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Innovations in designing microwave electro-technological units with hybrid chambers

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Abstract

Aim of study: Microwave (MW) electro-technological units based on electromagnetic radiation of ultrahigh-frequency can involve thermal MW modification of dielectrics and non-thermal MW modification of polymers.

Area of study: Russian Federation.

Material and methods: The paper considers a method for making a unit with a hybrid chamber, where thermal and non-thermal MW modifications were carried out simultaneously, and the remaining energy after non-thermal MW modification of polymers was used for heating the dielectric.

Main results: A microwave electro-technological unit with a hybrid chamber replaced two separate devices that implemented these MW modifications. It was cheaper and required one MW generator. The unit took up less space than two separate apparatuses, and upgraded the existing microwave dryer to perform thermal MW modification of a lumber pile and non-thermal MW modification of polymer materials. The existing microwave dryer was redeveloped by solving the boundary value problem in electrodynamics and heat and mass transfer.

Research highlights: The research presents a microwave electro-technological unit with a hybrid chamber, combining thermal and non-thermal MW modifications of dielectric and polymer materials. As a result of upgrading the existing microwave dryer, it was possible to carry out both thermal and non-thermal MW modifications, namely, microwave drying of timber and microwave drying of up to seven different polymer objects.

Additional key words: microwave electro-technology; electro-technological unit; thermal MW modification; non-thermal MW modification; microwave timber dryer.

Abbreviation used: HC (hybrid working chambers); MW (microwave); MWETU (microwave electro-technological units); UHF (ultra high frequency).

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Introduction

A microwave electro-technological unit with a hybrid chamber and the application of ultrahigh-frequency electromagnetic energy allow thermal modification of dielectric materials and non-thermal modification of polymer materials. As a result, the properties and parameters of the processed objects change faster and more uniformly than when heated by traditional methods.

The paper proposes a design of an ultra-high-frequency electro-technological unit with a hybrid chamber. Such a design allows a simultaneous thermal microwave modification of the dielectric material and non-thermal microwave modification of the polymer material.

Heat treatment processing of dielectric materials and products is widely used in the polymer materials industry (Wang et al., 2018; Ghasri et al., 2019; Zhan et al., 2020), in the forestry and timber manufacturing industry (Rezaei et al., 2017; Lv et al., 2018; Aniszewska et al., 2021), in agriculture (Monton et al., 2019; Sivyakov & Grigorieva, 2019; Nirmaan et al., 2020) in medicine (Jia et al., 2017; Liu et al., 2019; Feng et al., 2020), in the food industry (Zhang et al., 2016; 2017; Patel et al., 2019). With the development of the ultrahigh-frequency range in electronics, it became possible to apply the energy of the microwave electromagnetic field for heat treatment. Many researchers in the 1950-1980s focused their attention on microwave irradiation, since dielectric parameters are maximum within the microwave range, providing a faster and more uniform heat release.

Investigators observed a specific microwave effect of the electromagnetic field on microorganisms during the microwave pasteurization of milk. Milk pasteurization took place at a much lower temperature than a conventional one (Ignatov et al., 1978). In the 1990s, the microwave effect on polymers (polysulfone, polycaproamide) was studied. It was found that microwave treatment changes (improves) polymer properties (Arkhangelskiy et al., 2012). Soon afterwards, this microwave effect was called non-thermal.

The non-thermal microwave treatment of polymers attributed new properties that expanded the scope of their application. The drying unit was cost-effective but not energy-saving since the energy remaining after the non-thermal MW modification was dissipated in the ballast load in running water (Arkhangelskiy et al., 2012).

This disadvantage can be eliminated if non-thermal and thermal microwave (MW) modifications are carried out simultaneously in a microwave electro-technological unit with a hybrid chamber. Non-thermal effects of electromagnetic radiation can also occur at lower intensities than the thermal threshold. The microwave energy remaining after non-thermal MW modification of the polymer in the working chamber will be used for thermal MW modification of the dielectric (Arkhangelsky & Grishina, 2007; Dobrodum & Arkhangelskiy, 2017a; 2017b).

