10. Yamashita, Y. Newly Developed Repairs on Welded Area of LWR Stainless Steel by Friction Surfacing [Text] / Y. Yamashita, K. Fujita // Journal of Nuclear Science and Technology. – 2001. – Vol. 38, Issue 10. – P. 869–900. doi: 10.1080/18811248.2001.9715112
11. Ivanov, V. Improving the Efficiency of Strip Cladding by the Control of Electrode Metal Transfer [Text] / V. Ivanov, E. Lavrova // Applied Mechanics and Materials. – 2014. – Vol. 682. – P. 266–269. doi: 10.4028/www.scientific.net/amm.682.266
12. Royanov, V. A. Equipment for electric arc metallizing with pulsed discharge of the air-spraying jet [Text] / V. A. Royanov, V. I. Bovikov // Welding International. – 2015. – Vol. 30, Issue 4. – P. 315–318. doi: 10.1080/01431161.2015.1058006

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INVESTIGATION OF THE EFFECT OF CHARACTERISTICS OF GAS-CONTAINING SUSPENSIONS ON THE PARAMETERS OF THE PROCESS OF ULTRASONIC WAVE PROPAGATION

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У роботі виконано дослідження закономірностей зв'язку флуктуацій числа і розмірів зважених у рідини часток на характеристики поля об'ємних ультразвукових хвиль. Виявлено, що величина згасання об'ємних ультразвукових коливань високої частоти (≥5 мГц) у реальній пульпі залежить практично тільки від концентрації твердої фази і крупності часток подрібненого матеріалу

Ключові слова: газові бульбашки, збагачення руди, об'ємні ультразвукові хвилі, розподіл часток, характеристики пульпи

В работе выполнено исследование закономерностей связи флуктуаций числа и размеров взвешенных в жидкости частиц на характеристики поля объемных ультразвуковых волн. Обнаружено, что величина затухания объемных ультразвуковых колебаний высокой частоты (≥5 мГц) в реальной пульпе зависит практически только от концентрации твердой фазы и крупности частиц измельченного материала

Ключевые слова: газовые пузырьки, обогащение руды, объемные ультразвуковые волны, распределение частиц, характеристики пульпы

1. Introduction

Ultrasonic methods and technologies are widely used at present in various research projects. Specifically, they are applied when examining, identifying, and controlling quality of different materials [1]. For example, in order to distinguish characteristics of the varieties of enriched ore raw materials [2–4].

To optimize control over processes of enrichment mineral resources, an important aspect is the availability of qualitative information on the characteristics of technological media [5]. A need to exercise operational control over characteristics of the solid phase of the pulp is also stressed by the existence of uncertainty in the parameters of technological units [6]. It should be noted that the application of ultrasonic methods in a given case would provide the required performance speed and measurement accuracy.

Significant losses of the useful component in wastes of enrichment production lead not only to a decrease in performance indicators, but also negatively affect the environment [7, 8]. One of the ways to reduce the negative impact of the loss of a useful component is to improve efficiency of flotation processes. Paper [9] proposed a method for ultrasonic treatment of particles of the enriched ore materials in order to better clean grains of the useful component from the gangue. A positive effect is also noted of ultrasonic oscillations on the formation of gas bubbles and maintaining a cavitation regime, which also improves efficiency of flotation [10, 11].

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Ultrasonic oscillations represent periodic disturbances of the state of elastic medium that are characterized by a change in its physical properties that occur synchronously with disturbance. At the propagation of ultrasound oscillations of the local volume of the medium are transferred to neighboring regions by means of elastic waves that are characterized by a change in the density of medium in space and which carry energy of fluctuations. Basic relations that describe ultrasonic oscillations and waves in a medium follow from equation of state of the medium, Newton's equation of motion, and continuity equation [12].

Using ultrasonic methods and technologies for examining, recognition and quality control of different materials makes it possible to significantly improve accuracy of measurement and efficiency of technological processes. At the same time, there are certain difficulties related to the complexity of processes of ultrasonic wave propagation in gas-containing suspensions. Specifically, there are still insufficiently studied regularities of the effect of fluctuations in the amount and dimensions of particles, suspended in fluid, on the characteristics of ultrasonic field.

2. Literature review and problem statement

The best studied and mostly used among all currently known ultrasonic waves are the surface waves by Rayleigh [13]. These are waves that propagate along the border of solid space. A Rayleigh wave consists of two flat inhomogeneous waves longitudinal and transverse. These waves, and the Rayleigh wave composed of them, are the waves with vertical polarization. Rayleigh waves have the greatest concentration of energy on the surface of a solid body. However, characteristics of the process of their distribution are highly dependent on the condition of the propagation surface. There is a possibility of reflection of wave scattering that is caused even by microdefects of this surface.

The main types of ultrasonic surface waves also include waves on the border of two half-spaces – the Stoneley waves [13]. A Stoneley wave is characterized by elliptical polarization oriented along normal to the border of half-spaces. Stoneley waves propagate both in liquid and solid half-spaces. In this case, a component that propagates in a liquid half-space is exposed to the action of the same disturbing factors as typical volumetric ultrasonic oscillations. For example, one should expect a strong dependence of the magnitude of their attenuation on the content of gas bubbles in the industrial suspensions.

Similar to the Rayleigh waves in nature, but with horizontal polarization, are the Love waves [14]. The Love waves, similar to the surface waves, exist due to the addition to the half-space of a solid layer, which is a load for the half-space. It should be noted that Love waves are characterized by strong dependence on the condition of the surface layer, which makes their use during measurements difficult.

Surface waves also include waves in plates: normal waves with horizontal polarization (transverse normal waves) and normal waves with vertical polarization – the Lamb waves [13, 15]. These waves are characterized by large enough concentration of energy and are less affected by disturbing factors than the Rayleigh and Love waves.

When investigating processes of deposition of particles of crushed ore in the iron ore pulp, authors of papers [16, 17] applied surface Lamb waves and volumetric ultrasound waves.

The propagation of ultrasound in liquid under conditions of cavitation is considered in [18]. Numerical methods were employed to determine the energy dissipated by bubbles. A direct dependence was established between the energy lost by gas bubbles and the attenuation of ultrasonic waves, which leads to the formation of traveling waves. Based on the results described above, authors of [19] calculated the magnitude of the Bjerknes force and predicted structures of gas bubbles that are generated as a result of traveling waves.

Study into dissipation of acoustic waves in fluids in the presence of bubbles is reported in paper [20]. The resulting model makes it possible to predict nonlinear attenuation of ultrasonic waves inside. It is noted that the predicted values of damping are much higher than the numbers estimated by previous models.

Theoretical study of ultrasound propagation in bubbly liquids with the experimental test of results was performed in work [21]. The approach was proposed implying consideration of a non-uniform pressure field outside of bubbles. The instability of bubbles is quantitatively estimated using analytical methods.

A numerical tool for studying propagation of ultrasound in bubbly liquids is described in paper [22]. The proposed model is based on the method of finite volume and finite-difference method. A given model solves the differential system created by the wave equation, and the Rayleigh-Plesset equation, connecting a sound pressure field to bubbles oscillations. The results obtained make it possible to observe physical effects caused by the presence of bubbles in a liquid: nonlinearity, dispersion, attenuation.

