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APPLIED RADIO PHYSICS

THE PROBLEM OF SIMULATION OF MICROWAVE TRAVELLING WAVE PROCESS PLANT FOR DRYING TIMBER *

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Physical aspects of modeling of the electromagnetic field capacity distribution in the microwave chamber for wood drying submitted to the passage of the running wave are presented. Refinements of the available electromagnetic models which make it possible to remove existing shortages are given. The numerical analysis of the electromagnetic field capacity distribution in equidistant array of Hertz radiators is carried out. The analysis of the Hertz electric dipole electromagnetic phase characteristics is given for the conducting medium equivalent to the timber pile.

KEY WORDS: *microwave chamber, shaped timber drying, heat power, local overheating, slotted-waveguide irradiator, electromagnetic power distribution*

1. INTRODUCTION

The use of microwave energy for drying timber is more efficiently than high frequency energy as the power transmitted to a dielectric by the electromagnetic field is proportional to the frequency, the square of intensity of the electric field and dielectric loss factor. The microwave ranges with the following frequency values: 460, 915 and 2450 MHz are allocated for the industrial application in Russia. Absorption and conversion of microwave power in the lossy dielectric into heat is calculated depending on the complex permittivity and loss factor. Humid timber has the greatest value of the dielectric loss factor. When using microwave energy for drying saw-timber one should take into account a number of advantages peculiar only to the given type of energy:

– the possibility to concentrate a high heat energy on the unit of timber volume, it is impossible with the traditional methods of drying;

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– the possibility to receive a selective heating of timber and temperature distribution in the material required according to the technology with a low sluggishness of the process.

But a number of reasons causes unsatisfactory results of the microwave energy application to the lumber drying. Among them there are:

– the low-power microwave sources operating at the frequencies 2450 MHz, this is unacceptable for the lumber packages drying;

– the package one-sided radiation, this results in its nonuniform heating and drying across the width;

– the material local overheating due to surface waves formation resulting in the saw-timber inflammation;

– the microwave energy nonuniform distribution over the lumber pile.

The electrodynamic model of the timber drying process in a drying chamber where microwave heating is provided by the slotted-waveguide irradiators placed along the chamber, i.e., parallel to the lumber pile is considered in [1]. But the clear recommendations for designers and maintenance personnel of such process plants have not been received in full measure in spite of the physically rigorous statement of the problem, the use of the specialized computer simulation program and the experimental confirmation of the obtained results.

The authors of the given work have tried to consider the solution of problems which would contribute to improvements in the available electrodynamic models and make an attempt to find a concrete algorithm for the microwave drying chambers computer-aided design.

2. STATEMENT OF THE PROBLEM

A great number of theoretical and experimental investigations, incorporating analysis of the physical singularities of sloping and curvilinear slots radiation in the near and intermediate zone, investigation into singularities of polarization and diffraction effects of radiation and mutual action of radiators is devoted to simulation of the slotted-waveguide irradiators.

Let us consider setting up of the problem close to [1] corresponding to the waveguide transmission line placement in the traveling wave drying unit – conveyer-type driers with crossed motion, where direction of the material movement and electromagnetic field flow are perpendicular to each other (Fig. 1).

The slotted-waveguide irradiators are placed along the pile, i.e., radiation from every slot is directed perpendicular to the end face of boards. The length of each slot was assumed to be equal to 0.5 λ. Such a radiating system forms a two-dimensional equidistant antenna array excited smoothly and cophased. It is known that the metallic plane, along which the slot is placed, is an infinite plane, then the radiation pattern of such a slot is an identical one to the radiation pattern of the wire oscillator.

It is known that for the wire oscillator there is a rigorous solution of the external electrodynamic problem defining the value of the electromagnetic field components at any distance from the radiator. When the planes of the desk inserted into the slot and electric field E intensity coincide, the intensity of the desk irradiation with the microwave energy is the maximum one. At the desk movement through the waveguide each its part receives similar portion of energy. If several waveguides are placed along the line of the desk motion then each section of the desk receives an equal portion of energy with a time interval. In such a unit an interrupted or cyclic drying process is realized, it is less energy consuming than the continuous one.