Non-thermal MW modification and development of apparatuses with hybrid chambers are still being studied. Another challenge is innovations in the design of microwave electro-technological units with hybrid chambers (Jia et al., 2017; Chen et al., 2018). There are two possible solutions. Firstly, it is possible to design a unit with a hybrid working chamber of two sequentially connected processing modules of non-thermal and thermal MW modifications, or one combined processing unit. Secondly, it can be equipment based on an existing (known) microwave electro-technological unit of a thermal MW modification, having undergone modernization to conduct both types of MW modifications at once (Ventsova & Safonov, 2021; Safonov, 2022). This option is of particular interest.

The research goal was the modification of the existing MW dryer, which combines thermal and non-thermal MW modifications of dielectric and polymer materials, will increase the efficiency of its use in industrial processing plants by reducing electrical energy consumption and increasing the number of finished products. The specific objectives of this work were to: (i) consider the order of innovative activities to design a microwave electro-technological unit with a hybrid camera; (ii) provide the technical characteristics and description of a microwave dryer for timber drying; (iii) develop a unit with a hybrid chamber based on the existing microwave dryer. The novelty of the paper is to present a microwave unit with a hybrid working chamber combining non-thermal modifications of polymers and thermal modification of a dielectric.

The proposed modification of the existing microwave dryer was carried out for the first time. The working chamber of the MW dryer is essentially a combination of two or more working chambers of non-thermal and thermal microwave modifications, and the dryer can simultaneously produce two or more types of products. This gives rise to a number of specific features of such units that microwave electro-technological units producing one type of product do not have.

Material and methods

A microwave electro-technological unit with a hybrid chamber comprises of processing modules of non-thermal and thermal microwave modifications. It produces at least two types of products: polymer material (product) that has undergone non-thermal microwave modification and dielectric material (product) that has undergone thermal microwave modification.

A non-thermal MW modification processing module consists of a transmission line and a working chamber of a non-thermal modification. The transmission line transfers microwave energy from a microwave energy source to the working chamber of a non-thermal MW modification. It is a waveguide of the same usually rectangular cross-section as the waveguide of the microwave generator, the source of the microwave energy. If the magnetron operates at a frequency of 2450 MHz, it is a rectangular waveguide with a cross-section of 45 × 90 mm, at 915 MHz – 100 × 220 mm. The length of the transmission line, a possible waveguide rotation, is determined by the convenience of the unit placing and operating.

The working chamber of a non-thermal MW modification provides 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 performed on a waveguide of the same cross-section as the transmission line that supplies it with microwave energy from a microwave energy source, with a partial value of the polymer being processed.

Since the polymer rests in the microwave electromagnetic field for seconds during non-thermal microwave modification, process cameras must work continuously and have outlets for loading and unloading the processed object. To prevent microwave radiation through the outlets, the working chamber must have loading and unloading gateways. Their inner walls must be covered with an oxide or carbon film that absorbs microwave radiation well.

Since the non-thermal MW modification consumes little microwave power, the working chamber of the non-thermal MW modification must be passable; that is, the microwave power from this chamber must be supplied to the input of the processing module of the thermal MW modification.

The thermal MW modification processing module consists of a transmission line and a working chamber of a thermal modification. The transmission line transfers the remaining microwave power after the non-thermal MW modification to the input of the working chamber of the thermal MW modification. It is performed on a rectangular waveguide as a similar transmission line of the non-thermal MW modification processing module.

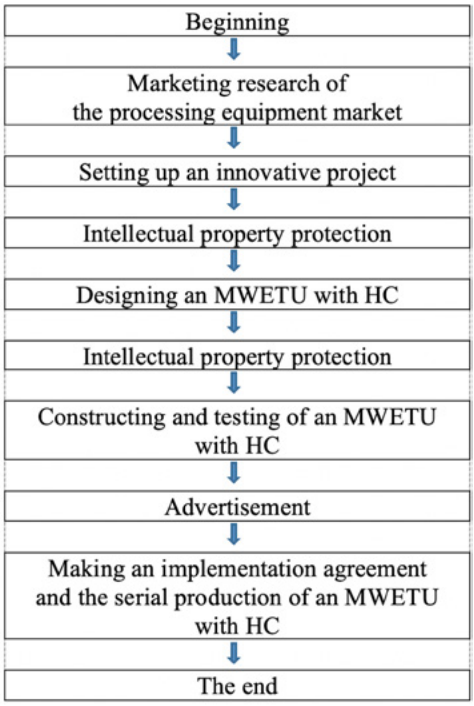

Figure 1. Stages of innovation activity in developing a microwave electro-technological unit (MWETU) with hybrid working chambers (HC).

