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THE ANALYTICAL EXPRESSIONS TO DESCRIBE WAVE PROPAGATION AND HEAT RELEASE DURING MICROWAVE TREATMENT OF POROUS INHOMOGENEOUS PLATE BASED ON THE W.K.B. SOLUTION MODEL

ABSTRACT

In this paper study for wave propagation in non-homogeneous porous plate sample with slowly varying refractive index is presented. It is based on simple symmetric solution of the wave equation for linearly polarized electromagnetic wave aligned into the porous plate perpendicularly to the external surface. Using correct boundary conditions both the transverse electric (T.E) and transverse magnetic (T.M) modes, named shortly by (T.E.M) mode for electromagnetic wave, are considered. The Wentzel-Kramers-Brillouin (W.K.B.) solutions for symmetric incident irradiation of fixed power generated at the plate surfaces was obtained. It is done the analysis of the reflection and transmission coefficients on the surfaces of plate.

Keywords: *porous media; electromagnetic waves; dielectric loss factor; computer sciences*

INTRODUCTION

One of the most well-known analytical methods for studying one-dimensional optical and quantum structures is the W.K.B method [1,2,24]. This method is widely used for calculation of eigenvalues of guided optical structures. Also, this method is used to study the wave propagation in inhomogeneous structures [2]. In all of these papers, a solution consistent of non-uniform backward and forward waves with constant coefficients being determined by boundary conditions is assumed. These predetermined forms of solution cannot represent all possible forms of solution and their application is then limited to slowly varying structures. A new method for analytical calculation of band structure of inhomogeneous nonmagnetic one-dimensional optical structures [3] is introduced. In this method, a representation of W.K.B formulation with non-constant and primarily unknown coefficients is considered as the general solution of wave equation in the structure and by using a method similar to what is used in [4,5-7] analytical expressions are obtained for those non-constant coefficients. One of the advantages of this method, which leads to analytical and simple expressions for unknown coefficient functions, for both electromagnetic T.E and T.M waves modes. In order to extend

this method to both magnetically and electrically inhomogeneous structures the modified forms of W.K.B solution with nonconstant and unknown coefficients as the general solutions to wave equation we have been considered. Based on a method similar to the previously reported differential transfer matrix method [1,2,5-7], analytical expressions are then obtained for the unknown coefficients. All studies are done for both cases of T.E and T.M polarizations. Some scientific results was obtained in the monograph [9] for infinity layer with admixture in the Onsager [11] approach of effective field. There is also very interesting research [15] where method of calculation of transmitted and reflected electromagnetic waves coefficients for anisotropic layer is demonstrated according to investigation of Faraday[24,25] effect in unbounded medium. The new idea in this publication consist for applying of well known W.K.B. solution to resolve the boundary layer problem into the porous media with varying by time due to moisture content changes ащк dielectric properties of isotropic body into the internal volume and on the surfaces of sample. For this purpose we are considering the transmission and reflection coefficients as slowly varying with time functions. Also it was possible to defines a small parameter by means of which we can separate the solutions of wave equation for the small and large thickness of plate. The conditions of slowly varying with coordinate dielectric and with time volume properties of components for the porous body is supplemented by a necessary condition under which it is possible to apply the approximation [24] of the effective macroscopic field. The electromagnetic method and analytical relations described in this paper can be used to investigate of E.M.F wave adsorption and shielding in the produced carbon films [25] as well as for influence of E.M.F. wave on the capacity of lithium-metal-anodes (L.M.A) [26] or at the some assumption may be applied to estimate of temperature dependence on the conduction of cuprum films [27] in photovoltaic cells, flexible electronics and active matrix displays under influence of the E.M.F. dielectric or microwave irradiations.

RESULTS

On the investigation of microwave electromagnetic wave propagation in porous wetted or humidified media a local averaging method [8] is used, according to which for inhomogeneous (not magnetically) multiphase material with dielectric loss and weak conduction properties (C.B.W.C) (C.B.W.C is denoted as Composite Bodies with Weak Conductivity) [9] under frequency dispersion of dielectric constant of components an effective generalized complex dynamical dielectric permeability is defined (E.G.C.D.D.P) (from the designation E.G.C.D.D.P is Effective Generalized Complex Dynamical Dielectric Permeability) [9], which in the approach of effective macroscopic field is a lineal response of not interaction among ourselves the averaged mezoscopic volumes R.E.V (its cluster approach, where R.E.V is Representative Averaged Volume) on the external harmonically disturbance (that is plate monochrome harmonically electromagnetic wave). Such dielectric permeability $\bar{\varepsilon}_{\omega}^{\text{eff}}(\vec{x},t)$ [10] takes a possibility for reviewing of porous media, such as homogeneous isotropic dielectric, whose electro-physical properties change continuously in space and time (this is an approximation of a continuous medium or field approach). It is assumed that the mutual movement of phases caused by the hydrodynamic (mechanical) movement of liquid or gas in the porous skeleton is insignificant at distances commensurate with the length of the electromagnetic wave. Moreover, according to the condition of weak variation of the volumetric characteristics of the porous material, a slight (weak) time dependence of the E.G.C.D.D.P during the period of oscillations is noted. In this regard, the

effective complex dielectric constant $\bar{\varepsilon}_{\omega}^{\text{eff}}(\vec{x},t)$ is considered as a weakly varying function of coordinates and time, and the field equations, from which we obtain an expression for the power of microwave heating sources, are solved separately from the mass and heat transfer (transport) equations in the simulated porous (moistened) material.

According to the solution of the averaged equations obtained in the harmonic approximation [11] of electromagnetic field

$$\vec{\nabla}\times\left\langle\vec{E}_{*}^{t}\right\rangle(\vec{x})=-i\omega\mu_{0}\left\langle\vec{H}_{*}^{t}\right\rangle(\vec{x}),\vec{\nabla}\times\left\langle\vec{H}_{*}^{t}\right\rangle(\vec{x})=i\omega\bar{\varepsilon}_{\omega}^{\text{eff}}(\vec{x},t)\left\langle\vec{E}_{*}^{t}\right\rangle(\vec{x}),$$
$$\vec{\nabla}\cdot\left\langle\vec{E}_{*}^{t}\right\rangle(\vec{x})=0,\vec{\nabla}\cdot\left\langle\vec{H}_{*}^{t}\right\rangle(\vec{x})=0, \tag{1}$$

where $\langle\Phi_{*}^{t}\rangle(\vec{x})$, $\Phi=\left\{\vec{E},\vec{H}\right\}$ is the complex amplitude of electromagnetic field (EMF) in the porous region and $\bar{\varepsilon}_{\omega}^{\text{eff}}(\vec{x},t)$ is the effective generalized complex dynamical dielectric permeability (E.G.C.D.D.P) (here time t has the content of a parameter with the help of which the phase shift is taken into account) is slowly (weakly) variable functions of coordinates, an equation for plate (transverse) polarized (T.E.M) [12] monochromatic wave in the terms of монохроматичної хвилі у electric field strengths for C.B.W.C [9] will look like

$$\Delta\left\langle\vec{E}_{*}^{t}\right\rangle(\vec{x})+k_{0}^{2}[\bar{n}_{\omega}^{\text{eff}}(\vec{x},t)]^{2}\left\langle\vec{E}_{*}^{t}\right\rangle(\vec{x})=0. \tag{2}$$