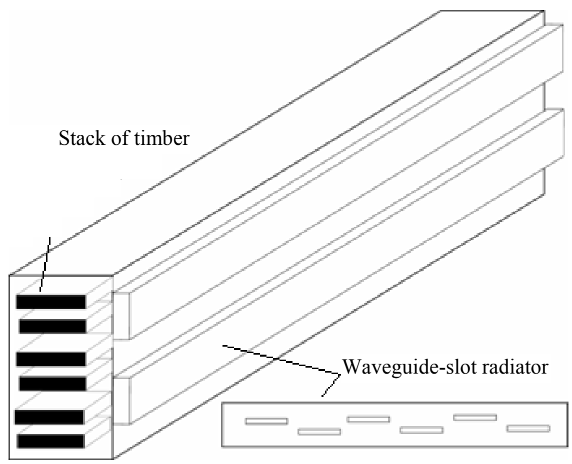

FIG. 1: Process unit for drying saw-timber

In the electrodynamical model shown in Fig. 1 the distance between each slot till the pile corresponded to the far zone of the individual radiator. But as applied to the waveguide with 10 cut slots the pile is in the near zone as for such a system, forming an antenna array, the far zone distance is well described by the relation $R_{fz} > 2L^2/2$. In [1] power was calculated using the relations which are plausible to the far zone of the individual slot radiator.

According to our investigations, where the linear array electromagnetic field power was calculated using Pointing theorem for the complex amplitudes by the following relation

$$\dot{S} = \left[\dot{E}, \dot{H}\right] \tag{1}$$

this results in significant difference in the spatial distribution of the microwave power as compared to the case when the relation similar to [1] is used, i.e., to the relation $P = \omega\varepsilon'\varepsilon'' \cdot E^2$.

To simulate the electromagnetic field distribution inside the timber, the rigorous relations should be used for calculation of the axial radiator current density distribution (the Pilkington integral equation) in the form

$$\left(\frac{d^2}{ds^2}+k^2\varepsilon\mu\right)\int_{-L}^{L} J(s')\frac{e^{-ik\sqrt{\varepsilon\mu}R(s,s')}}{R(s,s')}ds' = iwE_{os}(s)\,, \qquad (2)$$

where $E_{os}(s)$ is the field of the extraneous sources; $R(s,s')=\sqrt{(s-s)^2+r^2}$ is the distance between the observation and integration points; ε_1 and μ_1 are dielectric and magnetic permeability of the material; $k=2\pi/\lambda$; s is the longitudinal coordinate, $k_1=k\sqrt{\varepsilon_1\mu_1}$.

In conformity to the timber representing lossy dielectric, i.e., $\mu_1=0$, $\varepsilon_1=\varepsilon_1'+i\varepsilon_2''$. For the wood with a high humidity $\varepsilon_1'=8,\ \varepsilon_2''=1.3$, for the wood with a mean humidity $\varepsilon_1'=5,\ \varepsilon_2''=0.9$, for the wood with a low humidity $\varepsilon_1'=2,\ \varepsilon_2''=0.23$.

With the aim to determine the field distribution into a desk let us make use of the expressions from [7] uniquely determining the vibratory radiation field in the material medium in the spherical coordinate system ρ,θ,φ :

$$E_p(\rho,\theta)=\frac{k_1\rho}{w\varepsilon_1}\int_{-L}^{L} J(s)G(\rho,\theta,s)\left(\frac{2R}{\rho}W_1\cos\theta-ik_1sW_2\sin^2\theta\right)ds\,,$$

$$E_\theta(\rho,\theta)=\frac{k_1\rho}{w\varepsilon_1}\int_{-L}^{L} J(s)G(\rho,\theta,s)\left[\frac{2R}{\rho}W_1-ik_1sW_2(\rho-s\cos\theta)\right]ds\,, \qquad (3)$$

$$H_\varphi(\rho,\theta)=\frac{ik_1\rho\sin\theta}{c\sqrt{\varepsilon_1\mu_1}}\int_{-L}^{L} J(s)G(\rho,\theta,s)RW_1ds\,,\ G(\rho,\theta,s)=\frac{e^{-ikR}}{R^3}\,,$$

$$R=\sqrt{\rho^2-2\rho s\cos\theta+s^2}\,,\ W_1=1+1/ik_1R\,,\ W_2=1+3/ik_1R-3/k_1^2R^2\,.$$

3. ANALYSIS OF RESULTS

A complicated nature of the dependence is demonstrated in Figs. 2 and 3 which show the electromagnetic field power distribution for the linear equidistant array with five and four radiators. They clearly demonstrate the field distribution nonuniformity in the direction perpendicular to the radiators arrangement as compared to the direction along which the radiators are arranged. The radiators arrangement scheme described in [4] is applicable to the drying chamber model shown in Fig. 1. The algorithm researches [2] have shown that neglect of the near field peculiarities results in significant errors in detection of the value and spatial distribution of the radiation "maxima" and "minima" which are in the intermedial zone of the radiators array. The place of each radiator is shown as a circle on the Z axis in the plots of Figs. 2 and 3 representing the electromagnetic field power distribution in the free space, which area corresponds to the space before the beginning of the pile arrangement corresponding to the intermediate (middle) zone of the radiators array. All components of the electromagnetic field – the Hertz dipoles, the distance between them corresponding to 0.5 λ, were taken into account.