Nonlinear propagation of ultrasonic waves in the mixtures of air bubbles in water, under conditions of a heterogeneous distribution of bubbles, is reported in work [23]. Modeling is performed using a set of differential equations that describes connection between an acoustic field and bubble vibration. In this case, it is assumed that the attenuation and nonlinear effects are due solely to the presence of bubbles. The heterogeneity of bubble distribution is represented in the form of clusters of bubbles that can act as acoustic screens and which affect behavior of ultrasonic waves.

A method for predicting the number of active bubbles in the field of acoustic cavitation was proposed in paper [24]. The influence of ultrasonic frequency on the number of active bubbles was examined. It was shown that an increase in ultrasound frequency leads to a significant increase in the number of bubbles.

Results of modeling a primary Bjerknes force in an ultrasonic wave in the presence of bubbles in a fluid are given in work [25]. It is noted that the obtained results at small amplitudes are consistent with the classical theory. At the same time, it is shown that at an increase in amplitude the force field has important modifications that greatly affect the motion of bubbles.

Simulation of the distribution of fluid flow rate, caused by ultrasound action, is reported in paper [26]. Based on a comparison of modelling results and experimental data, the authors estimated ultrasonic absorption coefficient.

Work [27] considers models of certain complex phenomena, such as vibration of the walls of the tank and nonlinear phenomena caused by ultrasonic cavitation.

A study into nonlinear frequency mixing for ultrasonic waves in a resonator is described in paper [28]. The analysis is carried out using numerical experiments under both linear and nonlinear modes. Differences in parametric mixing at high and low amplitudes are shown using numerical methods.

A method of numerical simulation of propagation of ultrasonic oscillations in the gas-liquid two-phase flow is reported in work [29]. As a result of the analysis, the authors selected two characteristic parameters of ultrasound signals that are sensitive to the gas-liquid ratio, specifically standard deviation of the amplitude and the mean value of frequency.

A study into propagation of sound waves in two-component mixtures of liquid and polydisperse gas bubbles of different composition was performed in [30]. The authors presented a system of differential equations for the perturbed motion of the mixture and obtained a variance ratio. They obtained equilibrium speed of sound, low frequency and high frequency asymptotic of linear attenuation coefficient. Characteristic medium radii of bubbles were determined.

An analysis of the scientific literature, which we performed, revealed that in the process of development of methods for ultrasonic control over characteristics of technological media, mostly used are the Rayleigh, Love, Stoneley, Lamb waves. However, employing these types of waves implies significant constraints associated with condition of the propagation surface, as well as with the content of gas bubbles in the examined medium. Failure to comply with the mentioned restrictions leads to a larger measurement error. It is noted in some papers that a promising direction for eliminating the shortcomings is the use of volumetric ultrasound waves.

3. The aim and objectives of the study

The aim of present study is to identify patterns of connection between fluctuations in the number and size of particles, suspended in the controlled volume of a fluid, and characteristics of the field of volumetric ultrasonic waves propagating in it.

To accomplish the aim of the study, the following tasks have been set:

– to identify dependences of the ultrasound radiation field characteristics on quantitative and qualitative parameters of particles of a solid phase in the examined medium;

– to explore special features of the effect of quantitative and qualitative parameters of gas bubbles in the investigated medium on the characteristics of ultrasonic field;

– to investigate the effects of fluctuations in the number and size of solid particles and gas bubbles on the characteristics of ultrasonic field.

4. Materials and methods of research

During propagation of acoustic waves, a fluid undergoes irreversible energy losses, caused by internal friction (viscosity) and, to a certain extent, by thermal conductivity of the medium.

The expression to determine the magnitude of a flat wave absorption in a fluid, depending on the viscosity of medium, was obtained in the works of Stokes [14]. The sound absorption coefficient, predetermined by thermal conductivity of the medium, was defined in the works by Kirchhoff and Beeker [14].

The presence of particles of the solid phase and gas bubbles introduces certain features to the process of attenuation and scattering of the ultrasonic wave energy.

Scattering of waves on the particles of solid phase becomes considerable if the wavelength l is commensurate with dimensions of the particles themselves. If the wave passes a medium containing a large number of randomly spaced particles, the phases of waves, scattered in an arbitrary direction, are non-coherent. As a consequence, the full intensity of the ultrasonic wave at a given point is equal to the sum of the intensities of waves coming from all scattering centers. In this case, the scattering cross-sections are additive, which is why linear absorption $\Sigma_c(\lambda)$ and scattering $\Sigma_s(\lambda)$ coefficients can be determined from formulae

$$\Sigma_c(\lambda) = n\sigma_c(\lambda);$$

$$\Sigma_s(\lambda) = n\sigma_s(\lambda), \tag{1}$$

where n is the particle concentration (number of particles per unit volume); $\sigma_c(\lambda)$ and $\sigma_s(\lambda)$ are full cross-sections of absorption and scattering of acoustic wave on a particle.

Full absorption and scattering cross-sections depend not only on the wavelength of ultrasonic oscillation, but also on the size of particles r. The linear absorption and scattering coefficients should be understood as magnitudes that determine the average share of energy, absorbed and scattered by the medium at unit path length per unit of time.

Main characteristic of the ultrasonic emission field must be derived from the kinematic equation. Before we record this equation, we shall introduce the notion of a scattering coefficient differential by angles

$$\Sigma_S(\vec{\Omega} \to \vec{\Omega}') = n\sigma_S(\vec{\Omega} \to \vec{\Omega}'), \tag{2}$$

where $\sigma_S(\vec{\Omega} \to \vec{\Omega}')$ is the cross-section of energy scattering, differential by angles, on the particle of a solid phase. Magnitude $\sigma_S(\vec{\Omega} \to \vec{\Omega}')d\vec{\Omega}'$ is part of the energy scattered by a particle to the element of solid angle $d\vec{\Omega}'$. It is obvious that a full cross-section of the scattering s_S is associated with a differential scattering cross-section by relation

$$\sigma_S = \int_{4\pi} \sigma_S(\vec{\Omega} \to \vec{\Omega}')\mathrm{d}\vec{\Omega}'. \tag{3}$$

Kinetic equation, whose solution is a function $I_\lambda(\vec{r},\vec{\Omega})$, can be obtained by considering energy balance in the elementary volume of a phase space

$$\vec{\Omega}\nabla I_\lambda(\vec{r},\vec{\Omega}) = -\Sigma(\lambda)I_\lambda(\vec{r},\vec{\Omega}) + \\ + \int \mathrm{d}\vec{\Omega}'\Sigma_S(\vec{\Omega}' \to \vec{\Omega})I_\lambda(\vec{r},\vec{\Omega}') + S_\lambda(\vec{r},\vec{\Omega}), \tag{4}$$

where $\Sigma(\lambda) = \Sigma_c(\lambda) + \Sigma_S(\lambda)$, $S_\lambda(\vec{r},\vec{\Omega})$ is the density function of ultrasound source radiation, which defined the mean magnitude of energy emitted per unit time by a single phase volume. Phase coordinates are understood as a set of variables $\vec{r}$ and $\vec{\Omega}$, with the elementary phase volume defined by the product of $d\vec{r} \cdot d\vec{\Omega}$. A change in the intensity of ultrasonic beam in (4), with direction $\vec{\Omega}$ at point $\vec{r}$, occurs for the following reasons. First, due to its weakening-absorption and scattering (the first term of the right side). Second, as a result of scattering energy flow, which formerly had direction $\vec{\Omega}'$, to direction $\vec{\Omega}$ (the second term of the right side). Third, due to the energy coming to this bunch from sources (the last term of the right side). Equation (4) can be reduced to an integral equation of the following form:

$$I_\lambda(\vec r,\vec\Omega)=\int d\vec r'\int d\vec\Omega'\sum\nolimits_s(\vec\Omega'-\vec\Omega)\frac{e^{-\tau(\vec r',\vec r,\lambda)}}{|\vec r-\vec r'|}\times$$
$$\times\delta\left[\vec\Omega\text{-}\frac{(\vec r-\vec r')}{|\vec r-\vec r'|}\right]I_\lambda(\vec r',\vec\Omega')+I_\lambda^0(\vec r,\vec\Omega), \qquad (5)$$

where $\tau(\vec r',\vec r,\lambda)=\Sigma(\lambda)|\vec r-\vec r'|$, $\delta(\cdot)$ is the Dirac delta-function;

$$I_\lambda^\circ(\vec r,\vec\Omega)=\int_0^\infty S_\lambda(\vec r-\xi\vec\Omega,\vec\Omega)e^{-\tau(\xi,\lambda)}\mathrm{d}\xi$$

is the free term of integral equation (5) that defines the intensity of the unscattered ultrasonic wave; $\xi=|\vec r-\vec r'|$.

Solution to equation (5) can be written as a series by Neumann [15], which is a decomposition of the solution by multiplicity of scattering of ultrasonic waves. The first term of the Neumann series defines the field of non-scattered radiation of ultrasonic waves, the second term defines once-scattered radiation, etc.

However, it is impossible to obtain an analytic expression even for the once-scattered radiation. Therefore, one should employ numerical methods for solving integral equations of the form (5). One of the most common is the Monte Carlo method [16].

Attenuation of ultrasonic waves in water in the presence of solid particles and air bubbles occurs mainly due to the absorption and scattering of wave energy waves on particles and bubbles. To theoretically study patterns of ultrasound propagation, it is required to know the appropriate cross-sections of absorption and scattering.

We shall assume that there are solid spherical particles of radius r and density r_1 in water, then the absorption cross-section for such a particle would be determined from formula [14]

$$\sigma_c(\lambda)=\frac{4\pi r^3}{3}k\left(\frac{\rho_1}{\rho_\circ}-1\right)^2\frac{S}{S^2+(\rho_1/\rho_0+\tau)^2}, \qquad (6)$$

where $k=2\pi/\lambda$ is the wavenumber, r_0 is the density of a fluid;

$$S=\frac{9}{4Br}\left(1+\frac{1}{Br}\right);$$

$$B=(\pi\nu/\mu)^{\frac{1}{2}},\quad \tau=\frac{1}{2}+\frac{9}{4Br};$$

$\mu=\eta/\rho_0$, η is the viscosity coefficient of a liquid; ν is the frequency of ultrasonic oscillations.

Absorption cross-section determines part of the energy absorbed by a particle. These energy losses are due to friction (viscosity) at particle fluctuations.

Diffraction phenomena, caused by inhomogeneities in the medium (suspended particles), lead to the scattering of energy of sound waves. The cross-section of this process is determined from expression

$$\sigma_S(\lambda)=\frac{4\pi}{3}\cdot r^3\cdot\frac{1}{6}k^4\cdot r^3, \qquad (7)$$

where r is the radius of the particle.

Expression (7) shows that $\sigma_S(\lambda)\sim 1/\lambda^4$, which is why an increase in frequency leads to the increase in a scattering cross-section.

Fig. 1 shows dependences of the magnitude of cross-sections of absorption, scattering and attenuation of ultrasound on the particles of a solid phase in water on the frequency of acoustic oscillations. The radius of the particles was 0.01 cm. Ultrasound scattering becomes significant when the wavelength λ of acoustic oscillations is commensurate with the size of the particles.

The presence of gas bubbles in the fluid also leads to the absorption and scattering of sound energy. However, in contrast to the solid phase particles, the absorption and scattering on gas bubbles is resonant in nature.

The main reasons for this phenomenon are as follows:

a) heating the bubble and releasing the heat into a fluid at periodic changes in the volume of a bubble that act on it under the influence of a sound wave;

b) scattering of part of the sound energy, due to the fact that an oscillating bubble is a spherical source of sound;

c) energy losses through the formation of fluid flows around an oscillating bubble.

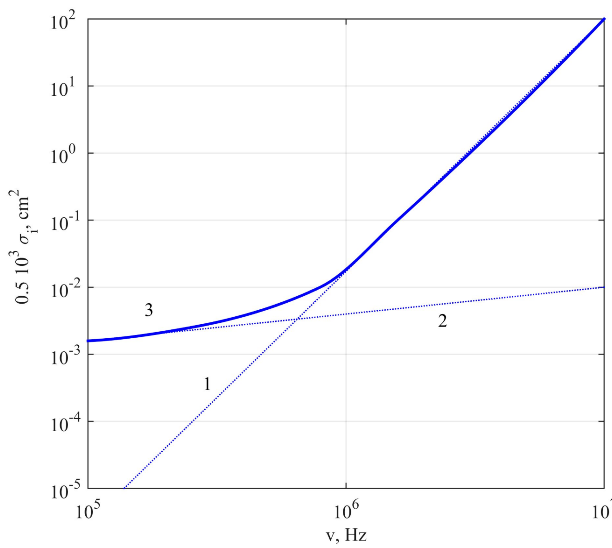

Fig. 1. Dependence of the magnitude of cross-sections of ultra sound absorption and scattering on suspended particles on oscillation frequency: 1 – scattering cross-section ss; 2 – absorption cross-section ss, particle radius r=0.01 cm; 3 – $\sigma=\sigma_c+\sigma_s$, particle radius r=0.01 cm

In order to characterize absorption and scattering of acoustic oscillations by oscillating gas bubbles, there were introduced the concepts of effective cross-sections of damping σ_p, absorption σ_c, and scattering σ_s. The effective cross-section of attenuation σ_p is understood as a cross-sectional area, perpendicular to the direction of incidence of the sound wave. In this case, the arriving sound energy is equal to the sum of the energies absorbed and scattered by a bubble.

The cross-sections of absorption and scattering of air bubbles are derived from formulae

$$\sigma_c=\frac{4\pi R^2(\delta/\eta-1)}{(\nu_0^2/\nu^2-1)^2+\delta^2};$$

$$\sigma_s=\frac{4\pi R^2(\delta/\eta)}{(\nu_0^2/\nu^2-1)^2+\delta}, \qquad (8)$$

where v_0 is the resonance frequency of the bubble of radius R; δ is the constant of attenuation; $\eta = 2\pi R/\lambda$.

An analysis of formulae (8) reveals that the maximum values of cross-sections are reached at $v=v_0$.

