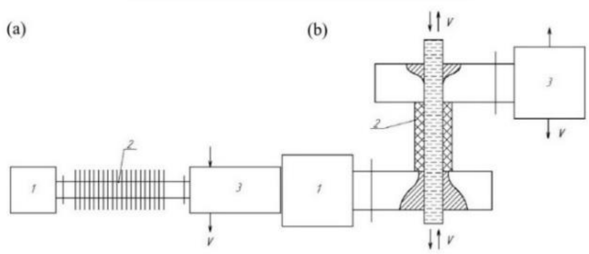

Figure 6. Microwave electrotechnological installation with a hybrid type working chamber: (a) microwave installation with HTC for processing polymer filaments and farm products; (b) microwave installation with HTC for microwave pasteurization of milk and farm products; 1 - microwave generator; 2 - a technological unit of non-thermal microwave modification; 3 - a technological unit of thermal microwave modification

Pre-sowing soil treatment accelerates the germination of weeds that can be removed before sowing. For these purposes, it is convenient to use the so-called BTC with unlimited volume (Figure 5). Methods for calculating such installations are given in works [2, 10].

Such microwave electrotechnological installation should be able to move one or more radiating horns over the treated soil. Calculations for the design of several small installations are given in research [12].

The use of hybrid-type working chambers in the production of farm products makes it possible to expand the capabilities of such installations significantly [30, 31]. Several types of products are processed simultaneously in a hybrid-type chamber [30-32]. In one of the technological blocks of such installations, a non–thermal microwave modification of the polymer is carried out, while in another technological block, a thermal microwave modification of the dielectric is carried out (Figure 6).

The non-thermal modification unit of the microwave installation is a working chamber and a power transmission line, which is a rectangular waveguide, the dimensions of which are determined according to the frequency of the microwave energy source: at 2450 MHz, the waveguide dimensions are 45x90 mm, at 915 MHz – 110x220 mm, and at 433MHz – 250x500 mm. The size of the transmission line, the possible presence of a waveguide rotation is determined by the condition of placement convenience and operation of a microwave electrotechnological installation with a hybrid type chamber.

The working chamber of non-thermal microwave modification serves to impart preferred technological properties to polymer materials (products). To reduce the reflection of the microwave electromagnetic wave from the entrance to the working chamber, it should be carried out on a waveguide of the same cross-section as the transmission line supplying it with microwave energy from a microwave energy source. Since with non-thermal microwave modification, the polymer is in the microwave electromagnetic field for seconds. Such cameras must work in a methodical mode, have holes for loading and unloading the processed object. To prevent microwave radiation through these openings, the working chamber must have loading and unloading gateways, the inner walls of which must be covered with an oxide or carbon film that absorbs microwave radiation well.

Since an exceptionally small proportion of microwave power is spent with a non-thermal microwave modification, the working chamber of a non-thermal microwave modification must be of a pass-through type, that is, the microwave power from this chamber must be supplied to the input of the technological unit of the thermal microwave modification.

The installation shown in Figure 6a supplies to the commodity market, for example, fruits, vegetables and polymer filaments that have been microwave dried, hardened in a non-thermal microwave modification technological unit. The installation shown in Figure 6b supplies two types of farm products to the commodity market: pasteurized milk and fruits and vegetables that have been microwave dried. Such installations are a new class of microwave installation, and their use to expand the possibilities of agricultural production is of great interest.

Finally, in agriculture, microwave energy can be used to implement technological processes in the production of building materials [14].

A microwave electrotechnological installation with a hybrid type working chamber for simultaneous processing of wood and polymer materials is shown in Figure 7.

