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UNIFORM LARGE-SIZED LUMBER DRYING SYSTEM USING MW RADIATION AND BASING ON A SINGLE-WIRE E_{00} WAVE ENERGY TRANSMISSION LINE

E. Ritter
Postgraduate Student*
E-mail: kritter315@gmail.com
V. Kismereshkin
Doctor of Technical Sciences, Professor
Department of Communications and Information Security
Omsk State Technical University
Mira str., 11, Omsk, Russian Federation, 644050
J. Cieslik
Professor
Department of Robotics and Mechatronics
AGH University of Science and Technology
Aleja Adama Mickiewicza str., 30, Krakow, Polad, 30-059
A. Savostin
PhD, Associate Professor*
D. Ritter
PhD, Associate Professor*
A. Aytulina
Postgraduate Student*
I. Kasimov
Postgraduate Student*
B. Bekkozhina
Postgraduate Student*
*Department of Energetic and Radioelectronics
M. Kozybayev North-Kazakhstan University
Pushkin str., 86, Petropavlovsk, Republic of Kazakhstan, 150000

In order to generalize the possibilities of using MW radiation in industrial processes, the given paper considers and analyzes various methods of wood drying. Technological and economic advantages of wood drying in an ultra-high frequency electromagnetic field are well justified. Wood drying in the ultra-high frequency range is considered as the most optimal in contrast to traditional methods. This method is based on the penetration of electromagnetic energy into the material and converting it into heat.

The paper reveals the possibility of more effective use of MW radiation. It proposes a method for drying wood and large-sized lumber basing on a single-wire transmission line of electromagnetic energy of the surface wave. The paper also describes the advantages of the proposed method: the use of a single wire covered with a thin layer of dielectric material, the use of a vibratory system for surface wave excitation, and the use of a flat reflector. Special attention is paid to the contact area of the wire with a flat reflector since the perfection of this contact largely determines the efficiency of surface wave excitation. The conducted research estimated the influence of the parameters of the vibratory surface wave excitation system in a single waveguide on the efficiency of its excitation. The proposed vibratory excitation device allows quite a simple step-by-step adjustment of the thermal power in the irradiated object.

The design of the dissipation load for surface wave lines has been successfully tested during the laboratory works where certain ways of unclaimed electromagnetic energy utilization were suggested.

Following the results of the conducted research, we proposed a physical model of a system for microwave drying of wood and large-sized lumber

Keywords: microwave lumber drying, single-wire transmission line, surface wave excitation, dissipation load

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1. Introduction

Modern wood drying plants are mainly based on the use of convective and aerodynamic drying chambers. The drying process there is quite long, even regarding coniferous species, and takes 3 to 5 days. It is possible to use more intensive technologies, for example, vacuum-type chambers that reduce the drying process to 10–12 hours, but they are not competitive in terms of the volume of the dried material.

The task of increasing the speed of wood drying while maintaining the high quality of the dried lumber and its low cost is very acute.

The need to dry lumber before its further use led to the creation of drying plants of various types.

From the entire spectrum of electromagnetic waves, electric vibrations of industrial frequency (induction heating), radio waves of high and ultra-high frequencies (MW heating) and infrared radiation (infrared heating) are mainly used for heating and drying wood.

Induction heating is the heating of conductive bodies due to the excitation of electric currents in them by an alternating electromagnetic field. The sources of the electromagnetic field are inductors. The industrial frequency of 50 Hz is used for wood drying. The process of inductive drying is as follows: a stack of lumber with ferromagnetic elements stacked between rows of boards is placed in an electromagnetic field of industrial frequency formed in an inductor-solenoid external to the stack. Ferromagnetic elements transmit heat to the wood by direct contact. The created temperature difference in the stack intensifies the drying process twice as compared to chamber drying. The disadvantage of this type of drying is the low quality of the dried material, which is due to largely uneven heating, local overheating, and large internal stresses. The cost of inductive drying is twice higher than the cost of the specified chamber drying [1].

Infrared heating is the heating of materials by electromagnetic radiation with a wavelength of 2–700 nm. This type of heating is based on the property of materials to absorb this part of the radiation spectrum. Infrared emitters consisting of an energy source and a reflector provide deep or surface heating of the irradiated body or, if necessary, local drying of the object. This type of wood drying is not widely used due to the low degree of penetration of infrared waves into the object [2].