Here $\bar{n}_{\omega}^{'}(\vec{x},\omega)=\bar{k}_{\omega}^{'}(\vec{x},t)/k_{0}=\sqrt{\bar{\varepsilon}_{\omega}^{\text{eff}}(\vec{x},t)}$ a is complex refractive index, $\bar{k}_{\omega}^{'}(\vec{x},t)$ a is the wave vector of porous (non-uniform) media, $k_{0}=\omega\sqrt{\mu_{0}\varepsilon_{0}}=\omega/c_{0}$ (where $c_{0}=1/\sqrt{\mu_{0}\varepsilon_{0}}$ a is the light velocity) is the wave vector of electromagnetic field in the vacuum, $\omega=2\pi\nu$ a is the corner frequency E.M.F (ν a is the linear frequency), μ_{0} and ε_{0} a is the magnetic and electric constant in the vacuum correspondingly.

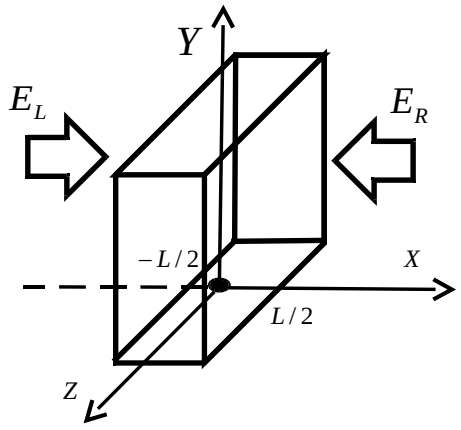


Fig.1. Symmetric under the condition $E_L \equiv E_R$of equality of field amplitudes irradiation of the porous plate

As a porous sample during the numerical experiment, we consider a flat wetted (unconfined) porous plate. With the selection of the direction of propagation of electromagnetic radiation along the axis Ox (abscissa axis X) with a fixed polarization of the wave along the axis Oy (ordinate axis Y) (Рис.1) a wave equation (2) takes a view

$$\frac{\partial^2\left\langle E_{*y}^t\right\rangle(x)}{\partial x^2}+k_0^2[\bar{n}_\omega^{\text{eff}}(x,t)]^2\left\langle E_{*y}^t\right\rangle(x)=0, \tag{3}$$

where E_{*y}^t is component of the electric field intensity vector along the axis Oy.

Use this wave equation by approach for Wentzel-Kramers-Brillouin (W.K.B) solutions [13,14,15-19] we find a partial solution of equation (3) in the form $\left\langle E_{*y}^t\right\rangle(x)=A\,e^{i\phi(x,t)}$, where A is the unknown complex constant, and $\phi(x,t)$ a is varing into the coordinate and time the phase of electromagnetic wave. After substituting the specified expression in (3) we get equation

$$\left(\frac{\partial\phi}{\partial x}\right)^2=k_0^2\left[\bar{n}_\omega^{\text{eff}}(x,t)\right]^2\left(1+i\frac{1}{k_0^2\left[\bar{n}_\omega^{\text{eff}}(x,t)\right]^2}\frac{\partial^2\phi}{\partial x^2}\right). \tag{4}$$

Let us assume an assumption that the last term in the previous equality can be neglected due to the weak variability of the phase ($\frac{d^2\phi}{\mathrm{dx}^2}\simeq 0$) perpendicular to the wave propagation front. When $\frac{\partial\phi}{\partial x}\simeq\pm k_0\bar{n}_\omega^{\text{eff}}$, from which we have $\frac{\partial^2\phi}{\partial x^2}\simeq\pm k_0\frac{\partial\bar{n}_\omega^{\text{eff}}}{\partial x}$ and the condition of weak invariance in the coordinate space (for variable x its one-dimensional case) according to relation (4) takes on a unique form

$$\frac{1}{k_0\left[\bar{n}_\omega^{\text{eff}}(x,t)\right]^2}\frac{\partial\bar{n}_\omega^{\text{eff}}(x,t)}{\partial x}\ll 1. \tag{5}$$

Then the ratio (4) is simplified due to the expansion into a series if the condition (5) is fulfilled

$$\frac{\partial\phi}{\partial x}\simeq\pm k_0\bar{n}_\omega^{\text{eff}}(x,t)\sqrt{1+i\frac{1}{k_0^2\left[\bar{n}_\omega^{\text{eff}}(x,t)\right]^2}\frac{\partial\bar{n}_\omega^{\text{eff}}(x,t)}{\partial x}}\simeq\pm k_0\bar{n}_\omega^{\text{eff}}(x,t)+\frac{i}{2\bar{n}_c}\frac{\partial\bar{n}_\omega^{\text{eff}}(x,t)}{\partial x}$$

and when integrating the last expression, we get

$$\phi(x,t)\simeq\pm k_0\int\bar{n}_\omega^{\text{eff}}(x,t)\,\mathrm{dx}+i\,\mathrm{Ln}\left[\sqrt{\bar{n}_\omega^{\text{eff}}(x,t)}\right].$$

Therefore, the partial solution of the wave equation (3) will be written in the form

$$\left\langle E_{*y}^t\right\rangle(x.,t)=A\frac{1}{\sqrt{\bar{n}_{\omega^{\text{eff}}(x,t)}}}\mathrm{Exp}\left(\pm\mathrm{ik}_0\int\bar{n}_\omega^{\text{eff}}(x,t)\mathrm{dx}\right). \tag{6}$$

The complex amplitude of the magnetic field intensity $\langle H_*^z\rangle$ we obtain according to field equation (1) by differentiation $\langle H_{*z}^t\rangle(x,t)=-\frac{1}{i\omega\mu_0}\frac{\partial\left\langle E_{*y}^t\right\rangle(x,t)}{\partial x}$, when

$$\langle H_{*z}^t\rangle(x,t)\simeq\mp\frac{A}{\eta_0}\sqrt{\bar{n}_\omega^{\text{eff}}(x,t)}\left(1\mp i\frac{1}{2}\frac{1}{k_0\left[\bar{n}_\omega^{\text{eff}}(x,t)\right]^2}\frac{\partial\bar{n}_\omega^{\text{eff}}(x,t)}{\partial x}\right)\mathrm{Exp}\left(\pm\mathrm{ik}_0\int\bar{n}_\omega^{\text{eff}}(x,t)\mathrm{dx}\right).$$

Here H_{*z}^t is component of the magnetic field intensity vector along the axis Oz, and $\eta_0=\sqrt{\mu_0/\varepsilon_0}$ a is wave resistance (impedance) in vacuum. If the weak variability condition (5) is observed, we obtain

$$\langle H_{*z}^{t}\rangle(x,t) = \mp\frac{A}{\eta_0}\sqrt{\bar{n}_{\omega}^{\text{eff}}(x,t)}\,\text{Exp}\big(\pm\text{ik}_0\int\bar{n}_{\omega}^{\text{eff}}(x,t)\text{dx}\big). \quad (7),$$

It should be noted that the choice of sign in expressions (6) and (7) has more illustrative than physical meaning.