Full cross-section of damping (or attenuation) is the sum of absorption and scattering cross sections

$$\sigma_p = \sigma_c + \sigma_S = \frac{4\pi R^2}{(\nu_0^2/\nu^2 - 1)^2 + \delta^2}. \quad (9)$$

For the case of air bubbles in water, the value of resonance frequency can be derived from formula

$$\nu_0 R = 0{,}328 \cdot 10^3 \text{ Hz·cm}. \quad (10)$$

The value of attenuation constant depends on the frequency of ultrasound. Within the interval of frequencies from 20 to 1,000 kHz, this value varies from 0.08 to 0.013 [17]. The absorption and scattering of ultrasound energy on air bubbles is resonant in nature. In this case, in order to calculate the attenuation of ultrasonic wave by air bubbles, it is required to know not only the appropriate cross-sections of damping, but also a distribution function of air bubbles by size.

We shall denote by $f(R)$ a distribution function of bubbles by size, then magnitude $f(R)dR$ defines part of bubbles whose dimensions range from R to $R+dR$.

Particular values for a volumetric part of air in water and a function of gas bubbles distribution by size were chosen taking into consideration results of the studies reported in [5, 18, 19].

5. Results of the study into a process of propagation of volumetric ultrasound oscillations in gas-containing suspensions

Dependence of the magnitude of cross-section of ultrasound damping by air bubbles on the frequency of a sound wave is shown in Fig. 2. The dependence presented was obtained for air bubbles of radius R=0.005 cm.

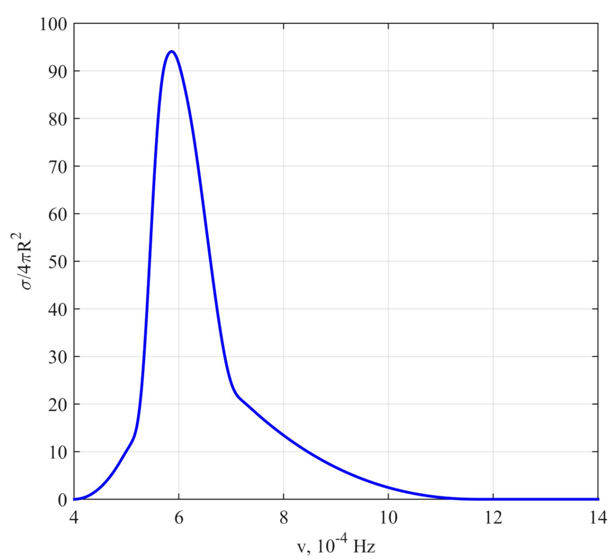

Fig. 2. Dependence of the magnitude of cross-section damping of ultrasound by air bubbles on the frequency of oscillations; R=0.005 cm

The existing theories of ultrasound propagation in a fluid with suspended particles presuppose the existence of particles of the same size. Since the granulometric characteristic of a shredded material in the pulp is probabilistic in nature, it is advisable to investigate the effect of fluctuations in the number and size of solid particles and gas bubbles on the characteristics of ultrasonic field.

The absorption and scattering of ultrasound on the particles, suspended in a fluid, depend on the wavelength of acoustic oscillations. At low frequencies, the ultrasound absorption dominates over scattering, which is why at these frequencies the radiation field forms mostly by the non-scattered acoustic oscillations. But even at high frequencies there are regions where the non-scattered radiation dominates over the scattered radiation. This happens at small distances from the source of radiation. Otherwise, the contribution of the scattered radiation becomes essential. From the point of view of examining the factors that influence the propagation of ultrasound in an actual pulp, each of these components is of a separate interest.

Suppose that a single disk source produces a directed beam of ultrasonic waves (Fig. 3). Such a source of acoustic oscillations can be described by the density of a source radiation

$$S_\lambda(\vec{r},\vec{\Omega}) = \delta(Z - Z_0)\frac{\delta(\cos\nu - 1)}{2\pi}\frac{St(\alpha - \rho)}{\pi\alpha^2}, \quad (11)$$

where $\cos\nu \equiv (\vec{\Omega}\cdot\vec{k})$; k is a unit vector, directed along the Z axis;

$$\rho = \sqrt{x^2 + y^2};$$

a is the radius of the disk source; Z_0 is the coordinate of plane of the disk source; $St(x)$ is a step function with property

$$St(x) = \begin{cases} 1, & X > 0; \\ 0, & X \le 0. \end{cases} \quad (12)$$

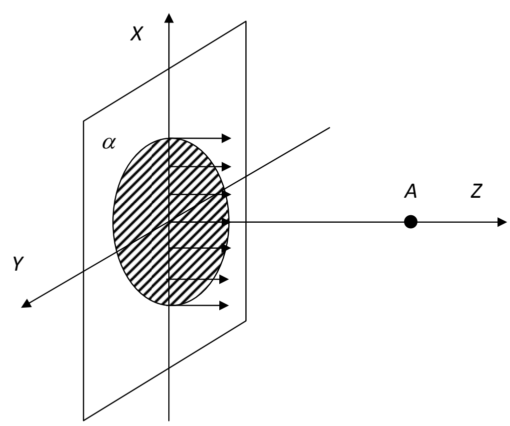

Fig. 3. Spatial orientation of the disk emitter of ultrasonic oscillations; α – emitter radius

The intensity of the ultrasonic non-scattered wave is determined by the free term of equation (5) through the density function of source radiation

$$\overset{\circ}{I}_\lambda(\vec{r},\vec{\Omega}) = \int_0^\infty S(\vec{r} - \xi\vec{\Omega},\vec{\Omega})e^{-\tau(\xi,\lambda)}d\xi. \quad (13)$$

Substituting (11) in this formula, we shall obtain

$$I_{\lambda}^{\circ}(Z,\rho,\cos\nu)=$$
$$=\frac{\delta(\cos\nu-1)}{2\pi}\frac{St(a-\rho)}{\pi a^{2}}\times\exp\left\{-\sum(Z-Z_{0})\right\}. \qquad (14)$$

The readout from a detector of ultrasonic waves radiation is proportional to the integral intensity, i. e. to magnitude

$$I_{\lambda}(\vec{r})=\int \mathrm{d}\vec{\Omega} I_{\lambda}(\vec{r},\vec{\Omega}). \qquad (15)$$

Following the integration of expression (14) by the angular variable, we shall obtain a value of integral intensity

$$I_{\lambda}^{\circ}(Z,\rho)=I_{0,\lambda}St(a-\rho)e^{-\Sigma(Z-Z_{0})}, \qquad (16)$$

where $I_{0,\lambda}$ is the intensity of the wave beam at points with coordinate $Z=Z_0$. Z_0 subsequently can be considered equal to zero. This means that the source is located at the coordinate origin.

Let us examine the case when a radiation detector is located along the axis of beam of acoustic oscillations. Then the detector readout will be equal to, in proportion to magnitude

$$I_{\lambda}^{0}(Z)=I_{0,\lambda}^{0}e^{-\Sigma^{Z}}. \qquad (17)$$

We can record with respect to (1) and (4)

$$\Sigma(\lambda)=n_{1}\sigma_{p}(\lambda,R)+n\sigma(\lambda,r), \qquad (18)$$

where n_1 is the concentration of air bubbles; n is the concentration of particles of the solid phase; $\sigma(\lambda, R)$ is the cross-section of damping the ultrasonic oscillations of wavelength λ on the air bubble of radius R; $\sigma(\lambda, r)$ a full cross-section of the attenuation of ultrasonic oscillations with wavelength λ on a solid phase particle of radius r.