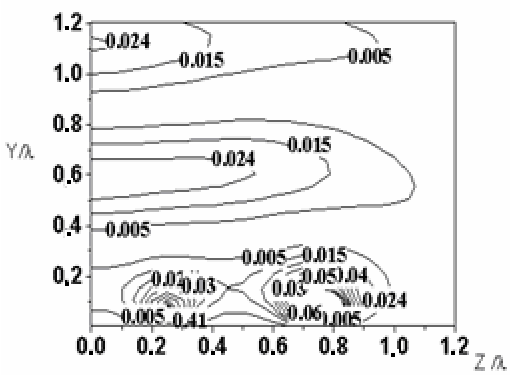

FIG. 2: Electromagnetic field power distribution of the array consisting of 14 radiators (1 square)

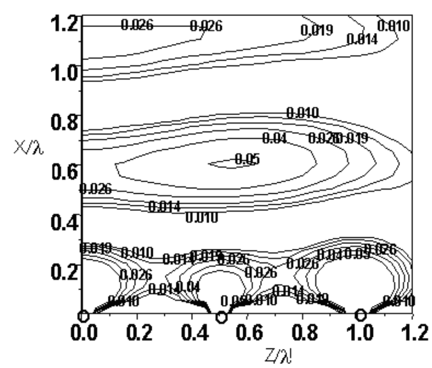

FIG. 3: Electromagnetic field power distribution of the array consisting of 5 radiators (1 square)

In the algorithm, according to which the calculations were carried out, their results were show in Figs. 2 and 3, the mutual action of the array radiators had been taken into account, the summarized components of electric and magnetic fields were calculated according to the principle of superposition for the observation point situated in the far-field zone of each radiator.

The algorithm for calculation of energy distribution in the form of the equal level lines is given in [4], according to it the power distribution is presented by virtue of symmetry in the plot (Fig. 2 for four radiators) only in the right-hand half relative to the axis Y. According to the given algorithm the electromagnetic field power distribution is presented for five radiators (Fig. 3) spaced at the intervals of 0.5 λ.

But the presented dependences cannot be used for description of regularities of the electromagnetic field distribution in the timber pile which to be considered as a dielectric. The analysis of the amplitude and phase characteristics of the electromagnetic field has shown that expressions for all components of E and H fields of the Hertz dipole are applicable to the analysis of short wire vibrator antennas [3-5]. It is impossible to obtain expressions for phase difference between transversal components of the electromagnetic field in the explicit form by relations (3).

The authors have carried out the analysis of the amplitude and phase relations between the components of the electromagnetic field of the Hertz dipole in the conducting medium with random values ε, μ and σ given in [5].

As the wave number in them is a complex value $k(\omega) = k'(\omega) + ik''(\omega)$, where $k''(\omega) < 0$, then the field of the dipole decreases with the increase in the distance from it as a result of the energy absorption in the medium.

In the general case (both strong and weak absorption) the real and imaginary parts of the wave number are expressed by the following relations [5]:

$$k'(\omega) = \frac{\omega}{\sqrt{2}}\sqrt{\varepsilon'\varepsilon_0\mu'\mu_0}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon'\varepsilon_0}\right)^2}+1\right)^{1/2},$$

$$k''(\omega) = \frac{\omega}{\sqrt{2}}\sqrt{\varepsilon'\varepsilon_0\mu'\mu_0}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon'\varepsilon_0}\right)^2}-1\right)^{1/2} \qquad (4)$$

Complex power flow in the direction $\theta = \pi/2$ is defined with the formula

$$S = H_\varphi E_\theta e^{i\varphi}, \qquad (5)$$

where φ is the phase difference between components of the field E_θ and H_φ [4].

In the case of a loss-free medium it should be assumed $\sigma = 0$, a $k = \omega\sqrt{\varepsilon\mu}$ [5,6]. in the latter case the formulae from [4] coincide with the similar expressions for the free space and all phase and amplitude relations have the same form as in [5] with the difference that the wave length will be shortened and is defined by the formula $\lambda = 2\pi/\omega\sqrt{\varepsilon\mu}$.