The weak invariance condition (5) in the coordinate space receives a clear formulation if we take into account that

$$k_0\bar{n}_{\omega}^{\text{eff}}(x,t) = \frac{2\pi\nu_0}{c_0}\bar{n}_{\omega}^{\text{eff}}(x,t) = \frac{2\pi}{\lambda_0}\bar{n}_{\omega}^{\text{eff}}(x,t) = \frac{2\pi}{\lambda_{\omega}^{\text{eff}}(x,t)} = k_{\omega}^{\text{eff}}(x,t),$$

where $\lambda_{\omega}^{\text{eff}}(x,t) = \lambda_0/\bar{n}_{\omega}^{\text{eff}}(x,t)$ and $k_{\omega}^{\text{eff}}(x,t) = k_0\bar{n}_{\omega}^{\text{eff}}(x,t)$ (here $\lambda_0 = c_0/\nu_0$ і $k_0 = 2\pi/\lambda_0$ is the electromagnetic wave length and wave vector in vacuum) there is a variable microwave E.M.F wavelength and wave vector in a continuous porous (effective) medium. Then the considered relation (5) acquires a transparent physical meaning

$$\frac{1}{\bar{n}_{\omega}^{\text{eff}}(x,t)}\frac{\partial\bar{n}_{\omega}^{\text{eff}}(x,t)}{\partial x} << k_{\omega}^{\text{eff}}(x,t), \quad (6)$$

where $k_{\omega}^{\text{eff}}(x,t) = \omega_0/\bar{c}_{\omega}^{\text{eff}}(x,t)$ (here $\bar{c}_{\omega}^{\text{eff}}(x,t) = c_0/\bar{n}_{\omega}^{\text{eff}}(x,t)$ is speed of light propagation in an effective medium) is a wave vector in a porous (moistened) medium modeled according to the effective dielectric [10] characteristics .

The condition of weak variation of the refractive properties of the material in the coordinate form (6) is usually ensured for most C.B.W.C due to the large value of the frequency ν_0 for microwave irradiation into the vacuum. In the future, we will neglect the dispersion of the dielectric (wave) properties of the material in connection with the constant value of the angular frequency $\omega_0 = 2\pi\nu_0$ of microwave irradiation both in the external environment and in the middle of the porous (moistened) material of an unlimited flat plate.

This way, we arrive at a closed (complete) set of conditions of weak variability of dielectric (wave) and volume (phase) properties of a single-phase (wetted) porous material in the coordinate and time space of the variables

$$\frac{1}{\theta_{\sigma}(x,t)}\frac{\partial\theta_{\sigma}(x,t)}{\partial t} << \omega_0 \quad \text{і} \quad \frac{1}{\bar{n}_{\omega}^{\text{eff}}(x,t)}\frac{\partial\bar{n}_{\omega}^{\text{eff}}(x,t)}{\partial x} << k_{\omega}^{\text{eff}}(x,t). \quad (6)$$

Here $\theta_{\sigma}(x,t)$ is the volume fraction of σ- phase, as well as the condition

$$\lambda_{\omega}^{\text{eff}}(x,t) = \frac{2\pi\upsilon_{\omega}^{\text{eff}}(x,t)}{\omega_0} >> l, \quad (7)$$

which determines the possibility of applying the approximation of the effective macroscopic field [11] in the study (calculation) of the effective electro-physical characteristics of a porous material within the framework of the approximation [8] of the theory of local spatial averaging. Here $k_{\omega}^{\text{eff}}(x,t) = 2\pi/\lambda_{\omega}^{\text{eff}}(x,t)$ and $\upsilon_{\omega}^{\text{eff}}(x,t) = c_0/\bar{n}_{\omega}^{\text{eff}}(x,t)$ a is wave vector and the phase speed of electromagnetic (T.E.M) wave propagation in the simulated environment, $\bar{n}_{\omega}^{\text{eff}}(x,t)$ a is the effective value of the refractive index, $\theta_{\sigma}(x,t)$ a is volume fraction of σ-phase, ω_0 a is constant angular frequency of E.M.F of the microwave range, l a is characteristic length of the region (R.E.V) for space averaging.

According to the properties of the solutions of the W.K.B model, when the conditions of weak variability (6) and (7) of the electro-physical characteristics of the porous (wetted)

material are met, the general solution of the wave equation (3) for a plane transverse (T.E.M) electromagnetic wave is written [20]

$$\langle E_{*y}^{t}\rangle(x) = \frac{1}{\sqrt{\bar{n}_{\omega}^{\text{eff}}(x,t)}}\Big(A(t)\sqrt{\bar{n}_{\omega}^{L}(t)}\text{Exp}[-\text{ik}_0\int_{-L/2}^{x}\bar{n}_{\omega}^{\text{eff}}(x,t)\,\text{dx}] + B(t)\sqrt{\bar{n}_{\omega}^{R}(t)}\text{Exp}[\text{ik}_0\int_{L/2}^{x}\bar{n}_{\omega}^{\text{eff}}(x,t)\,\text{dx}]\Big), \quad (8)$$

where $\bar{n}_{\omega}^{\alpha}(t) = \bar{n}_{\omega}^{'}(\pm L/2\,,t)$ $\alpha = \{L,R\}$ is the value of the refractive index at the edges of the plate, $A(t)$ and $B(t)$ are unknown functions of time.

In the left (L) and right (R) half-space, external (Fig. 1) in relation to the boundaries (edges) of the plate, which is modeled by a vacuum, the electric field intensity (with external microwave irradiation) is considered in the form of expressions

$$\langle E_{*y}^{L}\rangle(x,t) = E_L[\text{Exp}\,[-\text{ik}_0(x+L/2)] + C(t)\text{Exp}\,[\text{ik}_0(x+L/2)]], \quad (9)$$

$$\langle E_{*y}^{R}\rangle(x,t) = E_R[D(t)\text{Exp}\,[-\text{ik}_0(x-L/2)] + \text{Exp}\,[\text{ik}_0(x-L/2)]], \quad (10)$$

where $C(t)$ and $D(t)$ are unknown function of time, E_L and E_R a is the real amplitude of the external electromagnetic field.