Microwave heating is based on the penetration of electromagnetic energy into the material and converting it into thermal energy. Its absorption by the material components occurs in different ways, depending on their dielectric properties. The distribution of thermal energy in the material is different than in heat treatment – the maximum temperature is in the middle of the body. The temperature distribution created in the material body creates the most favorable conditions for accelerating the vapor diffusion from the inner layers of the material to the peripheral ones since all three gradients (temperature, pressure, and concentration) that determine the rate of diffusion are directed in one direction. As a result, energy costs for the drying process are reduced and its duration is shortened [3].

Microwave energy plays the role of a non-inertial volumetric heat source, which allows reducing the duration of technological processes by dozens of times. In contrast to existing methods of heat supply to materials, exposure to electromagnetic energy has a number of advantages. Depending on the characteristics of the material and the frequency of the electric field, it is possible to perform uniform heating over the whole volume of the assortment, or warm the material to a specified depth.

In addition, the use of microwave energy is justified and economically efficient.

One of the main indicators of the economic efficiency of microwave drying is the intensity of the process, which provides the necessary quality of lumber.

These advantages of microwave drying allow the creation of previously unworkable technological processes or significantly improve existing ones. In addition, the use of microwave energy is also economically justified. These advantages determine the need for further theoretical and experimental studies of microwave drying of wood and lumber.

2. Literature review and problem statement

The work [4] considers a number of MW applications that are ready for commercial use. These applications include MW timber modification for impregnation with preservatives and resins as well as pretreatment of hardwood sawn timber for drying and MW processing of timber and woodchips for pulping.

The paper [5] reports a three-dimensional comprehensive heat and mass transfer model developed to simulate the free liquid, vapor, and bound water in microwave drying of yellow poplar specimens.

The work [6] reports the results of an exploratory study designed to reduce heat and electricity consumption in microwave drying of pine.

The paper [7] points out trends in microwave drying toward reducing uneven heating.

The works [8–10] consider both the use of microwave wood processing and methodological aspects of the design and development of microwave installations for wood drying.

Recently, interest in microwave drying of solid wood has increased. One of the works [11] for drying wood in the installation proposes to use a combined principle of operation, including convective and dielectric heating.

The works [12, 13] propose microwave vacuum drying, which allows drying logs with an initial humidity of 80 % to a final humidity of 15 % with a reduction in energy consumption.

A small-sized dryer [14] allows achieving a high quality of the dried material due to a significant drying speed. A dryer includes a working chamber containing a magnetron unit and a system for distributing the energy of the electromagnetic field in the microwave range along the length.

This applies to the industry where emergency, economical drying of medium-sized wood is required. This includes drying timber, rounded logs, boards of various lengths, etc.

Known analogues:

– domestic: MW drying chamber of periodic action (MW wood dryer, MS-2 model);

– foreign: Koetter Dry Kiln inc. drying chambers, USA, for wood drying.

Disadvantages of well-known analogues, which served as a motive for the innovative offer, include local overheating of wood leading to fire, the high cost of generators and their short duration of operation, large dimensions and poor transportation of chambers.

The work [14] did not practically consider the methods of utilization of unclaimed energy and concentration of microwave energy on the object of drying.

There are no recommendations for using a microwave drying method based on a single-wire electromagnetic energy transmission line. There is insufficient coverage of practical solutions for selecting ways to evenly distribute microwave radiation to large objects.

Thus, there is no single approach to constructing microwave units based on the surface wave line. The lack of required information leads to the need for additional experimental studies.

3. The aim and objectives of the study

The aim of the study is the development of a system for microwave drying of wood and large-sized lumber using a single-wire transmission line and the effects associated with the transformation and re-radiation of surface waves.

To achieve the aim, the following objectives were set:

– to determine the parameters and materials of a single-wire transmission line;

– to develop a system of E – type wave excitation;

– to develop the design of the absorbing load;

– to develop model a large-sized lumber uniform drying system based on MW radiation.

4. Analysis of the effectiveness of the effect of the electromagnetic field on the object of drying

The main advantage of MW drying is that the MW energy is distributed instantly throughout the entire volume of the material being dried, providing rapid heating. In this case, the intensity of energy exposure is proportional to the humidity of the material. The higher the humidity, the higher the intensity of exposure. This feature in the drying process leads to an equalization of humidity in the cross-section and along the length of the material, which means that here automatically occurs the process that requires huge energy and time with conventional drying.

As can be seen from formula (1), the heat generated in wood under the influence of an electromagnetic field depends on the frequency and field strength, as well as on the dielectric properties of the wood:

$$P = 0.55 \cdot f \cdot \varepsilon \cdot \mathrm{tg}\delta \cdot E^2 \cdot 10^{-12}, \tag{1}$$

where ε is the dielectric permittivity of a dioptric material (wood); E is the electric field strength; f is the frequency of electromagnetic vibrations; tgδ is the tangent of the loss angle; P is the specific power.