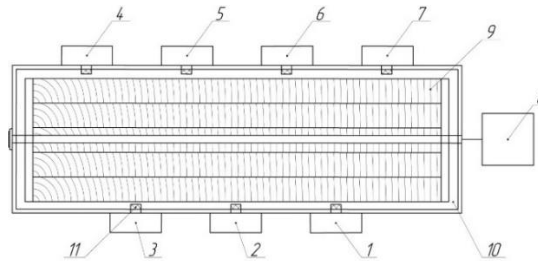

Figure 7. Microwave electrotechnological installation with a hybrid type working chamber: 1...7 - microwave generator; 8 - electric drive; 9 - a stack of timber (dielectric); 10 - working chamber for thermal microwave modification; 11 - zones for non-thermal microwave modification

In addition to thermal microwave modification (drying) of timber, seven technological processes of non-thermal microwave modification of materials such as polymer filaments, fibres, viscous, bulk polymers, polysulfone films, epoxy resin and compounds can be implemented in the installation [4, 33].

In this case, after each of the seven sources of microwave energy, a working chamber should be placed for non-thermal microwave modification of the corresponding polymer. All these microwave installations with HTC should modify polymers in a methodical mode. Each working chamber of non-thermal microwave modification must be designed to process a specific polymer with a given performance.

The expediency of using a microwave electrotechnological installation with a hybrid type working chamber can be explained by net discounted income (integral effect, economic efficiency) E_{Σ}.

Imagine E_{Σ} as follows:

$$E_{\Sigma} = E_{\Sigma const} - E_{\Sigma \mathrm{var}} \quad (1)$$

where, $E_{\Sigma const}, E_{\Sigma \mathrm{var}}$ – the constant and variable parts.

Then the finding $E_{\Sigma \max}$ is reduced to finding the conditions under which $E_{\Sigma \mathrm{var}.min}$ is achieved, so that the structure and parameters of a microwave electrotechnological installation with a hybrid-type working chamber with maximum economic efficiency are determined.

Technical and economic optimization of a microwave electrotechnological installation with a hybrid type working chamber is reduced to solving a system of equations:

$$\frac{\partial E_{\Sigma \mathrm{var}}}{\partial x_1} = 0; \quad \frac{\partial E_{\Sigma \mathrm{var}}}{\partial x_2} = 0; \quad \frac{\partial E_{\Sigma \mathrm{var}}}{\partial x_n} = 0 \quad (2)$$

where, $x_1, x_2, \ldots, x_n$ – are the independent parameters on which $E_{\Sigma \mathrm{var}}$ depends, that is, the global minimum of dependence $E_{\Sigma \mathrm{var}} = E_{\Sigma \mathrm{var}}(x_1, x_2, \ldots, x_n)$ is determined. In addition to independent parameters, $E_{\Sigma \mathrm{var}}$ also depends on regulatory and dependent parameters. The normative parameters do not vary during the calculation of $E_{\Sigma \mathrm{var}}$, they remain set in all cases. Dependent parameters in calculations should be determined through independent parameters. Independent parameters in the problems of technical and economic optimization of the installation are usually the number of microwave generators *M* in one installation, the microwave power *P* and frequency (wavelength λ) of the microwave generator, and if *M* and *P* are included in the expression $E_{\sum\text{var}}$ explicitly, then f – not. As a first approximation, we can assume that:

$$V \approx \lambda^3; S \approx (3-6)\lambda^2 \quad (3)$$

where, *V* and *S* – the volume and surface of the heated material.

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

$$Pr = \text{a}\text{P}^2 + bP + c \quad (4)$$

where, *Pr* – price; *a,b,c* – are the constants.

A similar method of calculating the optimal parameters and choosing the optimal installation structure is used in the design of microwave electrotechnological installations of thermal modification, and it is shown that by analyzing the structure of $E_{\sum\text{var}}$, in the ratio (1), it is possible to find the conditions for achieving $E_{\sum\text{max}}$, that is, to optimize the installation without resorting to solving the system of Eq. (2).