It should be noted that the gas phase in the pulp does not contain bubbles of the same radius. Therefore, in order to correctly assess the impact of air bubbles on the magnitude of attenuation of the ultrasound beam, it is required to take into consideration both the fluctuation in the number of bubbles in the volume and the distribution of bubbles by size. The latter is especially significant, because the damping cross-section on bubbles is resonant in nature. A similar accounting should be performed also for particles of the solid phase.

The situation described above corresponds to the geometry of experiment shown in Fig. 4. Detector D registers ultrasonic waves passed through controlled volume V. Fluctuations in the number of bubbles in controlled volume V affect detector D readout.

The concentration of air bubbles will be determined through the number of bubbles N_1 in volume V

$$n_{1}=\frac{N_{1}}{V}. \qquad (19)$$

As the number of bubbles fluctuates, N_1 is a random number with the Poisson distribution [20]

$$P_{N1}(k)=\frac{<N_{1}>^{k}e^{-<N_{1}>}}{k!}, \quad k=0,1,2,\ldots, \qquad (20)$$

where $<N_1>$ is the average value of number N_1 in volume V, which can be determined through the mean value of concentration $\vec{n}_1$

$$<N_{1}>=\bar{n}_{1}V. \qquad (21)$$

We shall select in expression (17) only the part that determines the attenuation of ultrasonic oscillations by air bubbles

$$I_{\lambda}^{\circ}(Z)=I_{\lambda}\exp\left\{-\frac{1}{V}\sum_{i=1}^{N_{1}}\sigma_{p}(\lambda,R_{i})Z\right\}. \qquad (22)$$

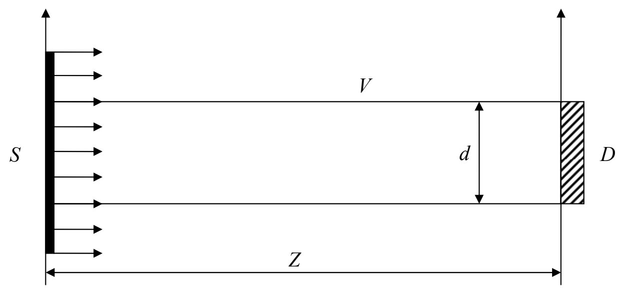

Fig. 4. Geometric interpretation of measuring channel: S – source of ultrasonic oscillations; D – detector; V – controlled volume; d – effective diameter of the region controlled by the detector

Detector D readout will be proportional to the value of $I_{\lambda}^{\circ}(Z)$, averaged by the fluctuations in the number and size of bubbles, that is, in proportion to magnitude

$$<I_{\lambda}^{\circ}(Z)>=I_{\lambda}<\exp\left\{-\frac{1}{V}\sum_{i=1}^{N_{1}}\sigma_{p}(\lambda,R_{i})Z\right\}>. \qquad (23)$$

We shall denote by ξ a random magnitude

$$\xi=\exp\left\{-\frac{1}{V}\sum_{i=1}^{N_{1}}\sigma_{p}(\lambda,R_{i})Z\right\}. \qquad (24)$$

To find the average value of magnitude ξ, we shall apply a formula of full mathematical expectation [20]

$$M\xi=\sum_{k=0}^{\infty}\cdot M\left(\frac{\xi}{k}\right)P_{N_{1}}(k). \qquad (25)$$

Here, $M\xi$ denotes the mathematical expectation of random magnitude ξ, $M(\xi/k)$ is the conditional mathematical expectation.

It is easy to show that

$$M\left(\frac{\xi}{k}\right)=\left[M\exp\left\{-\frac{1}{V}\sigma_{p}(\lambda,R)Z\right\}\right]^{k}, \qquad (26)$$

where

$$M\exp\left\{-\frac{1}{V}\sigma_{p}(\lambda,R)Z\right\}-$$
$$-\int_{0}^{\infty}\exp\left\{-\frac{Z}{V}\sigma_{p}(\lambda,R)\right\}f(R)dR=\eta_{1}. \qquad (27)$$

Here, $f(R)$ is the distribution function of gas bubbles by size.

Substituting expressions (20) and (27) to (25), we obtain

$$M\xi=\sum_{k=0}^{\infty}\cdot\eta_{1}^{k}\frac{(n_{1}V)^{k}}{k!}e^{-\bar{n}_{1}V}=$$
$$=e^{-\bar{n}v}\exp\left\{\bar{n}_{1},V\eta_{1}\right\}=e^{-\bar{n}_{1}V(1-\eta_{1})}. \qquad (28)$$

Similarly, with respect to the fluctuations in the number and size of particles of the solid phase, we shall obtain the averaged value for integral intensity of ultrasonic oscillations that passed through the controlled amount of pulp

$$< I_{\lambda}^{\circ}(Z) >= I_{\circ,\lambda} \exp\left\{-V\left[\overline{n}_1(1-\eta_1)+\overline{n}(1-\eta)\right]\right\}, \tag{29}$$

where

$$\eta = \int_{\circ}^{\infty} \exp\left\{-\frac{1}{V}\sigma(\lambda, r)Z\right\}\phi(r)\mathrm{d}r;$$

$\varphi(r)$ is the distribution function of solid phase particles by size, which has the same meaning as function $f(R)$.

Controlled volume V can be defined through Z

$$V = \frac{\pi d^2}{4} Z. \tag{30}$$

In this case, η and η_1 do not depend on variable Z.

As it is known, the intensity of the wave is proportional to the square of the amplitude of wave [17], which is why, if we know (29), it is possible to pass over to the amplitude dependence

$$< A_{\lambda}(Z) >= \\ = A_{o,\lambda} \exp\left\{-\frac{1}{2}\frac{\pi d^2}{4}\left[\overline{n}_1(1-\eta_1)+\overline{n}(1-\eta)\right]Z\right\}. \tag{31}$$

Character <x>, similar to the previous case, means averaging for the fluctuations in size and number of particles of solid and gaseous phases.

In order to study dependence (29), it is convenient to pass to the new magnitude α_λ:

$$\alpha_{\lambda} = \frac{1}{Z}\ln\frac{I_{o,\lambda}}{< I_{\lambda}^{\circ}(Z) >} = \\ = \frac{\pi d^2}{4}\left[\overline{n}_1(1-\eta_1)+\overline{n}(1-\eta)\right]. \tag{32}$$

It should be noted that the phase composition of heterogeneous media is assigned, as a rule, by the volumetric part of each phase, which is why when applying expressions (29), (31) and (32), it is more convenient to pass from the average concentration of the number of air bubbles $\overline{n}_1$ to their volumetric part W.

We shall consider this transition in more detail

$$\overline{n}_1(1-\eta_1) = \overline{n}_1 \cdot \int_0^{\infty}\left[1-\exp\left\{-\frac{4}{\pi d^2}\sigma_p(\lambda, R)\right\}\right]f(R)\mathrm{d}R = \\ = \int_0^{\infty}\left[1-\exp\left\{-\frac{4}{\pi d^2}\sigma_p(\lambda, R)\right\}\right]\frac{WF(R)\mathrm{d}R}{4/3\pi R^3} = WQ\,. \tag{33}$$

In a given expression, $WF(R)dR$ defines the volumetric part of those air bubbles whose radii are within R to $R+dR$.