The current frequency for a microwave source is a constant value. It is selected from the frequencies allowed for industrial use, as well as taking into account the depth of penetration of electromagnetic waves into the wood. The ranges of 433 MHz and 915 MHZ are allocated for industrial microwave heating in the CIS countries. The range for household microwave ovens is set to 2,500 MHz.

The electric field strength is a controlled value and depends on the initial power of the microwave source.

The electrical property of wood is determined by the tangent of the loss angle tgδ and dielectric permittivity ε. The values of ε and tgδ depend on the structure of the wood, its humidity, as well as on the frequency of electromagnetic radiation and other factors. The coefficient of dielectric loss ε" that characterizes the properties of the material under high-frequency heating is defined by the formula (2):

$$\varepsilon'' = tg\delta \cdot \varepsilon. \tag{2}$$

Wet wood has the highest loss coefficient and therefore heats up more intensely. During the drying process, the coefficient of wood loss decreases, therefore, the heat released in the wood also decreases. This characterizes the selectivity of microwave heating. When the electric field penetrates the wood, it attenuates exponentially (3):

$$E = E_0 e^{-ax}, \tag{3}$$

where E_0 is the electric field strength on the surface of the irradiated material (E_0=1); a is the attenuation coefficient of the electromagnetic wave; x is the distance from the surface of the irradiated material to the point of determining the electric field strength; e is the exponent.

Fig. 1 shows a graph of the dependence of the electric field strength on the depth of penetration of the microwave field into the wood at different frequencies. The solid line is for wood moisture of 30 %, the dotted line is for wood moisture of 10 %.

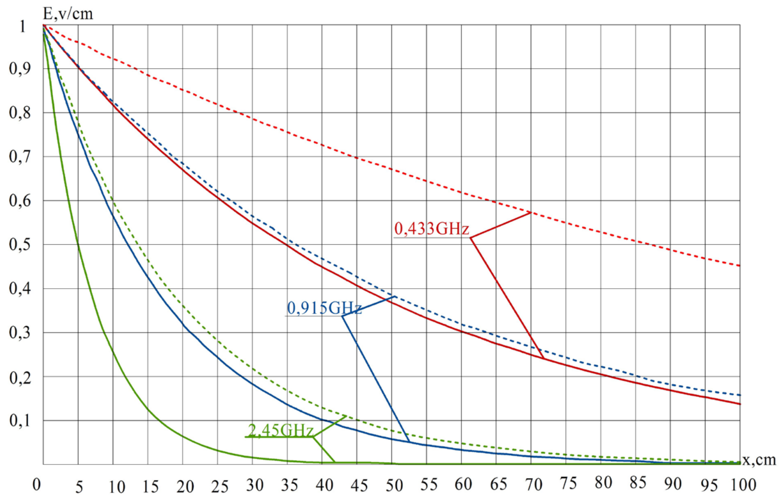

Fig. 1. Graph of the dependence of the electric field strength on the depth of penetration of the microwave field into the wood at different frequencies

Fig. 2 shows the graph of the total electric field strength during two-way microwave irradiation of a package of lumber 50 centimeters thick.

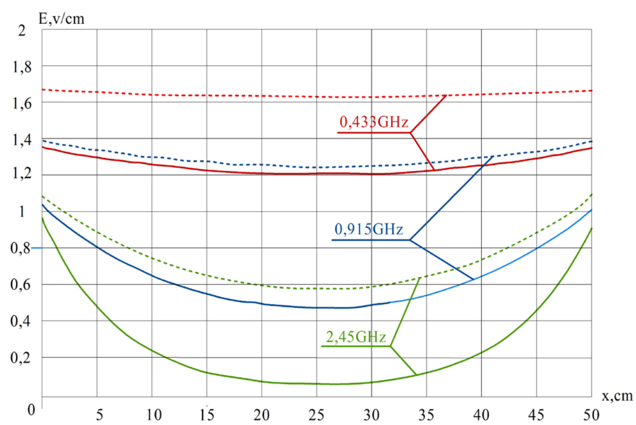

Fig. 2. Graph of the total electric field strength during two-way microwave irradiation of a package of lumber 50 centimeters thick

As can be seen from Fig. 2, the acceptable frequency for microwave drying of a package of lumber, timber and rounded logs is 0.433 GHz and 0.915 GHz. Household microwave ovens operate at a frequency of 2.45 GHz. The sources of microwave energy operating at this frequency are only suitable for the drying of thin materials. The above dependencies should be taken into account when designing systems for microwave drying of wood and lumber.