Results and discussion

Innovation is commonly understood as renewal, transformation. The innovation process is preceded by research, development, testing, and engineering. The development of microwave electro-technological units with hybrid working chambers (MWETU with HC) has gone through these stages (Fig. 1). This construction allows for simultaneous non-thermal Ultra High Frequency (UHF) modification of the polymer material and thermal UHF modification of the dielectric material in one installation. An UHF electrotechnological device with a hybrid type working chamber is cheaper, occupies a smaller area compared to two separate devices that produce a total of the same products with the same performance. The device has a maximum efficiency, maximum energy and decent economic efficacy, which determines its use.

In marketing research, attention should be paid primarily to equipment that provides heat treatment of dielectrics (heating, drying) and produces polymer materials and products that are competitors of the MWETU with HC. At this stage, the final decision is made which polymer and dielectric objects will be processed in the planned to the designed MWETU with HC.

The main part of the innovation activity is the equipment (machine/unit) design. The work is completed by signing an agreement on the introduction and serial production of the MWETU with HC.

Constructing an MWETU with HC by upgrading an electro-thermal unit in a microwave is an option for developing this new class of MWETU. The added non-thermal MW modification processing module for treating polymer increases the cost-efficiency of the modernized unit since it provides higher profit without increasing energy consumption. An entrepreneur supplies the commodity market with at least two types of products. Let us consider constructing an MWETU with HC on the example of upgraded microwave electro-thermal equipment for timber drying.

Wood, as a cost-effective natural resource, is widely used as a building and structural material in many industrial and civil construction areas. The properties of dried timber depend on the quality of microwave drying, being the main operations for wood processing (Aniszewska & Słowiński, 2016; He et al., 2017).

Thus, microwave drying can be implemented in an MWETU with a discrete arrangement of several magnetrons and a timber rotating mechanism in a radial chamber (Tuhvatullin, 2020; 2021). This arrangement ensures more uniform timber heating and reduces the drying time by 38.8%, increases the output by 27.3% and enhances the drying efficiency (Aipov et al., 2019; Tuhvatullin et al., 2019).

It should be noted that drying is the longest and most expensive process in woodworking production.

Developed according to the microwave wood drying studies findings, a microwave timber dryer has a radial

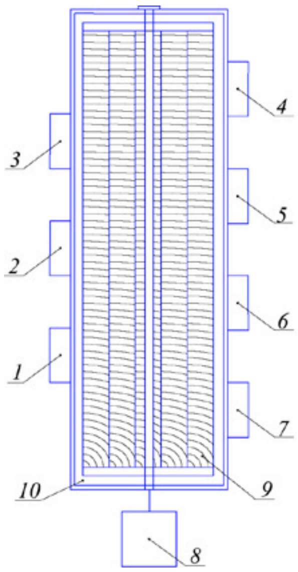

Figure 2. Functional chart of a microwave timber dryer: 1-7, sources of microwave energy on magnetrons; 8, electric drive; 9, a timber pile; 10, a radial working chamber.