According to the boundary conditions (4), the continuity of the components of the electric field intensity

$$\langle E_{*y}^{L}\rangle(-L/2\,,t) = \langle E_{*y}^{t}\rangle(-L/2), \langle E_{*y}^{R}\rangle(L/2\,,t) = \langle E_{*y}^{t}\rangle(L/2), \quad (11)$$

and derivatives, that determine the corresponding (perpendicular) components of the magnetic field intensity

$$\partial_x\langle E_{*y}^{L}\rangle(-L/2\,,t) = \partial_x\langle E_{*y}^{t}\rangle(-L/2), \partial_x\langle E_{*y}^{R}\rangle(L/2\,,t) = \partial_x\langle E_{*y}^{t}\rangle(L/2), \quad (12)$$

should be provided at any time.

This condition makes it possible to take into account the dependence of field amplitude on wetting at the boundaries (edges) of the plate, the value of which (volume fraction of liquid θ_L or liquid saturation η_L of pores) changes dynamically depending on the power of internal (thermal) heating sources and the implementation of heat and mass transfer conditions at the edges of the plate.

In accordance with the described expressions (8), (9) and (10) for the electric field strengths according to the continuity condition (11) of the components

$$E_L[1+C(t)] = A(t) + B(t)\gamma_{\text{RL}}(t)\delta(t)\; E_R[D(t)+1] = A(t)\gamma_{\text{LR}}(t)\delta(t) + B(t) \quad (13)$$

and continuity (12) of the derivatives

$$E_L[1-C(t)] = \bar{n}_{\omega}^{L}(t)[A(t) - B(t)\gamma_{\text{RL}}(t)\delta(t)]\; E_R[D(t)-1] = \bar{n}_{\omega}^{R}(t)[A(t)\gamma_{\text{LR}}(t)\delta(t) - B(t)] \quad (14)$$

We obtain a system of equations (13) and (14) to determine the unknown (variable in the simulation time interval) coefficients that determine the amplitude of the E.M.F at the edges of the plate, in the accepted notations

$$\gamma_{\text{LR}}(t) = \sqrt{\frac{\bar{n}_{\omega}^{R}(t)}{\bar{n}_{\omega}^{L}(t)}} = \frac{1}{\gamma_{\text{RL}}(t)} \quad \text{and} \quad \delta(t) = \text{Exp}[-\text{ik}_0\int_{-L/2}^{L/2}\bar{n}_{\omega}^{\text{eff}}(x,t)\text{dx}]. \quad (15)$$

Such coefficients, taking into account the ratio (15), will have the form

$$A(t) = E_L \frac{T_L^t - (E_R/E_L)\delta(t) T_R^t R_L^t \gamma_{\mathrm{RL}}(t)}{1 - [\delta(t)]^2 R_L^t R_R^t} \quad \text{and} \quad B(t) = E_R \frac{T_R^t - (E_L/E_R)\delta(t) T_L^t R_R^t \gamma_{\mathrm{LR}}(t)}{1 - [\delta(t)]^2 R_L^t R_R^t}, \tag{16}$$

where $T_\alpha^t = 2/[1 + \bar{n}_\omega^\alpha(t)]$ and $R_\alpha^t = [1 - \bar{n}_\omega^\alpha(t)]/[1 + \bar{n}_\omega^\alpha(t)]$ (here $\alpha = \{L, R\}$ is the index, which corresponds to the left (L) or right (R) edges of plate) are, respectively, the transmission and reflection coefficients of the (T.E.M) wave at the plate boundaries.

Thus, according to (8) and the expressions for the coefficients $A(t)$ and $B(t)$ (16), which are determined from the continuity conditions (11) and (12) of the field components, we obtain a partial solution of the wave equation (3) in the electric and magnetic field strengths

$$\langle E_{*y}^t \rangle(x) = \frac{1}{\sqrt{\bar{n}_\omega'(x,t)}} \left(\bar{A}(t) \mathrm{Exp}[-\mathrm{i}k_0 \int_{-L/2}^{x} \bar{n}_\omega^{\mathrm{eff}}(x,t)\, \mathrm{dx}] + \bar{B}(t) \mathrm{Exp}[\mathrm{i}k_0 \int_{x}^{L/2} \bar{n}_\omega^{\mathrm{eff}}(x,t)\, \mathrm{dx}] \right), \tag{17}$$

$$\langle H_{*z}^t \rangle(x) = \frac{1}{\eta_0} \sqrt{\bar{n}_\omega'(x,t)} \left(\bar{A}(t) \mathrm{Exp}[-\mathrm{i}k_0 \int_{-L/2}^{x} \bar{n}_\omega^{\mathrm{eff}}(x,t)\, \mathrm{dx}] - \bar{B}(t) \mathrm{Exp}[\mathrm{i}k_0 \int_{x}^{L/2} \bar{n}_\omega^{\mathrm{eff}}(x,t)\, \mathrm{dx}] \right). \tag{18}$$

Here $\bar{A}(t) = A(t)\sqrt{\bar{n}_\omega^L(t)}$ i $\bar{B}(t) = B(t)\sqrt{\bar{n}_\omega^R(t)}$ is determined according to relation (16) and normalized according to the values $\bar{n}_\omega^\alpha(t) = \bar{n}_\omega^{\mathrm{eff}}(\pm L/2, t)$ (where $\alpha = \{L, R\}$ a is the index of plate edges) of the refractive index at the edges of the plate, the complex amplitude of the electromagnetic wave, and $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$ a is the characteristic resistance (impedance) in vacuum.

Is known [12] that for the T.E.M the wave vector of waves in the continuous (effective) occur a relation $k_0 \bar{n}_\omega^{\mathrm{eff}}(x,t) = \beta(x,t) - i\alpha(x,t)$, where $\alpha(x,t) = -k_0 \mathrm{Im}[\sqrt{\bar{n}_\omega^{\mathrm{eff}}(x,t)}]$ and $\beta(x,t) = k_0 \mathrm{Re}[\sqrt{\bar{n}_\omega^{\mathrm{eff}}(x,t)}]$ are the indicators of absorption and propagation of the (T.E.M) wave.

Let's define the tangent of the dielectric loss $\mathrm{tg}\delta_\omega$ in the simulated porous (wetted) material

$$\mathrm{tg}\delta_\omega = -\frac{\mathrm{Im}[\,\bar{\varepsilon}_\omega^{\mathrm{eff}}]}{\mathrm{Re}[\,\bar{\varepsilon}_\omega^{\mathrm{eff}}]} = \bar{\varepsilon}_\omega^{\mathrm{eff}(2)} / \bar{\varepsilon}_\omega^{\mathrm{eff}(1)}, \tag{19}$$

where $\bar{\varepsilon}_\omega^{\mathrm{eff}} = \bar{\varepsilon}_\omega^{\mathrm{eff}(1)} - i\bar{\varepsilon}_\omega^{\mathrm{eff}(2)}$ is the effective generalized complex dynamic permittivity (E.G.C.D.P), $\bar{\varepsilon}_\omega^{\mathrm{eff}(1)} = \mathrm{Re}[\,\bar{\varepsilon}_\omega^{\mathrm{eff}}]$ and $\bar{\varepsilon}_\omega^{\mathrm{eff}(2)} = \mathrm{Im}[\,\bar{\varepsilon}_\omega^{\mathrm{eff}}]$ a is the designation of the real and imaginary part, respectively.