In order to show the fundamental difference between microwave drying of wood from other types, let's refer to Fig. 3, 4.

Schematically, the processes of drying logs by convective and microwave methods are shown in Fig. 3, 4. Conditionally, the log is divided into two zones – central and outer. When using convective drying of logs, first the surface layers are getting dried. The central zones remain swollen. This leads to the stretching of the surface layers around the swollen central zone and therefore to the formation of cracks on the surface of the log (Fig. 3). With the microwave method of log drying, first of all, the central zone is dried. The dried-out central zone attracts the outer zones (Fig. 4).

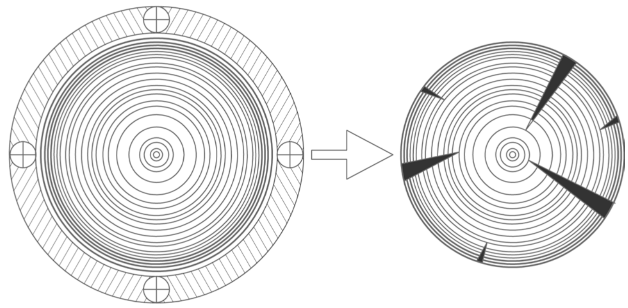

Fig. 3. Convective drying of logs

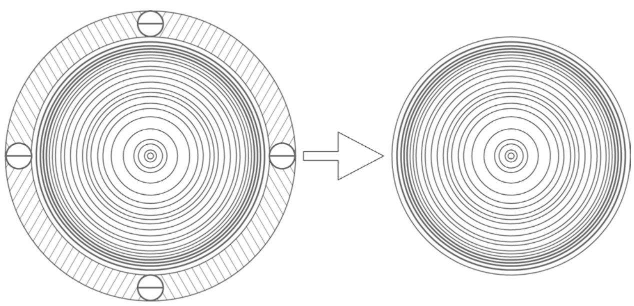

Fig. 4. Microwave drying of logs

When microwave drying, it is necessary to protect the wood from possible overheating of the wettest internal layers. This task can be solved by selecting the appropriate drying mode. The wood drying temperature should not exceed 100 °C for coniferous species and 90 and 70 °C for birch and oak, respectively. It should be noted that, contrary to popular opinion, the proposed microwave installations are actually relatively low in energy consumption. The energy consumption for drying one cubic meter of coniferous lumber is 65 kW/h or less (depending on the section) with 88 kW/h for birch and 130 kW/h or less for oak.

5. Determining the main parameters and selection of materials for a single-wire transmission line

A single-wire transmission line in the form of a single wire covered with a thin layer of dielectric material is also known as the Goubau line [15] along which an E_{00}–type wave propagates.

Fig. 5 shows the structure of the E_{00} surface wave field.

The characteristic feature of the E_{00} wave is the presence of the transverse components E_r, H_φ and the longitudinal component E_z that are symmetrical with respect to the wire axis [16].

The structure of the surface wave field has the following form:

$$E_z = -C_0 H_0^{(1)}(jkr)e^{-\gamma z}, \tag{4}$$

$$E_r = C_0 j\frac{\gamma}{k} H_1^{(1)}(jkr)e^{-\gamma z}, \tag{5}$$

$$H_\phi = -C_0 \frac{\omega\varepsilon_a}{k} H_1^{(1)} e^{-\gamma z}, \tag{6}$$

where $k=\gamma^2+\omega^2\varepsilon_a\mu_a$, $H_0^{(1)}$, $H_1^{(1)}$ is the Hankel function of the 1st type; C_0 is the constant; γ is the propagation constant; ω is the cyclic frequency; ε_a is the absolute dielectric permittivity; μ_a is the absolute magnetic permeability; z is the longitudinal coordinate along the wire axis; r is the boundary radius.

The nature of changes in the field components in the transverse direction can be described by the rapid decrease of the amplitudes of the fields outside the imaginary cylinder with radius r. The radius r of an imaginary cylinder is called the boundary radius. Speaking about longitudinal direction, there is a propagation of energy depending on the components of the field propagation constant. The value of the boundary radius, where 90 % of the energy is concentrated, depends on the coating of the wire and the ratio of the wire diameter to the coating diameter. Thus, almost all the energy coming from the generator is concentrated in the cross-section within the area defined by the boundary radius. This energy will interact with any inhomogeneity placed in this area. If the inhomogeneity lies in a conductor, the induced currents will re-radiate the energy of the surface wave field. If the inhomogeneity is performed by some dielectric material, then there will be energy losses along with the re-radiation, therefore the object will be heated and dried. This circumstance allows for microwave drying of wood materials placed in an area limited by the boundary radius.