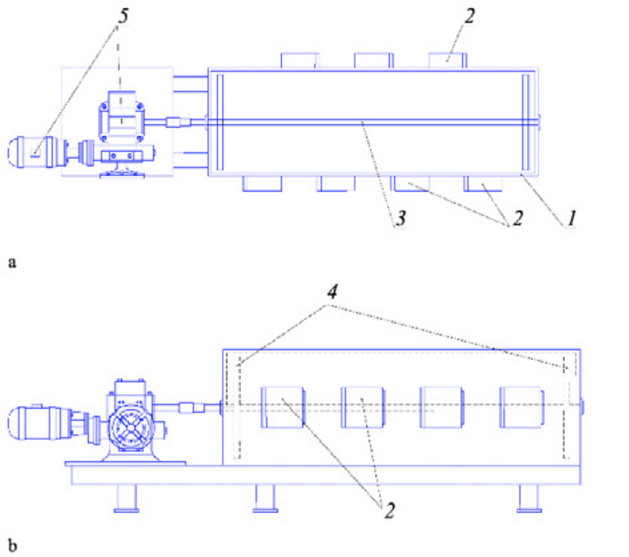

Figure 3. Microwave timber dryer: a, top view; b, side view (1, a camera; 2, a source of microwave energy; 3, a shaft; 4, fasteners for a timber pile; 5, an electric motor and a reducer).

working chamber of 2.42 × 0.6 × 0.6 m with discretely located magnetrons, each of 1.2 kW/2450 MHz (Figs. 2 and 3) (Aipov et al., 2019).

In working chamber 1 of the microwave timber dryer, there is a mounted shaft 3 with fasteners for timber piles 4. Timber piles are rotated by an electric motor with a reducer 5. The working chamber has a cover for tight-sealing of the dryer.

The microwave dryer was made without horn emitters to reduce the metal consumption, weight, and occupied area. It decreased energy efficiency and lowered the cost of the equipment. As a result, the dryer's cost-efficiency increased. The microwave dryer treated pine boards of 2 × 0.15 × 0.05 m each from the initial humidity of 84.5% to 9%, the initial temperature of 22.5 ºC to 78 ºC for 14 hours, the boards did not get any defects.

If the microwave dryer, the heat MWETU, was equipped with a non-thermal MW modification processing module, the upgraded equipment becomes an MWETU with a hybrid chamber (HC).

Figure 4 shows a general view of the microwave timber dryer. Figure 5 presents photos of the main construction parts of the microwave dryer. Figure 6 shows a functional chart of an MWETU with HC that produces a non-thermal MW modification of polymer filaments and a thermal MW modification (microwave drying of timber with a rotating pile).

The microwave dryer used seven microwave energy sources; therefore, the MWETU with HC based on this microwave dryer has seven working chambers of a non-thermal MW modification. Each chamber was assembled on a segment of a rectangular homogeneous waveguide with flanges at its ends and longitudinal slits in the middle of wide walls, through which thin polymer threads, fibres, and other materials were stretched.

While non-thermal MW modification in the waveguide of 45 × 90 mm cross-section at 2450 MHz required less microwave power than was produced by the microwave generator of one microwave energy source (according to Arkhangelskiy et al. (2012), non-thermal MW modification of polycaproamide threads required 100 W at 0.9 cm/s of thread transportation rate), the MWETU with HC would employ P=1, 2 kW for this MW modification or the

Figure 4. General view of the microwave dryer: 1, a shaft that provides rotation of a timber pile; 2, magnetrons; 3, the housing of the microwave dryer; 4, a cover of the working chamber made of steel mesh.

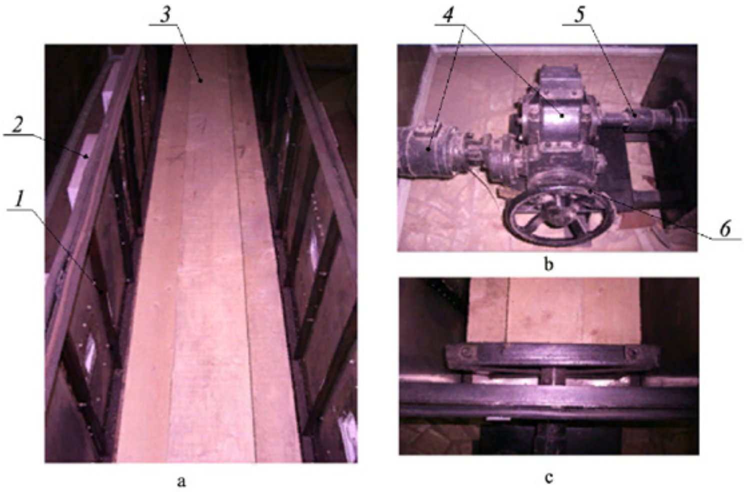

Figure 5. The main parts of the microwave dryer: a, internal view; b, electric drive; c, frame with fasteners (1, working chamber; 2, magnetron; 3, timber pile; 4, electric drive; 5, shaft; 6, mechanism for manual rotation of a timber pile).