In the case of small absorption $(\sigma/\omega\varepsilon << 1)$ the expressions for the Hertz dipole can be written more thoroughly. The corresponding conversions result in the following:

$$E_\theta = i\frac{\dot{I}^e L}{2\lambda}\sqrt{\frac{\mu}{\varepsilon}}e^{-|k''|R}\sin\theta\frac{1}{(k'R)^2}\sqrt{\left((k'R)^4-(k'R)^2-2(k'R)\left((k'R)^2+1\right)\right)}\frac{e^{-ik'R}}{R}e^{i\varphi_{R^4}}, \quad (6)$$

$$\varphi_{E\theta} = \arctan\frac{2\left((k''R)-(k'R)^2\right)}{(k'R)^2\left((k'R)^2-1-(k''R)\right)}, \quad (7)$$

$$E_R = i\frac{\dot{I}^e L}{2\lambda}\sqrt{\frac{\mu}{\varepsilon}}e^{-|k''|R}\cos\theta\frac{1}{(k'R)^2}\sqrt{(k'R)^2-2(k'R)^3(k''R)+1}\frac{e^{-ik'R}}{R}e^{i\varphi_{ER}}, \quad (8)$$

$$\varphi_{ER} = \arctan\frac{(k'R)^2-2(k''R)}{1+k''R}, \quad (9)$$

$$H_\varphi = \frac{\dot{I}^e L\pi}{\lambda^2}e^{-|k''|R}\frac{\sin\theta}{(k'R)^2}\sqrt{(k'R)^2+1-2(k''R)(k'R)^3+2\frac{\sigma}{\omega\varepsilon}(k'R)^2\left((k''R)-(k'R)-1\right)}\times$$
$$\times e^{-ik'R}e^{i\varphi_{E\varphi}}, \quad (10)$$

$$\varphi_{B_\varphi} = \arctan\frac{(k'R)^2-2(k''R)^2-\frac{\sigma}{\omega\varepsilon}(k'R)(1+k'R)}{(k'R)(1+k'R)+\frac{\sigma}{\omega\varepsilon}\left((k'R)^2-2(k''R)\right)}, \quad (11)$$

where $k' = \omega\sqrt{\varepsilon\mu},\ k'' = -\frac{1}{2}\sqrt{\frac{\mu}{\varepsilon}}\sigma,\ |k''| << k'$.

It is evident from these expressions that the amplitudes and phases of all field components as compared to free space are defined not only by permeability ε and μ, but also by the medium conductivity σ.

First let us consider general regularities of the losses action in the medium on the nature of the wave processes in the near and intermediate field zones [4]. With this object in view the real part of permittivity $\varepsilon(\omega)$ was take equal to a definite value and its imaginary part varied over a wide limits and calculations of dependences on the distance to the observation point of amplitudes and phases of the field components [5] as well the field power flow densities were carried out. As it is shown in [3-4] the features of the wave processes in the vicinity of the radiator are defined largely by the phase difference between components E_θ and H_φ in the observation point. Figure 4 shows the phase difference dependence of the components E_θ and H_φ on the distance with $\varepsilon' = 10$ and loss tangent variation from 0.001 to 10. In the calculations the frequency of the alternating current exciting Hertz dipole is assumed to be equal to 10 MHz. It follows from the figure that with small losses $(\tan\delta = 0.001...0.01)$ the phases difference between transverse components of the electric and magnetic fields are not distinct from the phase difference of these components for Hertz dipole in the free space [3,4]. With ($\tan\delta = 10...1$ in Fig. 4), which corresponds to low humidity of wood (10%), qualitative variations are observed, in particular, in the vicinity of the radiator the phase difference is equal to 85^o and in the far-field zone it passes through zero and reaches several degrees.

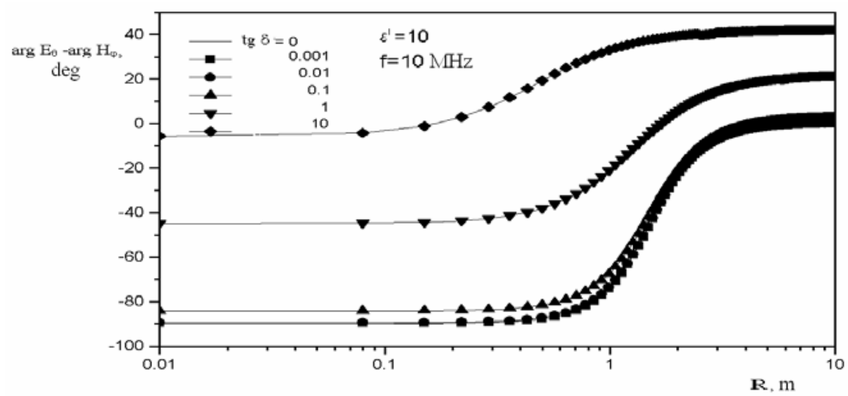

FIG. 4: Dependence of phase difference between the cross components of the electromagnetic field on the distance