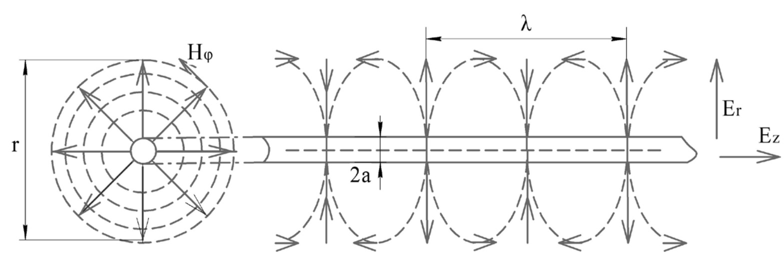

Fig. 5. Structure of the surface wave electromagnetic field E_{00}

The intensity of the concentration of microwave radiation on the drying object depends on the specific conductivity of the applied wire in a single-wire transmission line. For a greater concentration of microwave radiation on the drying object, a wire with a dielectric coating should be used. In this case, the single-wire line will have a small attenuation when the surface wave propagates, and the main part of the electromagnetic energy will be concentrated in a small volume around the wire [15].

According to calculations (4)–(6), it can be seen that the boundary radius r in relation to the wavelength changes as 3.2:1.6:1. For the wavelength of λ=120 mm, wire diameter of a=6 mm and coating thicknesses t=0.2 mm, 0.6 mm and 0.9 mm. Thus, the density of the electromagnetic radiation flux largely depends on the ratio of the wire diameter and coating thickness. This condition should be taken into account when designing microwave installations based on a single-wire transmission line.

When implementing a single-wire transmission line in the form of a single wire, the determining factor is the choice of wire material. We have studied several conductors whose properties are shown in Table 1.

Table 1

Properties of conductors used in a single-wire transmission line

No.	Metal	Specific conductivity, $10^4, \frac{1}{\text{Om} \cdot \text{cm}}$	$\delta_{(\text{mm})} \cdot \sqrt{f_{(\text{kHz})}}$, penetration depth	Tensile strength limit $\frac{\text{kg}}{\text{mm}^2}$	Temperature coefficient of linear expansion, 10^{-5}, $\frac{1}{C^0}$
1	copper	57	2.11	27÷45	1.7
2	aluminum	33.3	2.75	8 ÷25	2.3
3	zinc	16.7	3.9	14 ÷29	3.2

When implementing a single-wire transmission line, the dielectrics should be carefully selected, since often they play the role of power elements of the structure (Table 2).

Table 2

Properties of dielectrics used in a surface waveguide

No.	Dielectric type	Dielectric permittivity, ε	Operating temperature range, °C	Density, $\frac{\text{kg}}{\text{m}^3}$	Strength limit, $\frac{\text{kg}}{\text{mm}^2}$
1	Fluoro-plast-4	2÷2.2	200	1.65÷1.8	20
2	Polyamide	3÷4.5	250	1.02÷1.1	60
3	Fiber-glass laminate STEF	5÷6	150	1.77÷1.9	350

We studied a fragment of a bimetallic wire made of aluminum alloy with a steel core. Here, the wire was externally coated with a film of aluminum oxide Al_2O_3 (ε=9, tgδ=$2.7 \cdot 10^{-3}$, ρ=$1 \cdot 10^{10}$ Ohm·m), which has a high dielectric constant and the ability to tolerate significant heating temperatures. The results of experimental work and theoretical calculations show a significant discrepancy in the values of the boundary radius. Thus, at a frequency of 1,000 MHz, a pure aluminum wire has a calculated boundary radius of $r_0 \approx 4$ m. The thickness of the oxide film is $t=5 \cdot 10^{-5}$ m. In fact, the boundary radius amounts to one wavelength. It is assumed that the coating of the wire is more complex and is a three-layer coating of Al_2O_3, the thickness of the skin layer of $2.7 \cdot 10^{-3}$ m and the wire itself. In this regard, the use of bimetallic aluminum wire in industrial installations is quite acceptable.

A fragment of the R-274M cable was also examined. The research results are shown in Table 3.

Table 3

Parameters of wave propagation in a surface waveguide at various frequencies

Frequency, GHz / Parameter	0.4	0.8	1.6	3.2
$\frac{r_0}{\lambda}$	0.284	0.258	0.237	0.211
r_0, m	0.930	0.097	0.044	0.019
δ, mm	$8.6 \cdot 10^{-3}$	$4.3 \cdot 10^{-3}$	$2.15 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$

As can be seen from the values given in Table 3, the specified cable can also be used as a wire for a surface wave line in the microwave range.

