Ultrasonic testing of the crushed ore particle size distribution in the pulp flow

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Abstract
The method of measurement of pulp solid phase concentration and particle size distribution based on the high energy ultrasound radiation pressure influence is proposed.

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Three types of controlled parameters, which characterizing respectively the quality and quantity of processed ore materials, and the production situations, the state of the technological equipment are necessary for effective concentrating factories process control [7,8,13,14]. The known ultrasonic testing methods of the pulp parameters allow to identify two of its main characteristics – density and particle size distribution [1-3, 9-12,15-18]. Pulp is a randomly inhomogeneous heterogeneous medium, which contain the solid particles of different size in water with a distribution described by the function $F(r)$, where r – is the particle radius. The content of particles in the slurry can be set either by concentration

$$n = N \cdot V^{-1}, \tag{1}$$

or through their volume fraction W. The ultrasonic wave amplitude with frequency of ν, which passed the distance Z in the medium can be described by the formula [5,6]

$$A_\nu(Z) = A_o exp\{-ZN/V\int_o^{r_m} drF(r)\sigma(\nu,r)\}, \quad (2)$$

where N – is the number of particles in the effective controlled amount of pulp V; A_o – is the amplitude of the wave, which passed the same distance through the clean water; r_m – maximum solids size.

In this expression, $\sigma(\nu,r)$ – is ultrasound attenuation cross-section with frequency ν on a solid spherical particle of radius r and density ρ_T [1, 2]

$$\sigma(\nu,r) = \sigma_\nu + 1/\left(\sigma_s^{-1} + \sigma_d^{-1}\right), \quad (3)$$

where $\sigma_\nu = \frac{4\pi r^3}{3}\left(\frac{\omega}{c}\right)\left(\frac{\rho_T}{\rho_o}-1\right)^2 \frac{S}{S^2+\left(\frac{\rho_T}{\rho_o}+\tau\right)^2}$; ω = $= 2\pi\nu$; c – is ultrasound speed in the medium; ρ_o – is liquid density; $S = \frac{9}{4Br}\left(1+\frac{1}{Br}\right)$; $B = \left(\frac{\pi\nu}{\mu}\right)^{\frac{1}{2}}$; τ = $=\frac{1}{2}+\frac{9}{4Br}$; $\mu = \eta/\rho_o$; η - is fluid viscosity coefficient; $\sigma_s = \frac{4\pi r^3}{3}\frac{1}{6}\left(\frac{\omega}{c}\right)^4 r^3$; $\sigma_d = \frac{4\pi r^3}{3}\left(\frac{\omega}{c}\right)^{\frac{1}{3}} / 4\pi r$.

In (3) the values σ_ν and σ_d determine viscous-inertial and diffraction losses, and σ_s – losses caused by ultrasound scattering. As it is seen from (2), if to form the signal

$$A = \frac{1}{Z}\ln(I_o/I_\nu) = \frac{N}{V}\int_o^{r_m} drF(r)\sigma(\nu,r), \quad (4)$$

then it contains information about the solid particles concentration and their size distribution. Integral in the expression (4) can be represented as

$$\int_o^{r_m} drF(r)\sigma(\nu,r) = \int_o^{r_1} drF(r)\sigma(\nu,r) + $$

$$+\int_{r_1}^{r_2} drF(r)\sigma(\nu,r) + \ldots + \int_{r_{m-1}}^{r_m} drF(r)\sigma(\nu,r), \quad (5)$$

where r_i – is the particle size intervals limits

$$\Delta r_i = r_i - r_{i-1}. \quad (6)$$

If value of interval Δr_i is small, then any of the integrals in right side of expression (5) can be represented as

$$\int_{r_{i-1}}^{r_i} drF(r)\sigma(\nu,r) \approx F(r_i)\Delta r_i\sigma(\nu,r_i). \quad (7)$$

Thus, the expression (4) can be represented as follows

$$A = \frac{N}{V}\sum_{i=1}^{m} f(r_i)\,\Delta r_i\sigma(\nu,r_i)\sum_{i=1}^{m}{}_{-i}\alpha(\nu,r_i), \quad (8)$$

where $\alpha(\nu,r_i) \equiv \sigma(\nu,r_i)$; c_i – is the concentration of particles, the size of which belongs to the interval Δr_i.

If to form such signals at different frequencies $\nu_j (1 \le j \le m)$, then we will have a system of algebraic equations

$$A_j = \sum_{i=1}^{m}{}_{-i}\alpha_{ji}, \quad (9)$$

where $\alpha_{ji} \equiv \alpha(\nu_j, r_i) = \Delta r_i \sigma(\nu_j, r_i)$.

Coefficients α_{ji} are defined by attenuation cross sections of $\sigma(\nu_j, r_i)$. The choice of frequencies ν_j is carried out by ultrasound wavelength λ_j and the particle sizes r_1 and r_m, and maximum wavelength should correspond to the radius r_m, while the minimum is equal to r_1. The described method is reflected in the work [4]. The drawbacks of this method for determining the particles concentration by size are obvious. Firstly, the accuracy of the concentration c_i determining depends on the number of system equations (9) and, in a great extent, from signal measurement error A_j. For an adequate description of particle size distribution the condition $m \ge 10$ should be fulfilled. At low frequencies, (ν <1 MHz) the measurement error A_j can be connected with the influence of the pulp gas bubbles. To improve the accuracy of signals A_j measurement at low frequencies, the preliminary pulp degassing is required. Secondly, the requirement to satisfy the condition $m \ge 10$ is practically connected with the implementation of a large number of ultrasonic measuring channels. The method for determining the pulp solid phase particle size distribution, based on the use of high-energy ultrasound radiation pressure for their prior spatial separation by size and density is devoid from these disadvantages [5-9]. The nature of change in particle concentration and size distribution in the high-energy ultrasound field depends on the density of the particles themselves, the frequency and intensity of the incident radiation [2-4, 9]. Let's estimate the ultrasound radiation pressure influence on the particles concentration change of radius r. Let's suppose that in the positive direction of axis x the pulp is flowing at a speed V and denote the concentration of the particle radius r at a depth Z at time point t by $n_r(Z,t)$. Considering the above we can write