Of course, the optimization of a microwave electrotechnological installation with a hybrid-type working chamber has its own peculiarities. So, if a non-thermal microwave modification is permissible at any voltage *E* in the working chamber of a non-thermal microwave modification, then optimization can be carried out according to the above methodology. If a non-thermal microwave modification can be performed only at a given value E_3 in the working chamber of a non-thermal microwave modification, then the power of the microwave generator (microwave energy source) is selected taking into account the section of the waveguide in the working chamber of a non-thermal microwave modification such that in this waveguide $E=E_3$. The frequency f of the microwave energy source is selected from those allowed for use in microwave electrical technology, on which the effect of non-thermal microwave modification takes place. The length of the homogeneous waveguide of the working chamber is chosen so that the voltage at its input is $\text{E}_3 + \Delta\text{E}_3$, and at the output - $\text{E}_3 - \Delta\text{E}_3$, that is

$$\text{E}_3 - \Delta\text{E}_3 = (\text{E}_3 + \Delta\text{E}_3)\text{e}^{-2\alpha l} \quad (5)$$

where, ΔE_3 – the permissible deviation is relative stresses from E to E_3; l – the length of the working segment of the working chamber of the non-thermal microwave modification; α – the attenuation coefficient of the electromagnetic wave propagating in the working chamber.

The ratio (5) makes it possible to determine the maximum volume of the polymer being processed (with a known cross-sectional area) and, knowing the time required for non-thermal modification, it is possible to calculate the performance of the working chamber of non-thermal microwave modification.

With a non-thermal microwave modification, α is little and no significant change in the microwave power at length *l*, it all comes from the working chamber of the non-thermal microwave modification to the entrance to the working chamber of the thermal microwave modification. If, using the synthesis of the working chamber of the thermal microwave modification, this chamber is designed to be perfectly aligned with the transmission line, then the dielectric is evenly heated. Knowing the power and volume of the dielectric in this chamber, it is possible to calculate the performance of the working chamber of the thermal microwave modification.

Knowing the performance of both technological units, it is possible to determine how many parallel microwave electrotechnological installations with a hybrid type working chamber will be required to ensure the annual volume of production.

4. CONCLUSIONS

The research work presents new designs of microwave electrotechnological installations with hybrid type chambers for drying both farm products and for drying dielectric and polymer materials. Microwave installations with hybrid type chambers have a great potential for their use in agriculture. In addition to thermal microwave modification (drying) of timber, seven technological processes of non-thermal microwave modification of polymers, such as polymer filaments, fibres, viscous, bulk polymers, polysulfone films, epoxy resin and compounds, can be implemented in microwave installations with an HTC built as a result of the modernization of the microwave dryer. In this case, after each of the seven sources of microwave energy, a working chamber should be placed for non-thermal microwave modification of the corresponding polymer. All these microwave installations with HTC should modify polymers in a methodical mode. Each working chamber of non-thermal microwave modification must be designed to process a specific polymer with a given performance.

When operating microwave electrotechnological installations with hybrid type cameras, the manufacturer receives two different products. Of course, an installation that produces two types of products that are equally necessary for the manufacturer is of interest. For example, 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 an installation, it is necessary to coordinate the performance of technological units of non-thermal and thermal microwave modifications. The fact is that the calculated length of the working chamber of the non-thermal microwave modification is very large, and, as a result, the performance of the working chamber of the non-thermal microwave modification is likely to be more than required. In this case, the manufacturer has a choice: it is possible to make significantly less non-thermal microwave modification in the working chamber, or not to do this, and in this case he will have at his disposal a part of the material that has undergone non-thermal microwave modification, which he can send to the commodity market regardless of the products of the working chamber of thermal microwave modification.

Currently, the authors have sent an application for the invention "Ultrahigh-frequency electrotechnological installation with a hybrid type working chamber" and an application for the method "Method of ultrahigh-frequency thermal and non-thermal processing of raw materials." Both applications are subject to substantive examination.

ACKNOWLEDGMENT

The research is carried out within the framework of a grant in the form of subsidies in the field of science from the budget of the Republic of Bashkortostan for state support of young scientists – candidates of sciences (the code of the competition is REC–SMI-2022).

REFERENCES

[1] Sivyakov, B.K., Grigoryan, S.V. (2019). Installation of microwave drying of farm products in farms. Electrical Engineering Issues, 1(22): 9-13.