Function $F(R)$ is associated with $f(R)$ through ratio

$$F(R) = \frac{R^3 f(R)}{\int_0^{\infty} R^3 f(R)\mathrm{d}R}. \tag{34}$$

Thus, taking into consideration the latter values, expression (32) can be represented in the form

$$\alpha_{\lambda} = \frac{1}{Z}\ln\frac{I_{o,\lambda}}{< I_{\lambda}^{\circ}(Z) >} = \frac{\pi d^2}{4}\left[WQ+\overline{n}_1(1-\eta)\right]. \tag{35}$$

In the calculation of α_λ, a distribution function of solid phase particles $\varphi(r)$ by size conformed with the beta distribution [20]

$$\alpha\phi(X) = \frac{1}{B(\alpha,\beta)}X^{\alpha-1}(1-X)^{\beta-1}, \tag{36}$$

where $\alpha = 2\overline{r}$; $\overline{r}$ is the average value of radius of solid phase particles, suspended in a fluid; $B(\alpha,\beta)$ is the beta function.

6. Discussion of results of examining the process of propagation of volumetric ultrasound oscillations in gas-containing suspensions

Fig. 5 shows dependence of α_λ on frequency for different values of parameters α and β.

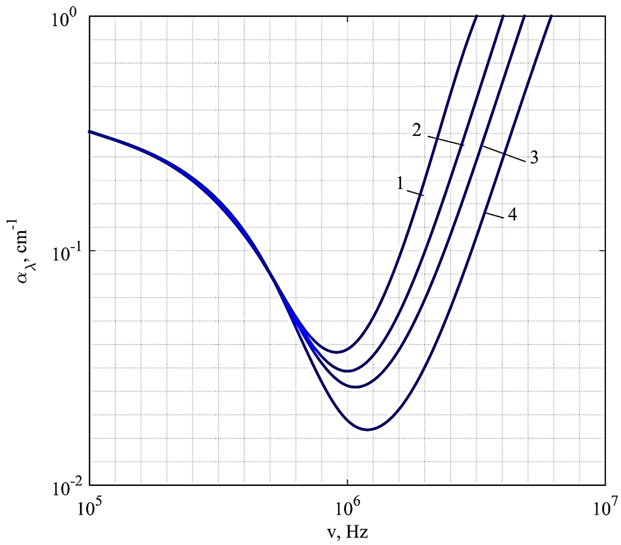

Fig. 5. Dependence of α_λ on the frequency of ultrasound for different values of parameters in the beta distribution: 1 – $\alpha=\beta=1$; 2 – $\alpha=\beta=2$; 3 – $\alpha=\beta=3$; 4 – $\alpha=\beta=\infty$

The value of α_λ depends on the concentration of solid phase particles n. Fig. 6 shows dependence of α_λ on frequency for different values of n. It is demonstrated in Fig. 6 that in the region where the ultrasonic beam attenuation on the particles of a solid phase dominates over the absorption by air bubbles, there is influence of the concentration of the number of particles. In this case, a change in n leads to a change in the absolute value of α_λ in this region of frequencies, though the slope of graphical dependences does not change. This fact can be used to determine the concentration of particles of the solid phase of pulp.

The magnitude of α_λ depends not only on the concentration of n, but also on the average particle size, which is clearly seen in Fig. 8. The dependences, shown in these figures, were obtained at $\alpha=\beta=3$. In the case when the value of α_λ is determined by the attenuation of ultrasound by the solid phase particles, the slope of α_λ curve does not depend on the average particle radius (Fig. 9, dotted lines indicate the slope of the linear section of charts). However, this does not prevent determining both the average size and the concentration of suspended particles.

This is explained by the fact that the average size of particles defines frequency V_k, at which components of the absorption and scattering on solid particles become equal. Therefore, given the value of V_k, one can tell the mean size of a particle. Fig. 9 shows constituents of $\sigma_{\lambda i}$, predetermined by the attenuation of ultrasonic oscillations by air bubbles, by the absorption and scattering on the particles of a solid phase, suspended in a fluid.

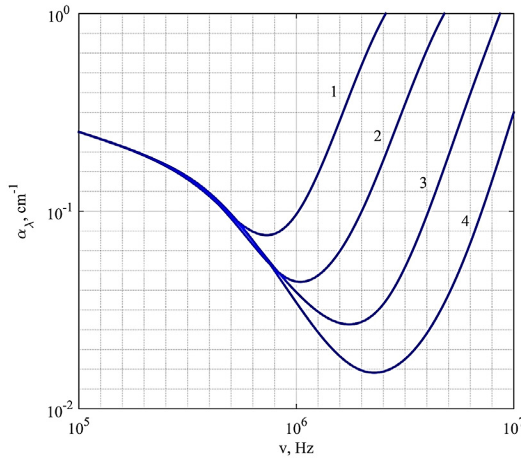

Fig. 6. Dependence of α_λ on the frequency of ultrasound for various concentrations of suspended particles: 1 – n_1=10^4 cm^{-3}; 2 – n_2=10^3 cm^{-3}; 3 – n_3=10^2 cm^{-3}; 4 – n_4=10 cm^{-3}; r=0.01 cm

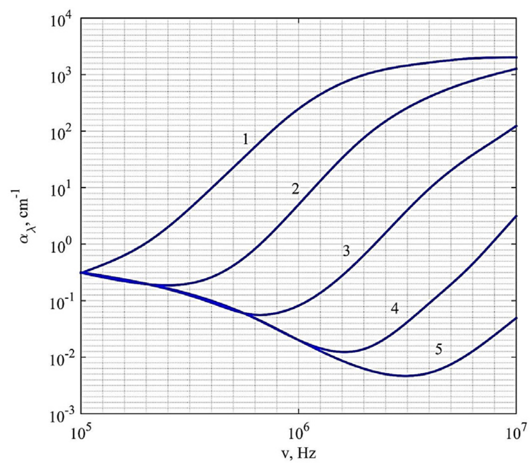

Fig. 7. Dependence of α_λ on the frequency of ultrasound for different values of average particle radius: 1 – $\bar{r}$=0.1 cm; 2 – $\bar{r}$=0.05 cm; 3 – $\bar{r}$=0.02 cm; 4 – $\bar{r}$=0.01 cm; 5 – $\bar{r}$=0.005 cm; n=10^2 cm^{-3}; α=β=3

Here we also show frequencies ν_{k1} and ν_{k2}, which are useful for the measurement of content of solid phase particles in the pulp with average 10^{-2} and 10^3 cm, respectively. The values of frequency V_k do not depend on the particle concentration.

Direction of development of the obtained results is to study the effects of ultrasonic oscillations on the trajectory of particle motion in a flow of pulp. The possibility to exert a targeted influence will in the future make it possible to shift to a measurement region the particles of a certain size grade. Thus, it could be obtained the information, important from a technological point of view, on the distribution of physical-mechanical and chemical-mineralogical characteristics of solid phase particles by size grades.