Then the absorption rates $\alpha(x,t)$ and distribution $\beta(x,t)$ T.E.M wave can be described by expressions

$$\alpha(x,t) = k_0 \frac{\sqrt{\mathrm{Re}[\bar{\varepsilon}_\omega^{\mathrm{eff}}(x,t)]}}{\sqrt{2}} \sqrt{\sqrt{1 + \mathrm{tg}^2\delta_\omega(x,t)} + 1}, \tag{20}$$

$$\beta(x,t) = k_0 \frac{\sqrt{\mathrm{Im}[\bar{\varepsilon}_\omega^{\mathrm{eff}}(x,t)]}}{\sqrt{2}} \sqrt{\sqrt{1 + \mathrm{tg}^2\delta_\omega(x,t)} - 1} \tag{21}$$

under conditions of satisfying the rationed $2\alpha\beta = k_0^2 \sqrt[3]{\mathrm{tg}^2\delta_\omega} \mathrm{Re}[\bar{\varepsilon}_\omega^{\mathrm{eff}}]$ relation.

Considering the specified ratio $k_0 \bar{n}_\omega^{\mathrm{eff}}(x,t) = \beta(x,t) - i\alpha(x,t)$, where $\alpha(x,t) = -k_0 \mathrm{Im}[\sqrt{\bar{n}_\omega^{\mathrm{eff}}(x,t)}]$ and $\beta(x,t) = k_0 \mathrm{Re}[\sqrt{\bar{n}_\omega^{\mathrm{eff}}(x,t)}]$ its the values of absorption and

propagation of a plane electromagnetic wave, we also obtain the effective values of the wavelength$\lambda_\omega^{\text{eff}}(x,t)$ and penetration depth $D_p^{\text{eff}}(x,t)$ of T.E.M wave

$$\lambda_\omega^{\text{eff}}(x,t)=\lambda_0\frac{\sqrt{2}}{\sqrt{\bar{\varepsilon}_\omega^{\text{eff}(1)}}}\frac{1}{\sqrt{\sqrt{1+\text{tg}^2\delta_\omega(x,t)}+1}},\qquad D_p^{\text{eff}}(x,t)=\frac{c_0}{\omega}\frac{\sqrt{2}}{\sqrt{\bar{\varepsilon}_\omega^{\text{eff}(2)}}}\frac{1}{\sqrt{\sqrt{1+\text{tg}^2\delta_\omega(x,t)}-1}}.$$

Here $\text{tg}\delta_\omega(x,t)=\bar{\varepsilon}_\omega^{\text{eff}(2)}/\bar{\varepsilon}_\omega^{\text{eff}(1)}$ is tangent of the dielectric loss (dielectric loss factor).

The power of the E.M.F energy flow during a wave propagation process can be calculated according to the definition of the Pointing vector [11] by the relation

$$\langle P_x^t\rangle(x)=\tfrac{1}{2}\text{Re}\big[\langle E_{*y}^t\rangle(x)\langle \bar{H}_{*z}^t\rangle(x)\big],\tag{22}$$

where $\langle \bar{H}_{*z}^t\rangle\equiv\langle H_{*z}^t\rangle^*$ a is the complex conjugate value of the averaged amplitude of the magnetic field intensity.

Having analyzed the expression (15), for the model parameter δ we obtain

$$\delta(t)=\text{Exp}[-\text{ik}_0\textstyle\int_{-L/2}^{L/2}\bar{n}_\omega^{\text{eff}}(x,t)]=e^{-\bar{\alpha}(t)}[\text{Cos}[\bar{\beta}(t)]-\text{iSin}[\bar{\beta}(t)]]=\bar{\delta}(t)e^{-i\bar{\beta}(t)}.\tag{23}$$

Here $\bar{\alpha}(t)=-\int_{-L/2}^{L/2}\alpha(x,t)\,\text{dx}$ and $\bar{\beta}(t)=-\int_{-L/2}^{L/2}\beta(x,t)\,\text{dx}$ is the integral value of the coefficients of absorption and propagation of the electromagnetic wave through the thickness L plate accordingly, and $\bar{\delta}(t)=e^{-\bar{\alpha}(t)}$ is the amplitude multiplier, which is determined by the time-varying (due to the movement of fluid phases in the porous material) damping coefficient.

Then, according to the definition (22) and the expressions for the intensity of the electric (17) and magnetic (18) fields for the power of the microwave radiation flux in the accepted (23) notation, we obtain

$$\langle P_x^t\rangle(x)=\frac{1}{2\eta_0}\text{Re}[\sqrt{\frac{\bar{n}_\omega^{\text{eff}}(x,t)}{\bar{n}_\omega^{\text{eff}}(x,t)}}\times(|\bar{A}(t)|^2\text{Exp}[-2\int_{-L/2}^{x}\alpha(x,t)\,\text{dx}]+$$
$$+\bar{\delta}(t)e^{-i\bar{\beta}(t)}\left\{\bar{A}(t)\bar{B}(t)\text{Exp}[2i\int_{-L/2}^{x}\beta(x,t)\,\text{dx}]-\bar{A}(t)\bar{B}(t)\text{Exp}[2i\int_{x}^{L/2}\beta(x,t)\,\text{dx}]\right\}-$$
$$-|\bar{B}(t)|^2\text{Exp}[-2\int_{x}^{L/2}\alpha(x,t)\,\text{dx}])].\tag{24}$$

In the approach of large thickness L of plate ($\bar{\delta}(t)\simeq 0$) and symmetrical edges ($E_L=E_R=E_0$, here E_0 is the amplitude value of the intensity of the external E.M.F) the relation (24) for the power of the energy flow in a porous wetted material with effective wave properties simplified

$$\langle P_x^t\rangle(x)=P_{\text{in}}|\bar{n}_\omega(t)|\,|T(t)|^2\text{Re}[\sqrt{\frac{\bar{n}_\omega^{\text{eff}}(x,t)}{\bar{n}_\omega^{\text{eff}}(x,t)}}]\times(\text{Exp}[-2\textstyle\int_{-L/2}^{x}\alpha(x,t)\,\text{dx}]+$$
$$\text{Exp}[-2\textstyle\int_{x}^{L/2}\alpha(x,t)\,\text{dx}]),\tag{25}$$

where $P_{\text{in}}=E_{0^2}/2\,\eta_0$ a is the power of external microwave irradiation, $\bar{n}_\omega(t)=\bar{n}_\omega^{\text{eff}}(\pm L/2\,,t)$ and $T(t)=2/[1+\bar{n}_\omega(t)]$ a is the value of the refractive index and the transmission coefficient of the electromagnetic T.E.M wave at the edges of the plate, $\bar{n}_\omega^{\text{eff}}(x,t)$

a is the refractive index in the inner part and at the edges of the porous (moistened) plate, $\alpha(x,t) = -k_0 \mathrm{Im}[\sqrt{\bar{n}_\omega^{\mathrm{eff}}(x,t)}]$ a is attenuation coefficient of T.E.M wave.