[2] Aldalbahi, A., Rahaman, M., Almoiqli, M. (2019). Performance enhancement of modified 3D SWCNT/RVC electrodes using microwave-irradiated graphene oxide. Nanoscale Research Letters, 14(1): 351. https://doi.org/10.1186/s11671-019-3174-9

[3] Wallace, C.A., Afzal, M.T., Saha, G.C. (2019). Effect of feedstock and microwave pyrolysis temperature on physio-chemical and nano-scale mechanical properties of biochar. Bioresources and Bioprocessing, 6(33): 33. https://doi.org/10.1186/s40643-019-0268-2

[4] Tukhvatullin, M.I., Aipov, R.S., Linenko, A.V., Galiullin, R.R., Kamalov, T.I. (2019). Microwave drying of wood, mathematical simulation of rotating lumber in the SHF field. International Journal of Advanced Science and Technology, 28(9): 208-218.

[5] Zhang, J., Chen, W., Gaidau, C. (2020). Influence of microwave on chromium complex composition in tanning liquor. Journal of Leather Science and Engineering, 2(10): 10. https://doi.org/10.1186/s42825-020-00024-1

[6] Lv, H., Chen, X., Liu, X., Fang, C., Liu, H., Zhang, B., Fei, B. (2018). The vacuum-assisted microwave drying of round bamboos: Drying kinetics, color and mechanical property. Materials Letters, 223: 159-162. https://doi.org/10.1016/j.matlet.2018.04.038

[7] Kurian, J.K., Gariepy, Y., Orsat, V., Raghavan, G.S.V. (2015). Comparison of steam-assisted versus microwave-assisted treatments for the fractionation of sweet sorghum bagasse. Bioresources and Bioprocessing, 2: 30. https://doi.org/10.1186/s40643-015-0059-3

[8] Luo, J., Shen, P., Yao, W., Jiang, C., Xu, J. (2016). Synthesis, characterization, and microwave absorption properties of reduced graphene oxide/strontium ferrite/polyaniline nanocomposites. Nanoscale Research Letters, 11: 141. https://doi.org/10.1186/s11671-016-1340-x

[9] Vovchenko, L., Lozitsky, O., Sagalianov, I., Matzui, L., Launets, V. (2017). Microwave properties of one-dimensional photonic structures based on composite layers filled with nanocarbon. Nanoscale Research Letters, 12: 269. https://doi.org/10.1186/s11671-017-2034-8

[10] Arkhangelsky, Y.S., Voronkin, V.A. (2003). Element base of microwave electrotechnological equipment. Saratov State Technical University, Saratov.

[11] Pyushner, G. (1968). Heating with ultrahigh frequency energy. Energiya, Moscow.

[12] Rogov, I.A., Nekrutman, S.V., Lysov, G.V. (1981). Technique of ultra-high-frequency heating of food products. Light and food industry. Moscow.

[13] Aipov, R.S., Gabitov, I.I., Tuhvatullin, M.I., Linenko, A.V., Tuktarov, M.F., Akhmetshin, A.T. (2019). Process unit for drying sawn timber rotating in the ultra-high frequency field with a discrete arrangement of magnetrons. Bulgarian Journal of Agricultural Science, 25(S2): 3-11.

[14] Weng, X., Zhou, Y., Fu, Z., Gao, X., Zhou, F., Jiang, J. (2021). Effects of microwave pretreatment on drying of 50 mm-thickness Chinese fir lumber. Journal of Wood Science, 67: 13. https://doi.org/10.1186/s10086-021-01942-2

[15] Liu, Y., Song, B., Zhang, J., Gaidau, C., Gu, H. (2020). Aluminum tanning of hide powder and skin pieces under microwave irradiation. Journal of Leather Science and Engineering, 2: 23. https://doi.org/10.1186/s42825-020-00037-w

[16] Zhou, J., Yang, X., Zhu, H., Yuan, J., Huang, K. (2019). Microwave drying process of corns based on double-porous model. Drying Technology, 37: 92-104. https://doi.org/10.1080/07373937.2018.1439952

[17] Nirmaan, A.M.C., Rohitha Prasantha, B.D., Peiris, B.L. (2020). Comparison of microwave drying and oven-drying techniques for moisture determination of three paddy (Oryza sativa L.) varieties. Chemical and Biological Technologies in Agriculture, 7: 1. https://doi.org/10.1186/s40538-019-0164-1

[18] Khasanov, E.R. (2015). Influence of microwave current treatment modes on disinfection and stimulation of seed germination with subsequent inlay. Bulletin of the Bashkir State Agrarian University, 3(35): 77-81.