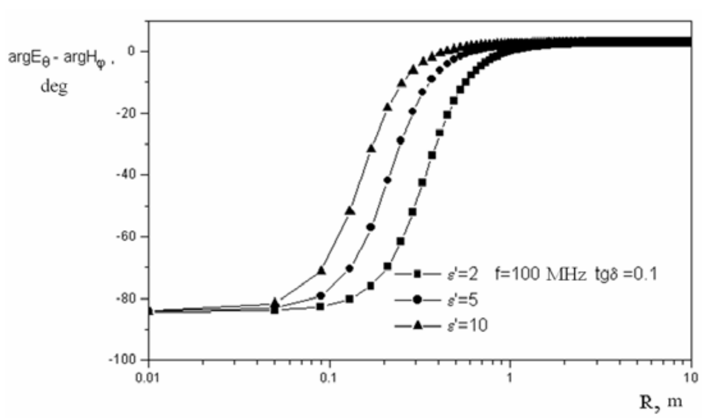

FIG. 5: Dependence of phase difference between the cross components of the electromagnetic field on the distance at different environment parameters

With further decrease in losses $\tan\delta = 10...1$ in Fig. 5 (which corresponds to variation of ε′ in the process of drying softwood) these particularities are amplified and result in a qualitative variation in the wave processes nature. In particular, in the vicinity of the radiator with $\tan\delta = 1$ the phase difference $\Delta\varphi = -45^0$ and passes through zero at a distance of about 1 m, and then increases and in the far zone, where the corresponding curve transforms into the horizontal straight line, the phase difference is equal approximately to +20^o. These features are enhanced even more with the increase in losses. Hence**,** with $\tan\delta = 10$ in the vicinity of the radiator the phase difference is equal to – 7^o, it passes through zero at the distance of the order of 0.3 m and further on it increases up to + 45^o, i.e., in the wave zone the nature of the Hertz dipole has the reactive nature. The phase difference of + 45^o between the components results in that the energy flow depending on the distance decreases faster than $e^{-2|k''|R}/R^2$ described by the law. Additional calculations have shown that peculiarities of the field nature variation in the near, intermediate and far-field zones of the Hertz dipole radiation depending on the losses in the medium reveal themselves the stronger, the greater ε' is and the greater losses are. Let us consider the action of the absolute value of the real part of the medium permittivity ε' on the nature of the wave processes in the Hertz dipole near zone. Figure 5 demonstrates calculations of phase difference of the transverse components of the electric and magnetic fields depending on the distance with ε' equal, respectively, to 2, 5 and 10 and the losses parameter $\sigma/\omega\varepsilon'\varepsilon_0 = 0.1$. From the calculations it is seen that in the context of not very high losses the phase difference of the components in the vicinity of the radiator equals to – 83^o and with the increase in the distance from the radiator to the observation point the nature of the waved processes differs greatly. In particular, the greater ε', the closer the near reactive fields are to the antenna. In the wave zone the phase difference for all three calculated versions of the medium is a similar one and it equals approximately to +5^o. Thus, it can be seen from the above calculations that the phase difference between components in the wave zone is defined not only by the value of the medium permittivity but by the losses in this medium. In Fig. 5 it is seen that the far-field zone region, i.e., the region where the phase difference between E and H equals to 0 degrees decreases with the decrease in ε'.

4. CONCLUSIONS

1. Simulation of the electromagnetic field distribution in the microwave chamber for drying timber by differing analytical expression for calculations of the components of electromagnetic field in the space between the walls of the chamber and the pile differs by different ε and $k(\varepsilon)$.

2. The superposition principle for finding summarized components of the electromagnetic fields E and H is applicable at the distances corresponding to the region inside the timber pile, i.e., in the far-field zone.

3. Calculation of the electromagnetic power distribution in the space inside the chamber should be carried out using the Pointing theorem for complex amplitudes at any distance from the radiators array.
4. At the increase in the electromagnetic field power losses in the timber pile the reactive field region length, i.e., the electromagnetic field power distribution along the pile will differ (decrease) significantly, all other thing being equal.
5. At construction of the electrodynamic model it should be taken into account that at the beginning of the drying process the region of the near reactive field is father than the radiators and it is displacing to them in the drying process.

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