Let us assume that the total amount of E.M.F energy, which is supplied to the material under study during microwave irradiation due to scattering (dissipation) effects, is completely transformed into heat. Thus, we neglect the processes of work performed by the studied thermodynamic system at the expense of internal (ponderomotive) forces acting on the porous carcass or skeleton (including thermal expansion of the plate).

Then the expression for calculating the power of sources of electromagnetic (dielectric or microwave) heating has the same form

$$\dot{q}^t(x) = -\partial \langle P_x^t \rangle (x) / \partial\, x \tag{26}$$

where $\langle P_x^t \rangle (x)$ is the value of the Pointing vector [4] at the edges and in the inner volume of the plate.

Given the identical transformation in the form of a ratio

$$\mathrm{Re}\left[\sqrt{\frac{\bar{\varkappa}_\omega^{\mathrm{eff}}(x,t)}{\bar{n}_\omega^{\mathrm{eff}}(x,t)}}\right] = \sqrt{\frac{1}{2}\left(1 + \frac{1}{\sqrt{1+\mathrm{tg}^2\delta_\omega}}\right)}. \tag{27}$$

For the power of internal heat sources $\dot{q}^t(x)$ with symmetrical external (microwave) irradiation, which is determined by the expression for the E.M.F energy flow in the material (25) when approaching large thicknesses $(\bar{\delta}(t) \simeq 0)$ of the plate according (26) and (27) we have

$$\begin{gathered}\dot{q}^t(x) = 2P_{\mathrm{in}}|\bar{n}_\omega(t)|\,|T(t)|^2\alpha(x,t)\sqrt{\frac{1}{2}\left(1 + \frac{1}{\sqrt{1+\mathrm{tg}^2\delta_\omega(x,t)}}\right)} \times \\ \times \left(\mathrm{Exp}\left[-2\int_{-L/2}^{x}\alpha(x,t)\,\mathrm{dx}\right] + \mathrm{Exp}\left[-2\int_{x}^{L/2}\alpha(x,t)\,\mathrm{dx}\right]\right)\end{gathered}. \tag{28}$$

In relation (28), the notation is equivalent to the physical quantities described according to (25).

NUMERICAL DATA

When numerically modeling the power of heat sources (26) according to the ratio (24) in the EMA [4] approximation, the Bruggeman formula [10] was used

$$\sum_\sigma \theta_\sigma \frac{\varepsilon_c^\sigma(\omega) - \bar{\varepsilon}_\omega^{\mathrm{eff}}}{\varepsilon_c^\sigma(\omega) + 2\bar{\varepsilon}_\omega^{\mathrm{eff}}} = 0 \tag{29}$$

and the expression (30) obtained in [21] for finding the uniform η_L^{eqv} wetting of the porous material

$$\eta_L^{\mathrm{eqv}} = (\eta_L^{\mathrm{cr}} - \eta_L^{\mathrm{ir}}) \Bigg/ \left[1 + \left(\frac{P_{\mathrm{amb}}\sqrt{k_{\mathrm{in}}/\langle\varphi\rangle}}{\sigma}\right)^{\frac{1}{1-m}}\right]^m + \eta_L^{\mathrm{ir}}. \tag{30}$$

Here $\langle\varphi\rangle$ a is the averaged porosity, η_L^{cr} and η_L^{ir} a is the critical and residual saturation of pores with liquid, P_{amb} is the value of the pressure in the surrounding environment, k_{in}a is intrinsic permeability of the frame, σ a is the surface tension coefficient, m a is model parameter.

For the researched material, namely historical ceramic brick (with $\langle\varphi\rangle = 0.46$ as averaged porosity) and in two modifications (with $\langle\varphi\rangle = 0.40$ - modA and $\langle\varphi\rangle = 0.52$ - modB), with known values of the dielectric (static) permeability of the phases,

Table 1. *Dielectric constant components for the studied material (historical ceramic brick) according to the model of spherical inclusions (ε_S - solid phase, ε_L- water, ε_G- air)*[1]

ν, Gz	ε_S		ε_L		ε_G	
	$\varepsilon_S^{'}$	$\varepsilon_S^{''}$	$\varepsilon_L^{'}$	$\varepsilon_L^{''}$	$\varepsilon_G^{'}$	$\varepsilon_G^{''}$
$2.45 \cdot 10^9$	5,86	0,703	80	20	1	0

which are given above in Table 1, by relation (24) we obtain the corresponding graphical dependences for the real $\bar{\varepsilon}_\omega^{\text{eff}(1)}$ (Fig.2) and imaginary $\bar{\varepsilon}_\omega^{\text{eff}(2)}$ (Fig.3) part of the effective generalized complex dynamic permittivity (E.G.C.D.D.P) $\bar{\varepsilon}_\omega^{\text{eff}}$ of the porous moistened material at a typical (standardized) frequency of external microwave irradiation $\nu_0 = 2.45 \cdot 10^{-9}\,[1/s]$ (2.45MGz) from saturation of pores η_L with liquid.

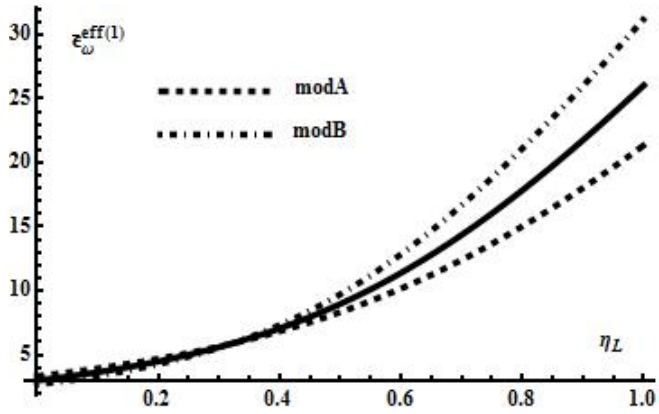


Fig. 2. Real part of $\bar{\varepsilon}_\omega^{\text{eff}}$ (E.G.C.D.D.P) for investigate material, as function of pore saturation η_L by water

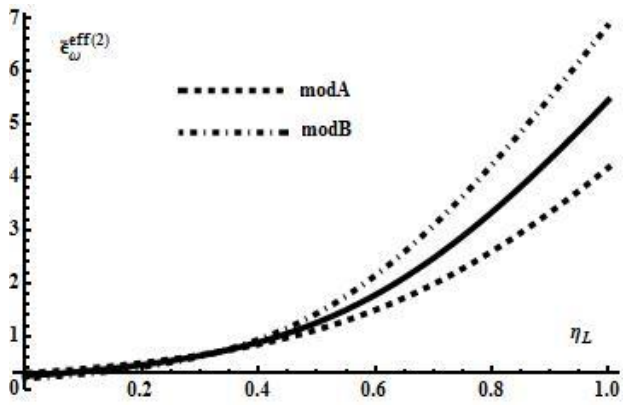


Fig.3. Imaginary part of $\bar{\varepsilon}_\omega^{\text{eff}}$ (E.G.C.D.D.P) for investigate material, as function of pore saturation η_L by water

The dependence of the tangent of the dielectric loss angle is also shown graphically below (Fig. 4). $\text{tg}\delta_\omega = \bar{\varepsilon}_\omega^{\text{eff}(2)} / \bar{\varepsilon}_\omega^{\text{eff}(1)}$ at different values of humidification η_L of the studied porous material at the specified frequency of microwave irradiation.