[19] Patel, J., Al-Ghamdi, S., Zhang, H., Queiroz, R., Tang, J., Yang, T., Sablani, S.S. (2019). Determining shelf life of ready-to-eat macaroni and cheese in high barrier and oxygen scavenger packaging sterilized via microwave-assisted thermal sterilization. Food and Bioprocess Technology, 12: 1516-1526. https://doi.org/10.1007/s11947-019-02310-1

[20] Zhang, H., Bhunia, K., Munoz, N., Li, L., Dolgovskij, M., Rasco, B., Tang, J., Sablani, S.S. (2017). Linking morphology changes to barrier properties of polymeric packaging for microwave-assisted thermal sterilized food. Journal of Applied Polymer Science, 134(44): 45481. https://doi.org/10.1002/app.45481

[21] Stepanenko, V.V., Kazhevnikov, V.Y. (2017). Disinsection of food products by microwave electromagnetic field energy. Questions of Electrotechnology, 4(17): 19-22.

[22] Wang, X.X., Sun, C.M., Wen, F.B., Jiang, S.Y., Cao, M.S. (2018). Strong mechanics and broadened microwave absorption of graphene-based sandwich structures and surface-patterned structures. Journal of Materials Science: Materials in Electronics, 29: 9683-9691. https://doi.org/10.1007/s10854-018-9005-4

[23] Aniszewska, M., Słowiński, K., Tulska, E., Zychowicz, W. (2021). Effects of microwave irradiation on the moisture content of various wood chip fractions obtained from different tree species. Journal of Wood Science, 67: 28. https://doi.org/10.1186/s10086-021-01958-8

[24] Liu, T.S., Liu, N., An, Q.D., Xiao, Z.Y., Zhai, S.R., Li, Z.C. (2019). Designed construction of composites with enhanced microwave absorption performance. Journal of Alloys and Compounds, 802: 445-457. https://doi.org/10.1016/j.jallcom.2019.06.243

[25] Ghasri, M., Bouhendi, H., Kabiri, K., Zohuriaan-Mehr, M.J., Karami, Z., Omidian, H. (2019). Superabsorbent polymers achieved by surface cross linking of polysodium acrylate using microwave method. Iranian Polymer Journal, 28: 539-548. https://doi.org/10.1007/s13726-019-00722-6

[26] Arkhangelsky, Y.S. (2011). Reference book on electrothermy. Publishing house "Scientific Book", Saratov.

[27] Arkhangelsky, Y.S., Kolesnikov, E.V. (2015). Chambers with running and standing waves. Bukva, Saratov.

[28] Arkhangelsky, Y.S., Trigorly, S.V. (2017). Beam-type chambers. Amirit, Saratov.

[29] Dobrodum, A.S., Arkhangelsky, Y.S. (2017). Coordination of the performance of a hybrid chamber of a microwave electrotechnological installation for non-thermal and thermal modification of processed materials. Electrical Engineering Issues, 4(17): 15-18.

[30] Arkhangelsky, Y.S., Grishina, E.M., Lavrentiev, V.A., Sleptsova, S.K. (2012). Microwave modification of polymers. Saratov State Technical University, Saratov.

[31] Tuhvatullin, M.I. (2020). Microwave electrotechnology: Issues and prospects. Scientific journal "Questions of Electrotechnology" Saratov State Technical University named after Gagarin Y.A., 4(29): 42-47.

[32] Dobrodum, A.S., Arkhangelsky, Y.S. (2017). Microwave electrotechnological installations with hybrid cameras. Questions of Electrical Technology, 3(16): 16-22.

[33] Tuhvatullin, M.I., Aipov, R.S. (2019). Technological installation for microwave drying of timber. Questions of Electrotechnology, 4(25): 12-17.