$$\frac{\partial n_r(Z,t)}{\partial t} = -\frac{\partial}{\partial Z}\left[V_r(Z,t)n_r(Z,t)\right]. \quad (10)$$

where $V_r(Z,t)$ – the displacement speed of the particle of radius r with a coordinate Z in an ultrasonic field. Speed is directed along the axis z, i.e. perpendicular to the pulp flow. By assuming that the intensity of the ultrasonic wave I changes exponentially (the initial value is I_0), its attenuation coefficient α depends on the sound frequency ν_o and considering the analysis, which carried out in [2], the particle concentration $n_r(Z,t)$ is defined by the formula

$$n_r(Z,t) = n_0 \frac{e^{\alpha z}}{e^{\alpha z} - \alpha\beta t} St(e^{\alpha z} - 1 - \alpha\beta t)\,, \qquad (11)$$

where $n_r(Z,0) = n_0$, $n_r(0,t) = 0$ – are initial and boundary conditions; $St(X) = \begin{cases} 0, & X<0 \\ 1, & X \geq 0; \end{cases}$ $\beta = \frac{2r(kr)^4}{27\eta c} I_0 (a_1^2 + a_1 a_2 + \frac{3}{4} a_2^2)$; $\epsilon_1 = 1 - \frac{rc^2}{\rho_s c_s^2}$; $\epsilon_2 = 2\frac{\rho_s - \rho}{2\rho_s + \rho}$; ρ_s, c_s – are the particle density and ultrasound speed in the particle material; ρ, c – density of investigated medium and ultrasound speed in it.

Displacement of ore suspension solid particles leads to their redistribution by size and concentration in zone of high energy ultrasound influence (Fig. 1).

With increasing of high energy ultrasound intensity from zero to a certain value and at a constant pulp flow rate all or only certain crushed material size classes can be removed to the measurement zone. In the low-frequency region ($\nu \leq 10^5$ Hz) the ultrasonic attenuation caused mainly by viscous inertial losses, so $\sigma \approx \sigma_\nu$. Then, the signal generated at the frequency $\nu_1 \leq 10^5$ Hz

$$S_1 = \ln(A_{0_1} / A_{\nu_1}) = Z_1 N \int_o^{r_m} F(r)\sigma_\nu(\nu_1, r) = = \frac{Z_1 W}{\aleph} \int_o^{r_m} F(r)\sigma_\nu(\nu_1, r)\, dr \qquad (12)$$

will be proportional to the pulp solid phase concentration, as it depends on the solid phase volume fraction W. In this expression,

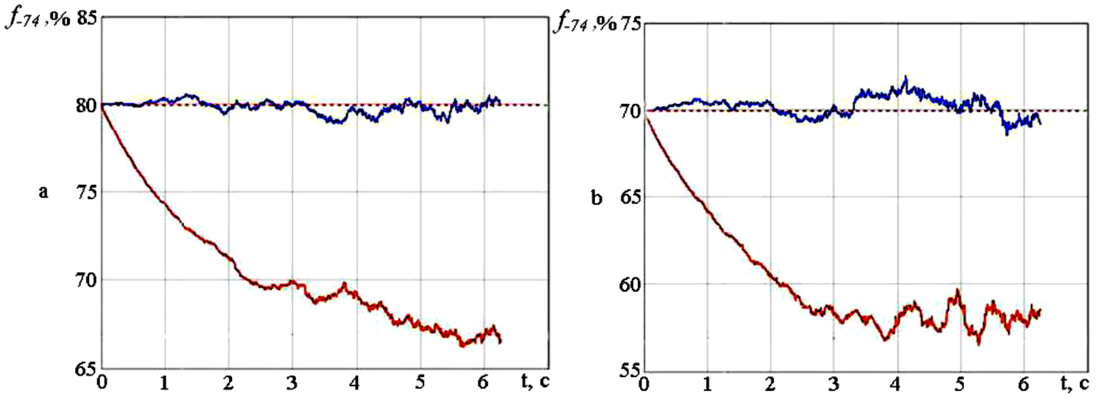

Figure 1. The particle size measurement in controlled volume of pulp under the influence of the high-energy ultrasound radiation pressure (pulp density - 1250 g/l, the initial class content -74 µm - 80% (a) and 70% (b)

$$\aleph = \int_o^{r_m} F(r)\, 4/3\pi r^3 (dr). \qquad (13)$$

Consequently about the pulp density or solid phase content in it one can judge by the magnitude of the signal S_1. In accordance with the above, we will control the value S_1 in measurement zone at each current moment of time. Then, with known law of change of high energy ultrasound intensity we will obtain the particle size distribution function of the crushed material in pulp flow.

Conclusions

The proposed measurement method does not require preliminary pulp degassing, because under the ultrasound radiation pressure influence the gas bubbles are removed from the measurement zone. Thus, the intensity measurement of high-frequency ultrasonic vibrations, which have passed through a controlled pulp volume, in the process of impact on it of high energy ultrasound with a given intensity allows to evaluate its solid phase particle size distribution.

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