non-thermal MW modification chamber would be built on a directional coupler. Its main channel supplied 1.1 kW of microwave power to the dryer and 100 W branches in the side waveguide with slots on the broad wall. Here polycaproamide threads underwent non-thermal modification. Moreover, the microwave energy from the side channel was fed into an additional working chamber of thermal MW modification to treat dielectric material at a microwave power of 100 W (Yudina & Arkhangelskiy, 2019).

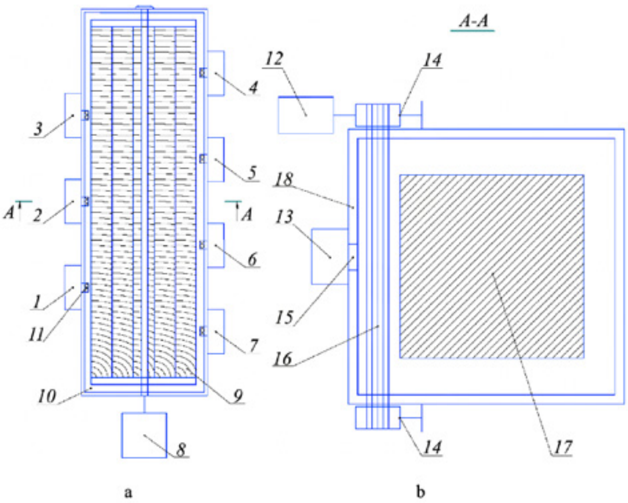

Figure 6. Functional chart of an upgraded microwave dryer MWETU with HC: a) MWETU with HC; b) cross-section according to A-A: 1-7, magnetrons (microwave energy sources); 8, electric drive; 9, dielectric (a timber pile); 10, a radial working chamber; 11, siting of modified threads or fibres; 12, electric drive of the transport system; 13, magnetron (microwave energy source); 14, transport system; 15, waveguide; 16, polymer threads; 17, a timber pile; 18, the wall of the MW unit's working chamber.

The length of the slots (the number of polymer threads) was determined by the results of marketing research, the demand for such modified threads on the commodity market.

It is important to note that each non-thermal MW modification processing module can produce the same or different polymer products. The MWETU with HC, in addition to drying a timber pile, could produce from one to seven different polymer objects. It requires equal microwave power of emitters. Otherwise, the pile boards will heat up and dry unevenly along the entire length, which will cause board warping.

If polymer objects subjected to non-thermal MW modification are located in the electromagnetic field of the microwave timber dryer chamber, then the working chamber turns into a combined hybrid chamber, and the microwave dryer turns into an MWETU with HC, the functional chart of which is shown in Fig. 7.

If polymer threads are subjected to non-thermal MW modification, they should be stretched in the microwave electromagnetic field at a speed of 0.9 centimetres per second, parallel to the voltage vector *E*. However, the rotation of a timber pile continuously alters the boundary conditions of the electrodynamics BVP (a vacuum switch), and therefore the structure of the electromagnetic field is constantly changing. This contributes to the drying of timber. To conduct non-thermal MW modification of polymer threads in such a combined hybrid working chamber, it was necessary to choose siting directly near the aperture of the radiating systems of the microwave dryer (Fig. 8).

Suppose the water vapour evaporating from the timber is dangerous for polymer objects undergoing non-thermal MW modification in the neighbourhood. In that case, polymer objects can be protected from water vapour by a moisture-proof thin dielectric radio-transparent partition separating the zones of the polymer objects from the