6. Evaluation of the efficiency of the surface wave excitation system

A wire covered with a thin layer of dielectric material is a single-wire line for transmitting electromagnetic energy only if special surface wave excitation devices are placed at its ends. Therefore, the development and research of such surface wave excitation devices are extremely important. The structure and properties of the surface wave field depend on the excitation devices.

We propose to use an excitation system in the form of a series of vibrators located around the wire, along the radial lines of the electric field intensity E_r. The proposed system is shown in Fig. 6.

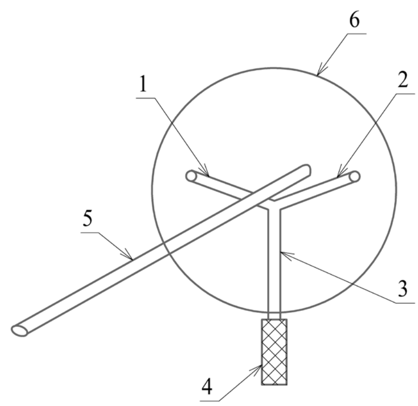

Fig. 6. Surface wave excitation system consisting of three vibrators

The proposed E_{00} type surface wave excitation system consists of three half-wave vibrators (1–3), one of which is connected to a coaxial feeder via a quarter-wave locking cup (4). The system formed of three half-wave vibrators is installed near a single wire with a dielectric coating (5). A flat disk-shaped reflector (6) can be installed on one side of such a system.

The excitation system works as follows. The signal power coming from the generator is evenly distributed among all vibrators from the entire set. The radiation of a set of vibrators leads to the excitation and propagation of a surface wave to both sides of the wire. The degree of connection is determined directly by the distance between the ends of the vibrators to the wire. The system proposed by us is much easier to create a surface wave than using a conical horn junction with a feeder attached to its neck.

The greatest advantages are shown in the proposed system in the case of installing a flat reflector near the vibrators. In this case, there are achieved unidirectional excitation of surface waves, as well as the possibility of mechanical attachment of exciting elements directly to the reflector. The reflector reflects the surface wave falling on it and, in general, the "wire-reflector" system shows the unidirectional propagation of the surface wave due to the radiation of a set of vibrators. Usually, the dimensions of a flat reflector should be at least half the wavelength, and the distance to the reflector should be chosen in the range of (0.1÷0.3) λ, which determines the alignment of the vibrators with the feeder. In addition, the field excitation in one direction from a flat reflector in combination with the possible galvanic isolation of the wire and the reflector will allow any homogeneous section of the wired network to be used as a single-wire transmission line. Another positive aspect of the proposed excitation system is that in essence, it is concentrated in a single section. Besides, the proposed excitation system of three vibrators was the most optimal from a constructive point of view.

We emphasize that special attention should be paid to the contact area of the wire with the flat reflector. Fig. 7 shows a fragment of a surface wave wire with a flat reflector mounted on it.

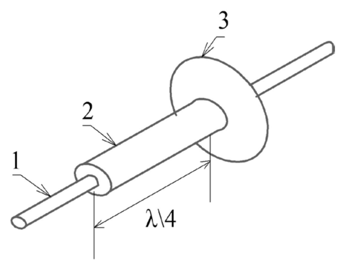

Fig. 7. Fragment of a surface wave wire with a flat reflector: 1 – surface wave wire; 2 – quarter-wave segment; 3 – flat reflector

As the results of additional research have shown, the perfection of this contact largely determines the effectiveness of excitation. In this regard, mechanical contact, soldering or welding make this connection extremely unstable, depending not only on the quality of performance, but also on external factors: temperature, humidity, or mechanical influences. Thus, a solution in the form of an open quarter-wave line segment is required here. The advantages of this method of decoupling are obvious. First of all, the galvanic connection of the excitation system and the reflector with the wire disappears, which expands the design possibilities and ensures stability in the operation of the excitation system.

Thus, the following solutions of the problem of designing systems for microwave drying of wood and lumber are of certain interest:

– concentrated excitation systems in the form of radial vibrators;

– installation of a reflector near the vibrator system;

– mechanical and galvanic isolation of the flat reflector and exciting elements from the wire.

7. Development of the design of the absorbing load of the components of the surface wave

The next stage of the study is to create a design of a dissipation load designed to absorb unclaimed electromagnetic energy when irradiating the drying object.