For such a material, according to the dependence of hydration η_L on the effective radius of pores $\bar{r}$ is established [21], that with porosity $\langle\varphi\rangle = 0.46$ the values of the residual $\eta_L^{\text{ir}} = 0.015$ and critical $\eta_L^{\text{cr}} = 1$ saturation of pores by liquid are known, as well as the value of the model parameter $m = 0.67$ in the van Genuchten [22] semi-empirical model of moisture release or retention . Then, according to relation (33), the macroscopic (homogeneous or uniform) value of the hydration of such a (porous) material under normal conditions (when $P_G^{\text{amb}} = 101325[\text{Pa}]$, where P_G^{amb} is pressure external to the wetted

[1] This is not dimensional quantities, its means if you takes any dielectric permittivity or constant and multiple on the ε_0, where ε_0 is a dielectric constant into the vacuum, you have receive the actual physical quantities in the dimensions of [F/m].

macroscopic porous material) corresponds to the value $\eta_L^{eqv} = 0.64$, which coincides with the maximum of the pore size distribution function over the effective radius.

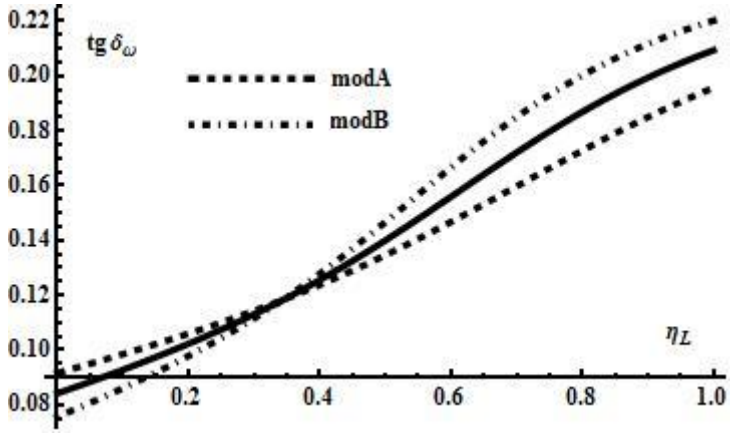


Fig.4. Dielectric loss angle tangent tgδ_ω, as function of pore saturation η_L by liquid

Under the described conditions of uniform (homogeneous) wetting of the porous material, the absorption (20) and propagation (21) indicators of the T.E.M wave, as well as the transmission and reflection coefficients in the expressions (16) for the amplitudes of the electromagnetic wave at the boundary surfaces of the porous plate (Fig. 1)) do not depend on time due to the constant value η_L^{eqv} of saturation. In this case, the E.M.F power distribution in the material under symmetric microwave irradiation according to (24) is determined by the thickness L of plate, the equilibrium value of pore liquid saturation η_L^{eqv} and dielectric (relaxation) properties of phases. This is due to the fact that EGCDDP $\bar{\varepsilon}_\omega^{eff}$ of moistened porous material ($\langle\varphi\rangle = 0.46$) defined according to the EMA approximation [10] (66) (Fig. 2 and Fig. 3), as well as the dielectric loss angle tangent tgδ_ω (Рис.4), are determined by the equilibrium constant value η_L^{eqv} for saturation of pores with liquid.

Then the power of internal heat source (microwave heating) according to expression (26) with the known ratio (24) for the flow of E.M.F energy in the material of the plate can be calculated numerically.

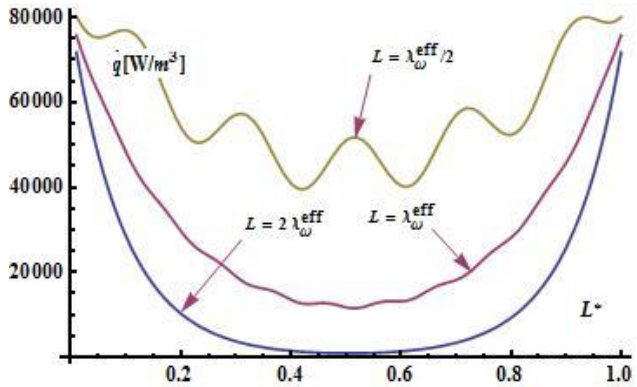


Fig.5. Power distribution of internal heating sources at large plate thicknesses

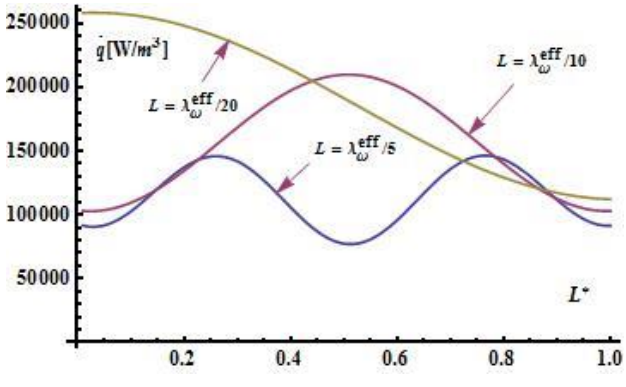


Fig.6. Power distribution of internal heating sources at small plate thicknesses

In conclusion, Fig. 5 and Fig. 6 show the results of numerical modeling of the power of internal (volumetric) heat sources $\dot{q}$ in a porous (unconfined) wetted plate at different thicknesses L of the plate (where $L^* = n\Delta L/L$ $(n = \Delta L/L)$ a is the dimensionless plate thickness, and n a is the number of breakpoints), which are multiples of the wavelength $\lambda_\omega^{\text{eff}}$ into media, for the following values of microwave irradiation parameters and properties (parameters or characteristics) of the investigated porous material: 1. External microwave irradiation: power - $P_{\text{in}} = 2500\ [W/m^2]$, frequency - $\nu_0 = 2.45 \cdot 10^{-9}\ [s^{-1}]$; 2. Porous humidified media: $\langle\varphi\rangle = 0.46$ - averaged porosity, $k_{\text{in}} = 2{,}29 \cdot 10^{-13}\ [m^2]$ - intrinsic permeability of the skeleton, $\eta_L^{\text{eqv}} = 0.64$ - equilibrium saturation pores by liquid, $T = 298{,}15\ [K]$ - thermodynamic temperature, $P_G = 101325$ [Pa] - value of pressure in gas phase, $\lambda_\omega^{\text{eff}} = c_0/\left|\bar{n}_\omega^{\text{eff}}\right| = 0.14\ [m]$ -wave length for electromagnetic wave in the porous media.