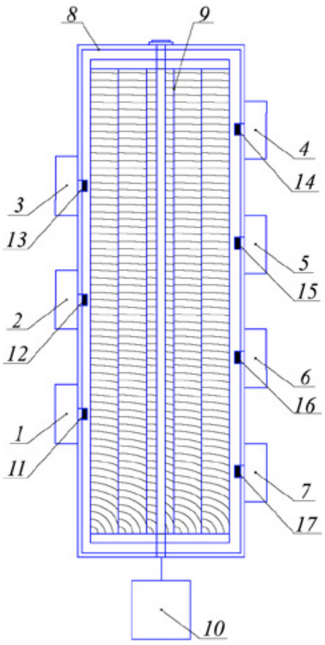

Figure 7. Functional chart of an MWETU with HC based on a microwave timber dryer: 1-7, sources of microwave energy on magnetrons; 8, working chamber; 9, timber pile; 10, electric drive; 11-17, siting of modified polymer objects.

zone where the timber pile undergoing thermal microwave modification rotates.

Let us compare the MWETU with HC shown in Figs. 6 and 7. The MWETU with HC in Fig. 7 favourably differed in a smaller occupied area (the area of the microwave dryer was reduced). It has less metal consumption, a more cross-sectional area of the polymer object siting. Still, it has a more complex transport system, being a significant drawback.

The absence of horn emitters in the microwave dryer, matching its working chamber with the microwave generator, creates an additional challenge for the MWETU with HC, assembled according to the scheme shown in Fig. 6. Indeed, the microwave energy reflected from the entrance to the working chamber of the microwave dryer creates a partially standing wave mode in the working chamber of the non-thermal MW modification. It creates dependence *E(z)* in this working chamber. When the length of the slots in the chamber of the non-thermal MW modification is greater than the wavelength in the waveguide, it will affect the quality of polymer thread modification (Zhang et al., 2018; Zlobina, 2018; Zhou et al., 2019).

The same situation occurs in the MWETU with HC (Fig. 7), if a quarter-wave matching transformer is not used in the working chamber of the microwave dryer (Fig. 9).

Thus, the higher cost-efficiency of the unit due to used horn emitters and quarter-wave matching transformers ensures the quality of the products.

As for the calculations carried out during the design of the MWETU with HC, the scientific foundations of the MWETU for thermal microwave modification of dielectrics are described, for example, in Arkhangelskiy (2011), Zakharov (2017), Arkhangelskiy et al. (2018), Tuhvatullin et al. (2019) and Tuhvatullin (2021). The procedure for calculating the working chambers of non-thermal MW modification is described in Arkhangelskiy et al. (2012). Technical and economic calculations in microwave electro-technology were considered in Arkhangelskiy & Kolesnikov (2017).

Conclusions

This paper discusses innovations in developing microwave electro-technological units with hybrid chambers. An alternative to the MWETU with HC is two microwave electro-technological units, one implementing a non-thermal MW modification of a polymer object and a thermal MW modification of a dielectric object.

The MWETU with HC is favourably different from two separate pieces of equipment, since it needs only one source of microwave energy. It occupies a smaller area, has less metal consumption, is cheaper, and has the maximum achievable energy efficiency. The MWETU with HC provides two or more products to the commodity market, bringing a very decent profit.

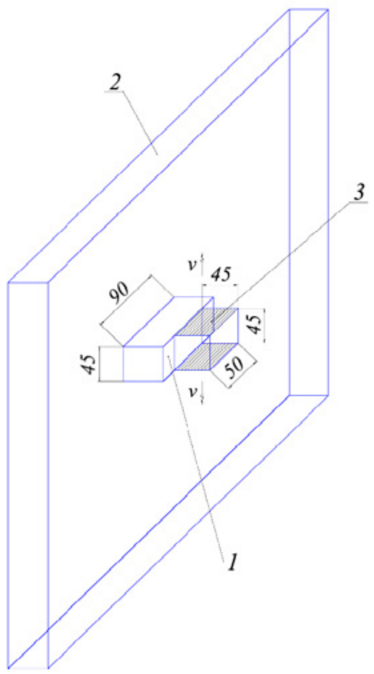

Figure 8. Siting of the polymer object in the microwave dryer chamber: 1, the emitter aperture (cross-section of a rectangular waveguide (45 × 90 mm); 2, the side wall of the working chamber; 3, siting of the polymer object; v, the motion speed of the modified object.