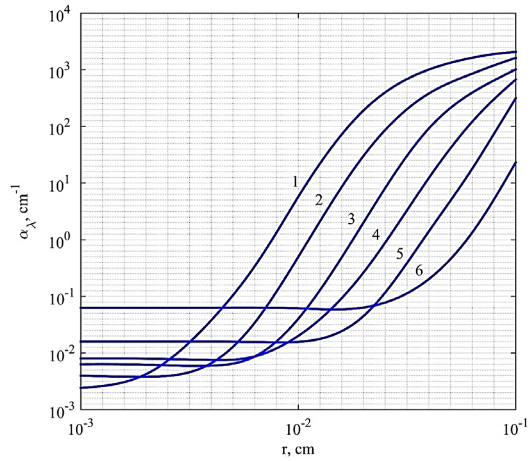

Fig. 8. Dependence of α_λ on the average radius of suspended particles for different frequency of ultrasonic oscillations: 1 – ν_1=10^7 Hz; 2 – ν_2=$5\cdot10^6$ Hz; 3 – ν_3=$2.5\cdot10^6$ Hz; 4 – ν_4=$1.6\cdot10^6$ Hz; 5 – ν_5=10^6 Hz; 6 – ν_6=$5\cdot10^5$ Hz; n=10^2 cm^{-3}

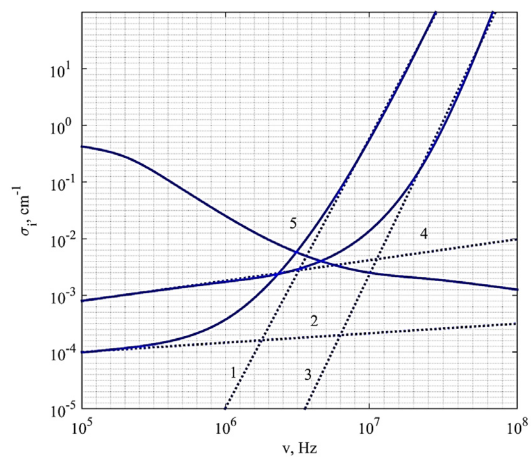

Fig. 9. Dependence of frequency of the components of α_λ on frequency of ultrasonic oscillations: 1, 3 – components, predetermined by the scattering on solid particles; 2, 4 – components, predetermined by the absorption of solid particles; 5 – components of the attenuation by air bubbles; 1, 2 – $\bar{r}$=0.01 cm; 3,4 – $\bar{r}$=0.001 cm

7. Conclusions

1. We have constructed an integral equation that makes it possible to determine characteristics of the absorption and scattering of radiation field of ultrasound in the presence of particles of solid phase in the examined medium. The solution to a given equation can be written in the form of the Neumann series. In order to solve the equation numerically, it is possible to apply a Monte Carlo method. It was established that the ultrasound scattering becomes considerable when the wavelength of acoustic oscillations is commensurate with the size of the particles.

2. It was established that in contrast to the solid phase particles, the absorption and scattering of ultrasonic waves on gas bubbles is resonant in nature. The magnitudes of absorption and scattering of bubbles reach their maximum values at the equality between frequency of ultrasonic oscillations and resonance frequency of the bubbles with a specific radius.

3. In order to correctly evaluate the impact of air bubbles on the magnitude of attenuation of ultrasound beam, it is required to take into consideration both the fluctuation in the number of bubbles in the volume and the distribution of bubbles by size. We found dependences of the integral intensity of ultrasonic oscillations, passed through a controlled amount of pulp, on fluctuations in the number and size of solid phase particles. The dependences obtained make it possible to determine the average size and concentration of suspended particles in the examined medium.