CONCLUSION

It follows from the considered graphical dependencies that at plate thicknesses $L > \lambda_\omega^{\text{eff}}$ the exponential law of power attenuation of Beer-Lambert microwave heating sources is realized. If $L \leq \lambda_\omega^{\text{eff}}$ wave a periodic effects take place, see Fig.5 (when $L = \lambda_\omega^{\text{eff}}$ or $L = \lambda_\omega^{\text{eff}}/2$) and Fig.6 (when $L = \lambda_\omega^{\text{eff}}/5$, $L = \lambda_\omega^{\text{eff}}/10$ or $L = \lambda_\omega^{\text{eff}}/20$), which can be localized at plate thicknesses that are commensurate with the minimum (Fig.6, $L = \lambda_\omega^{\text{eff}}/10$) symmetric with respect to the center of the plate by the amount of non harmonicas. It is clear that the wave (a periodic) properties of heat sources will change depending on the amount of equilibrium humidification η_L^{eqv} of the porous material of the plate, which is determined by the parameters of the structure: $\langle\varphi\rangle$ - porosity and k_{in} - intrinsic permeability of porous skeleton.

BIBLIOGRAPHY

1. Yeh P. Optical Waves in Layered Media. - New York: "Wiley", 1988, 416p.
2. Merzbacher E., Quantum Mechanics. - New York: "John Wiley", 1998, 672p.
3. Eghlidi M. H., Mehrany K., Rashidian B. Improved differential transfer matrix method for inhomogeneous one-dimensional photonic crystals // J. Opt. Soc. Am. B. - 2006., Vol. 23, No. 7, P. 1451-1459.
4. Eghlidi M. H., Mehrany K., Rashidian B. Modified Differential Transfer Matrix Method for Solution of One Dimensional Linear Inhomogeneous Optical Structures // J. Opt. Soc. Am. B. - 2005, **22**, P.1521-1528.
5. Khorasani S., Mehrany K., Differential transfer-matrix method for solution of one-dimensional linear nonhomogeneous optical structures // J. Opt. Soc. Am. B. - 2003, **20**,P. 91-96.
6. Mehrany K., Khorasani S., Analytical solution of non-homogeneous anisotropic wave equations based on differential transfer matrix method // J. Opt. A.: Pure Appl. Opt. - 2002, **4**, P. 624-635.
7. S. Khorasani, A. Adibi, “Analytical solution of linear ordinary differential equations by differential transfer matrix method,” Electron. J. Differ. Equations 2003, 1-18 (2003).
8. Howes A.H., Whitaker S. The spatial averaging theorem revisited // Chemical Engineering Science.-1980.-23.-№12.-P.1613-1623.

9. Modeling and optimization in thermomechanics of electrically conductive heterogeneous bodies (ed. by Y.Y.Buryak and R.M. Kushnir, Vol. 1,2) – Lviv: "Spolom", 2006, 474c.
10. O. R. Hachkevych, R. F. Terletskiy, T. V. Holubets. Calculation of effective electrophysical characteristics of hydrated porous materials // Mathematical methods and physical-mechanical fields. 2009. – **52**, No.1. – p. 159-171.
11. Landau L.D., Lifshitz E.M. Electrodynamics of continuous media.-Moskow: “Nauka”, 1982. - 480p.
12. Semyonov N.A. Technical electrodynamics. – M: “Svyaz”, 1973. - 480p.
13. Katselenbaum B.Z. High-frequency electrodynamics. Fundamentals of mathematical apparatus. – M: "Nauka", 1966. – 240p.
14. Ugwu E.I., Udun P.C. Determination of refractive index, reflectance // “Transmittance of FeZz Thin Film Deposited by Solution Growth Technique (SGW)”, JICCOTECH. Maiden Ed., 2005.
15. Bass F., Resnick L. The electromagnetic wave propagation through a stratified inhomogeneous anisotropic medium // Prog. in Electromagn. Res. -2004. – 48. – P.67-83.
16. Ayappa K.G., Davis H.T., Barringer S.A., Davis E.A. Resonant microwave power adsorption in slabs and cylinders // . I. Ch. I. Journal. – 1997. – 43 (3). – P.615-624.
17. Basak T. Analysis of resonance during microwave thawing of slabs // International Journal of Heat and Mass Transfer. – 2003. – 46. –P.4276—4301.
18. Chamchong M., Datta A.K. Thawing of foods in a microwave over. Effect of power level and power cycling // Journal of Microwave Power and Electromagnetic Energy. – 1999. – 34. –P.9-21.
19. Zang H, Datta A.K., Taub I.A. Doona C. Electromagnetics heat transfer and thermokinetics in microwave strerilization // A. I. Ch. I. Journal. – 2001. – 47. – P.1957-1968.
20. Holubets T.V., Terletskiy R.F. Application of the W.K.B. method. to the calculation of dielectric losses in a porous humidified medium under microwave irradiation // Applied problems of mechanics and mathematics. – 2011. – Вип. 9. – с.22-129.
21. Holubets T.V. Investigation of the structural properties of porous material according to the sorption isotherms or drainage curves // Mathematical Modelling and Computing. 2016.- Vol.3, No.1, P.23-32.
22. van Genuchten M.T. A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils // Soil Science Society of America Journal. – 1980. - 44, No. 5. - P. 892–898.
23. Brekhovskikh L.M. Waves in layered media. - New York, 1980. - 503p.
24. Tsang L., J.A. Kong, R.T. Shin. Theory of microwave remote sensing. - New York: "Wiley-Intersciences",1995. - 613p.
25. Jianwei L., Wei C., Qiang G., Hongming Z., Xinhai H. and Bin W.. In situ fabrication of magnetic and hierarchically porous carbon films for efficient electromagnetic wave shielding and absorption // ACS Appl. Mater. Interfaces. - 2022, Vol. 14, No. 29, P.33675–33685.
26. Y. Lianga, Y. Chena, X. Kea, Z. Zhanga, W.Wua, G. Lina, Z. Zhouc and Z. Shia. Coupling of triporosity and strong Au-Li interaction to enable dendrite-free lithium plating/stripping for long-life lithium metal anodes // Journal of Materials Chemistry A. - 2020, Vol.8, P. 18094-18105.
27. Young H. H., J.-Y. Won, H.-S. Yoo, J.-H. Kim, R. Choi, and J. K. Jeong. High performance metal oxide field-effect transistors with a reverse offset printed Cu source/drain electrode // ACS Appl. Mater. Interfaces. - 2016, Vol. 8, P.1156−1163.