When studying the dissipation loads, the task of creating a structure designed to absorb the components of the surface wave E_{00} came to the fore. As follows from the structure of the field (Fig. 5), power absorption in a cylindrical area defined by the boundary radius r can be performed through the longitudinal component E_z and the radial component E_r. According to this condition, the structure of the dissipation load was designed.

The proposed version of the dissipation load is shown in Fig. 8.

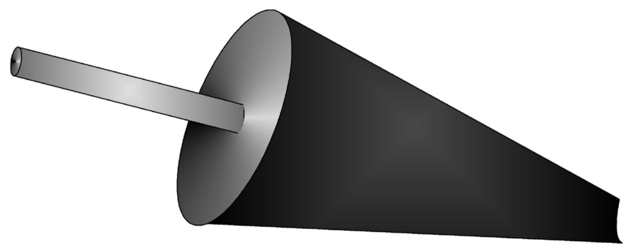

Fig. 8. Structural design of the load in the form of a composite sleeve

The study was carried out on a structure in the form of a composite sleeve beveled along the z axis and put on the wire of the E_{00} surface wave energy transmission line.

The principle of operation of such a load consists of placing dissipation materials in the plane of vibrations of the electric field intensity vector. It is a very simple design, but the volume of the composite at a frequency of 2.45 GHz is quite large.

The developed design of the dissipation load has been successfully tested during the laboratory works.

8. Discussion of the results of designing the large-sized lumber uniform drying system based on MW radiation

The research showed that the proposed vibratory excitation device generally forms two surface waves diverging along the z axis. When a flat reflector in the form of a disk is used in the system, the excitation of surface waves becomes unidirectional. Depending on the wave resistance of the segment, the quality of the dielectric, the correctness of the selected wave shortening factor, and the size of the reflector, the decoupling could reach 20 dB.

As a result of experiments with a single wire transmission line at different frequencies, the following results were achieved:

– uneven distribution of the surface wave field at a frequency of 433 MHz was ±22 dB in the no-load mode and ±11 dB in the load mode;

– uneven distribution of the surface wave field at a frequency of 915 MHz was ±9 dB in the no-load mode and ±5 dB in the load mode;

– uneven distribution of the surface wave field at a frequency of 2,400 MHz was ±10 dB in the no-load mode and ±1 dB in the load mode.

Thus, this research has predetermined the possibility of implementing the microwave drying system based on a single-wire transmission line.

The physical model of the system for uniform drying of large-sized lumber by microwave radiation is shown in Fig. 9.

The wire (1) of the waveguide is excited through a vibratory excitation device (2) using a set of generators (3). The energy of the surface wave propagates towards the ballast load (4). The drying object (5), placed at a certain distance from the wire axis, is located in the zone of concentration of surface wave energy and is heated simultaneously and evenly throughout the entire volume. Thus, the drying object is heated by the microwave energy of the surface wave. The microwave energy not spent on heating the drying object enters the ballast load (4), which is connected to the heating register of the heating system (6), the heat of which can be used to heat the room in winter. The entire installation is enclosed in a shield (7).

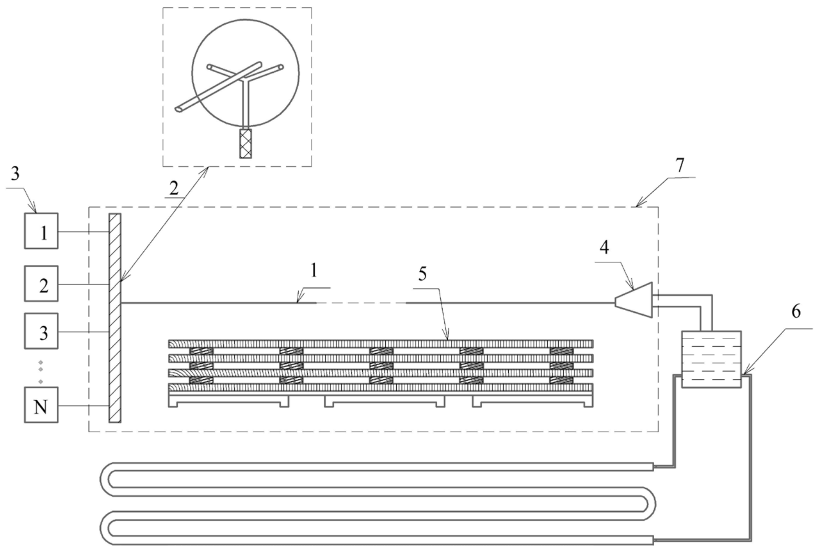

Fig. 9. Large-sized lumber uniform drying system based on MW radiation

The proposed system uses a vibratory surface wave excitation device (2), shown in Fig. 6, which allows exciting a surface wave and thus obtaining the necessary microwave power.