References

1. Rzhevskiy, V. V. Ul'trazvukovoy kontrol' i issledovaniya v gornom dele [Text] / V. V. Rzhevskiy, V. S. Yamshchikov. – Moscow: Nedra, 1968. – 120 p.
2. Morkun, V. Automation of iron ore raw materials beneficiation with the operational recognition of its varieties in process streams [Text] / V. Morkun, V. Tron // Metallurgical and Mining Industry. – 2014. – Issue 6. – P. 4–7.
3. Morkun, V. Identification of control systems for ore-processing industry aggregates based on nonparametric kernel estimators [Text] / V. Morkun, N. Morkun, V. Tron // Metallurgical and Mining Industry. – 2015. – Issue 1. – P. 14–17.
4. Golik, V. Metal deposits combined development experience [Text] / V. Golik, V. Komashchenko, V. Morkun, O. Burdzieva // Metallurgical and Mining Industry. – 2015. – Issue 6. – P. 591–594.
5. Morkun, V. Formalization and frequency analysis of robust control of ore beneficiation technological processes under parametric uncertainty [Text] / V. Morkun, N. Morkun, V. Tron // Metallurgical and Mining Industry. – 2015. – Issue 5. – P. 7–11.
6. Morkun, V. Distributed closed-loop control formation for technological line of iron ore raw materials beneficiation [Text] / V. Morkun, N. Morkun, V. Tron // Metallurgical and Mining Industry. – 2015. – Issue 7. – P. 16–19.
7. Golik, V. Feasibility of using the mill tailings for preparation of self-hardening mixtures [Text] / V. Golik, V. Komashchenko, V. Morkun // Metallurgical and Mining Industry. – 2015. – Issue 3. – P. 38–41.
8. Morkun, V. Ore preparation multi-criteria energy-efficient automated control with considering the ecological and economic factors [Text] / V. Morkun, V. Tron // Metallurgical and Mining Industry. – 2014. – Issue 5. – P. 4–7.
9. Cao, Q. Surface cleaning and oxidative effects of ultrasonication on the flotation of oxidized pyrite [Text] / Q. Cao, J. Cheng, Q. Feng, S. Wen, B. Luo // Powder Technology. – 2017. – Vol. 311. – P. 390–397. doi: 10.1016/j.powtec.2017.01.069
10. Morkun, V. Simulation of the Lamb waves propagation on the plate which contacts with gas containing iron ore pulp in Waveform Revealer toolbox [Text] / V. Morkun, N. Morkun, A. Pikilnyak // Metallurgical and Mining Industry. – 2014. – Issue 5. – P. 16–19.
11. Golik, V. Innovative technologies of metal extraction from the ore processing mill tailings and their integrated use [Text] / V. Golik, V. Komashchenko, V. Morkun // Metallurgical and Mining Industry. – 2015. – Issue 3. – P. 49–52.
12. Brazhnikov, N. I. Ul'trazvukovye metody [Text] / N. I. Brazhnikov. – Leningrad; Moscow: Energiya, 1965. – 248 p.
13. Viktorov, I. A. Zvukovye poverhnostnye volny v tverdyh telah [Text] / I. A. Viktorov. – Moscow: Nauka, 1981. – 286 p.
14. Kundu, S. Love wave propagation in heterogeneous micropolar media [Text] / S. Kundu, A. Kumari, D. K. Pandit, S. Gupta // Mechanics Research Communications. – 2017. – Vol. 83. – P. 6–11. doi: 10.1016/j.mechrescom.2017.02.003
15. Brazhnikov, N. I. Ispol'zovanie voln Lemba dlya signalizatsii urovnya zhidkih sred [Text] / N. I. Brazhnikov, N. S. Shavykina, A. P. Gordeev, V. S. Skripalev // Pribory i sistemy upravleniya. – 1975. – Issue 9. – P. 31–32.
16. Goncharov, S. A. Povyshenie effektivnosti obogatitel'nyh tekhnologiy putem vozdeystviya vysokoenergeticheskogo ul'trazvuka na pererabatyvaemoe syr'e [Text] / S. A. Goncharov // Visnyk Kryvorizkoho tekhnichnoho universytetu. – 2009. – Issue 23. – P. 236–239.
17. Podgorodetskiy, N. S. Avtomaticheskoe upravlenie protsessom raskrytiya poleznogo komponenta pri izmel'chenii rudy [Text] / N. S. Podgorodetskiy // Visnyk Kryvorizkoho tekhnichnoho universytetu. – 2007. – Issue 19. – P. 120–124.
18. Louisnard, O. A simple model of ultrasound propagation in a cavitating liquid. Part I: Theory, nonlinear attenuation and traveling wave generation [Text] / O. Louisnard // Ultrasonics Sonochemistry. – 2012. – Vol. 19, Issue 1. – P. 56–65. doi: 10.1016/j.ultsonch.2011.06.007
19. Louisnard, O. A simple model of ultrasound propagation in a cavitating liquid. Part II: Primary Bjerknes force and bubble structures [Text] / O. Louisnard // Ultrasonics Sonochemistry. – 2012. – Vol. 19, Issue 1. – P. 66–76. doi: 10.1016/j.ultsonch.2011.06.008
20. Jamshidi, R. Dissipation of ultrasonic wave propagation in bubbly liquids considering the effect of compressibility to the first order of acoustical Mach number [Text] / R. Jamshidi, G. Brenner // Ultrasonics. – 2013. – Vol. 53, Issue 4. – P. 842–848. doi: 10.1016/j.ultras.2012.12.004
21. Zhang, Y. Influences of non-uniform pressure field outside bubbles on the propagation of acoustic waves in dilute bubbly liquids [Text] / Y. Zhang, X. Du // Ultrasonics Sonochemistry. – 2015. – Vol. 26. – P. 119–127. doi: 10.1016/j.ultsonch.2015.02.016
22. Sastre, M. T. T. A numerical model for the study of the difference frequency generated from nonlinear mixing of standing ultrasonic waves in bubbly liquids [Text] / M. T. Tejedor Sastre, C. Vanhille // Ultrasonics Sonochemistry. – 2017. – Vol. 34. – P. 881–888. doi: 10.1016/j.ultsonch.2016.07.020
23. Vanhille, C. Nonlinear ultrasonic waves in bubbly liquids with nonhomogeneous bubble distribution: Numerical experiments [Text] / C. Vanhille, C. Campos-Pozuelo // Ultrasonics Sonochemistry. – 2009. – Vol. 16, Issue 5. – P. 669–685. doi: 10.1016/j.ultsonch.2008.11.013
24. Merouani, S. A method for predicting the number of active bubbles in sonochemical reactors [Text] / S. Merouani, H. Ferkous, O. Hamdaoui, Y. Rezgui, M. Guemini // Ultrasonics Sonochemistry. – 2015. – Vol. 22. – P. 51–58. doi: 10.1016/j.ultsonch.2014.07.015
25. Vanhille, C. Numerical simulations of the primary Bjerknes force experienced by bubbles in a standing ultrasonic field: Nonlinear vs. linear [Text] / C. Vanhille, C. Campos-Pozuelo // Wave Motion. – 2014. – Vol. 51, Issue 7. – P. 1127–1137. doi: 10.1016/j.wavemoti.2014.06.001
26. Xu, Z. Numerical simulation of liquid velocity distribution in a sonochemical reactor [Text] / Z. Xu, K. Yasuda, S. Koda // Ultrasonics Sonochemistry. – 2013. – Vol. 20, Issue 1. – P. 452–459. doi: 10.1016/j.ultsonch.2012.04.011
27. Tudela, I. Simulation of the spatial distribution of the acoustic pressure in sonochemical reactors with numerical methods: A review [Text] / I. Tudela, V. Sáez, M. D. Esclapez, M. I. Díez-García, P. Bonete, J. González-García // Ultrasonics Sonochemistry. – 2014. – Vol. 21, Issue 3. – P. 909–919. doi: 10.1016/j.ultsonch.2013.11.012

28. Vanhille, C. Nonlinear frequency mixing in a resonant cavity: Numerical simulations in a bubbly liquid [Text] / C. Vanhille, C. Campos-Pozuelo, D. N. Sinha // Ultrasonics. – 2014. – Vol. 54, Issue 8. – P. 2051–2054. doi: 10.1016/j.ultras.2014.07.004
29. Xu, Y. Study of the ultrasonic propagation law in the gas-liquid two-phase flow of deepwater riser through numerical simulation [Text] / Y. Xu, Z. Guan, Y. Jin, Y. Tian, Y. Liu, C. Xu, Y. Shi // Journal of Petroleum Science and Engineering. – 2017. – Vol. 159. – P. 419–432. doi: 10.1016/j.petrol.2017.09.051
30. Gubaidullin, D. A. Sound waves in two-fraction polydispersed bubbly media [Text] / D. A. Gubaidullin, Yu. V. Fedorov // Journal of Applied Mathematics and Mechanics. – 2013. – Vol. 77, Issue 5. – P. 532–540. doi: 10.1016/j.jappmathmech.2013.12.008

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ANALYSIS OF THE ELECTROMAGNETIC FIELD OF MULTILAYERED BIOLOGICAL OBJECTS FOR THEIR IRRADIATION IN A WAVEGUIDE SYSTEM

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Розглянуто хвилеводну систему з металевою сферою для опромінення біологічних об'єктів електромагнітним полем. Для створення хвилеводної системи було проведено теоретичний аналіз розподілу електромагнітного поля всередині біологічних об'єктів. Теоретичний аналіз взаємодії електромагнітного поля з біологічними об'єктами проведений для багатошарових структур. Розміри багатошарових біологічних об'єктів малі порівняно з довжиною падаючої хвилі. Вирази теоретичного аналізу можуть бути використані для дослідження механізму взаємодії електромагнітного поля з біологічними об'єктами

Ключові слова електромагнітне поле, багатошарові біологічні об'єкти, хвилеводна система, опромінення біологічних об'єктів

Рассмотрена волноводная система с металлической сферой для облучения биологических объектов электромагнитным полем. Для создания волноводной системы был проведен теоретический анализ по распределению электромагнитного поля внутри биологических объектов. Теоретический анализ взаимодействия электромагнитного поля с биологическими объектами был проведен для многослойных структур. Размеры многослойных биологических объектов малы по сравнению с длиной падающей волны. Выражения теоретического анализа могут быть использованы для исследования механизма взаимодействия электромагнитного поля с биологическими объектами

Ключевые слова: электромагнитное поле, многослойные биологические объекты, волноводная система, облучение биологических объектов

1. Introduction

Systemic information approach is linked to studying the effect of electromagnetic field on biological objects. It is based on the principles that a living organism is a finely-tuned informoenergetic field structure [1]. The ultimate biological effect depends on the biotropic parameters of electromagnetic field and exposure [2].

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