The main parameters of the MWETU with HC are as follows:

- a 2.42 × 0.6 × 0.6 m hybrid working chamber based on a beam chamber with discretely located 1.2 kW magnetrons at 2450 MHz on the side walls;

– an electric motor with a gearbox and a shaft with fasteners, providing rotation of a 2 × 0.15 × 0.05 m lumber stack for thermal microwave modification;

– a 45 × 90 mm waveguide at 2450 MHZ, the slits on its wide walls are used to transport 0.9 cm/s of polycaproamide strings for non-thermal microwave modification.

The goal of innovation activity can be achieved in two ways. Firstly, guided by the results of marketing research of the commodity market, polymer and dielectric objects are selected, which must undergo non-thermal and thermal microwave modifications in the projected microwave ETU (electrical installation) with KGT (readiness factor), after which the design, manufacture, testing, and implementation of the installation is carried out.

This research discusses the second way of achieving the goal of innovation activity, being of great practical interest: modernization of the existing microwave and thermal microwave modification, associated with equipping this installation with a non-thermal microwave modification technological unit. Possible opportunities are shown by the example of a redeveloped microwave timber dryer, in which a timber pile is manually or automatically rotated in the working chamber.

These two directions in creating an MWETU with HC are not competitors to each other. The example of a modernized microwave timber dryer given in this paper shows the expediency of upgrading existing MWETU to turn them into MWETU with HC and getting more profit, increasing the cost-efficiency of the existing processing unit.

The results of marketing research of the commodity market of polymer and dielectric materials, products can show the demand for such products, which can be obtained with a decent profit with the help of microwave electro-technological equipment. The given study showed how to arrange innovative activities to create an MWETU with HC, a new class of microwave units that differ favorably from MWETU, implementing only non-thermal microwave modification of polymers or thermal microwave modification dielectrics.

The present paper demonstrated the expediency of achieving this goal by using the existing MWETU of thermal MW modification, having modernized it. This innovative activity direction was demonstrated by the modification of a microwave dryer of lumber. The paper described the options for such modernization: technological blocks were placed between the microwave energy source and the conventional microwave dryer chamber, for example, for non-thermal microwave modification of polymer filaments, or these filaments are placed inside the working chamber of the microwave dryer, which makes the microwave dryer turn into a microwave oven with a combined hybrid-type working chamber. The upgraded microwave dryer, the MWETU with HC, can produce up to seven different polymer threads and dry a timber pile.

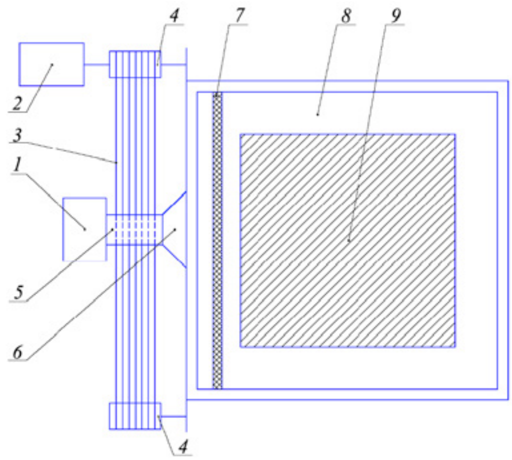

Figure 9. MWETU with HC based on a microwave timber dryer: 1, a microwave energy source; 2, electric drive; 3, polymer threads; 4, transport system for stretching polymer threads; 5, working chamber of non-thermal MW modification of polymer threads; 6, horn emitter; 7, quarter-wave matching transformer; 8, working chamber of the microwave dryer; 9, a timber pile.

This option of creating an MWETU with HC is not only of practical interest but also scientific since the scientific basis for designing an MWETU with HC is one of the present-day challenges in microwave electro-technology.

The practical modernization of the microwave dryer for a timber pile to build a microwave electro-technological unit with a hybrid chamber, on its basis carried out by the developer of the microwave dryer, will increase the variety of products and expand the possibilities of microwave electro-technology.

Authors' contributions

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Writing – original draft: M. Tuhvatullin, Y. Arkhangelsky, R. Aipov, E. Khasanov

Writing – review & editing: M. Tuhvatullin, Y. Arkhangelsky, R. Aipov, E. Khasanov

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