Preliminary analysis and calculations show that the use of a single-wire transmission line in a system for microwave drying of large-sized lumber has advantages over traditional ones. The main ones are as follows:

– minimum metal consumption of the entire drying system;

– minimum capacity that needs to be disposed of;

– minimum radiated power;

– energy spent in the ballast load can be disposed of and returned in the form of room heating in the winter season;

– possibility of implementing uniform drying even of large-sized lumber.

This research is limited to solving a statistical problem, since the dependence of energy consumption on the amount of moisture, permittivity, the tangent of the angle of dielectric loss and attenuation of energy with depth is a complex value. In the future, we are planning to make appropriate adjustments taking into account the features of the unit used.

It is also planned to conduct an analysis determining energy costs, which do not depend much on the drying method. To determine the reserves of energy savings, a certain criterion will be introduced into the system of automatic power control and drying completion time.

The further task of the research is to conduct a full-scale experiment on the unit based on the proposed system.

9. Conclusions

1. To irradiate the object, it was proposed to use a surface wave waveguide in the form of a single-wire transmission line (Goubau line).

2. An E_{00}-type surface wave excitation system has been developed. The proposed system is much easier to create a surface wave than a coaxial horn. A significant advantage of the system is that it is concentrated in a single section. The system is also optimal from a constructive point of view.

3. The design of the absorbing load was developed. The advantage of the proposed design is simplicity of its manufacturing.

4. A physical model of a system for microwave drying of large-sized sawn timber based on a single-wire transmission line with its constituent parts is proposed.

This work is an important step in paving the way to the microwave drying industry of wood processing enterprises.

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DEPENDENCE OF THE INTERNAL WAVE ENERGY FLUX ON THE PARAMETERS OF A TWO-LAYER HYDRODYNAMIC SYSTEM

Yu. Hurtovyi
PhD, Associate Professor*
O. Avramenko
Doctor of Physical and Mathematical Sciences, Professor, Head of Department*
V. Naradovyi
PhD, Senior Lecturer*
E-mail: naradvova1986@gmail.com
*Department of Applied Mathematics, Statistics and Economics
Volodymyr Vynnychenko Central Ukrainian State Pedagogical University
Shevchenka str., 1, Kropyvnytskyi, Ukraine, 25006

The study was performed to analyze the flux of energy of internal gravitational-capillary waves in a two-layer hydrodynamic liquid system with finite layer thicknesses. The problem was considered for an ideal incompressible fluid in the field of gravity as well as taking into account the forces of surface tension. The problem was formulated in a dimensionless form for small values of the coefficient of nonlinearity. The dispersion of the gravitational-capillary progressive waves was studied in detail depending on the coefficient of surface tension and the ratio of layer densities. It was proved that with the increase in the wavenumber, the group velocity begins to pass ahead of the phase velocity and their equality occurs at the minimum of the phase velocity. Dependence of the total average energy flux on the wavenumber (wavelength) and thickness of the liquid layers was calculated and graphically analyzed for different values of physical quantities, in particular, density and the coefficient of surface tension. It follows from the analysis that the energy flux of gravitational internal waves increases to a certain maximum value with an increase in the thickness of the lower layer and then approaches a certain limit value. For capillary waves, the energy flux of internal waves is almost independent of the thickness of the lower layer. It was also shown that the average energy flux for gravitational waves at a stable amplitude is almost independent of the wavelength. On the contrary, for capillary waves, the energy flux increases sharply with an increase in the wavenumber.

The results of the analysis of the energy flux of internal progressive waves make it possible to qualitatively assess physical characteristics in the development of environmental technologies that use internal undulatory motions in various aquatic environments as a source of energy

Keywords: energy flux, internal progressive waves, two-layer hydrodynamic system, anomalous dispersion

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1. Introduction

Internal waves are undulatory motions in a stratified fluid. Stratification means that, for example, ocean water is divided into layers of different densities which increase with depth. Stratification is caused by various natural phenomena: storms, melting of ice, heating of upper water layers, changes in ocean salinity, etc. It is at the boundary of layers with different densities that a whole class of different wave phenomena occurs.

The relevance of studying such phenomena is determined by the necessity of developing environmental technologies that use internal waves as a source of energy in various aquatic environments. Also, such a study will be useful in creating devices for damping internal waves where they are harmful. In this case, the mechanical en-