Iron ore flotation process control and optimization using high-energy ultrasound

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Abstract

The paper describes method allowing to effectively control the composition of iron ore pulp solid and gas phases to form the desired gas bubble size distribution function, which would coincide with the pulp solid particle size distribution in the flotation process using high-energy ultrasound.

Key words: *mineral processing, high-energy ultrasound, particle size distribution, the characteristics of pulp.*

1. Introduction

The flotation machines processes analysis, allows to identify the main input and output parameters, as well as disturbances [1,2].

The input parameters are: pulp density, reagents flow rate, compressed air flow rate, the pulp level, the pulp aeration degree. The disturbing effects are: the metal content in the ore, floatability of raw materials, particle size distribution of the ground product. The output parameters are: the metal content in the concentrate, the metal content in the tailings, plant productivity, concentrate output, the output of the tails.

Efficiency of the flotation process is directly related to the number of collisions between particles and bubbles, which are strongly dependent on the ratio of particle diameter to bubble diameter. Bubble size is considered to be one of the most important parameters affecting the performance of froth flotation cells.

In a flotation system if the bubbles are much larger than the particles, the hydrodynamic flow near the surface of the bubble will take away particles and thereby prevents attachment of valuable mineral particles to the bubble. If bubbles is much smaller than the particles, they can’t raise the hydrophobic ore particles to the pulp surface.

Hence, in order to provide optimal conditions for the flotation, it is necessary to generate bubble size distribution which would coincide to the particle size distribution of the pulp.

The task solution condition is to create such gas bubbles and iron ore particle size distributions in flotation process which provides disclosure of a useful component in the degree which technologically and economically proved for realizable beneficiation circuit.

High-intensity ultrasonic oscillations can speed up the traditional and implement new processes in liquid, solid and gaseous media. The efficiency of these processes are driven by the appearance of non-linear phenomena during the propagation of high-amplitude oscillations that cause cavitation, radiation pressure, micro-and macro flows, leading to rupture of mechanical and chemical bonds, increase the surfaces and speed of interaction, and the acceleration of the mass and heat transfer [3].

The use of ultrasound in the flotation technology related to a number of specific phenomena accompanying the propagation of ultrasonic vibrations in liquid media. Among these phenomena the special place is taken by cavitation. It is expressed in the appearance of gas bubbles (cavities) in the liquid in which ionization of molecules and atoms, pressure (up to several thousand atmospheres) and temperature (hundreds of degrees) increasing. It is known that gas (cavitation) bubbles are formed easily at the liquid-solid interface and energetic acting on the surface of the latter [4].

The task of research is mathematical modeling of the high-energy ultrasound radiation pressure effects on iron ore pulp flow to form the desired gas bubble size distribution function, which would coincide with the pulp solid phase particle size distribution in the flotation process.

2. Materials and methods

Let’s examine one of the possible ultrasonic measuring methods of pulp solid phase particle size distribution. As a rule, there are gas bubbles in the pulp. These bubbles affect ultrasonic waves, which propagates in such medium. Let N_1 is the number of gas bubbles and N is the number of solid phase particles in the tank with pulp of volume V. Let $F(R)$ is the solid phase particles distribution function and $f(R)$ is the bubble size distribution function. The ultrasonic wave amplitude attenuation which passed the distance z in the medium can be described with formula [5,6]

$$A_\nu(z) = A_0 \exp\left\{-\frac{z}{V}\left[\sum_{i=1}^{N_1}\sigma_p(\nu, R_i) + \sum_{j=1}^{N}\sigma(\nu, R_j)\right]\right\}, \tag{1}$$

where A_0 is the amplitude of the wave which passed the same distance through the water. $\sigma_p(\nu, R)$ is the part of ultrasonic wave attenuation of frequency ν on the bubble with the radius *R*. $\sigma(\nu, R)$ is the part of attenuation on sphere particle with the radius *R* and the density ρ_τ.

The ultrasound attenuation on gas bubbles is the result of the absorption and dispersion and its have resonance character. Attenuation on the solid phase particles is the result of viscous-inertial losses and diffractional wave scattering.

The amplitude attenuation of the passed wave $A_\nu(z)$ is a random value, because a number of solid phase particles and gas bubbles fluctuate in the controlled volume *V*. The mean value of the amplitude vibrations $\langle A_\nu(z)\rangle$ can be defined using Poisson's law of particles number distributions in the volume *V*. In that case $\langle A_\nu(z)\rangle$ can be express as

$$\langle A_\nu(z)\rangle = A_0 \exp\left\{-\frac{W_l}{\chi_1}V(1-\eta_1) - \frac{W_\tau}{\chi_2}V(1-\eta_2)\right\}, \tag{2}$$

Where W_e and W_τ are the volume fractions of the solid and gas phase in liquid.

$$\eta_1 = \int_0^\infty dR \cdot f(R) \cdot \exp\left\{-\frac{\sigma_p(\nu, R) z}{V}\right\}, \tag{3}$$

$$\chi_1 = \int_0^\infty \frac{4}{3}\pi R^3 f(R)\, dR, \tag{4}$$

$$\eta_2 = \int_0^\infty dR \cdot F(R) \cdot \exp\left\{-\frac{\sigma(\nu, R) z}{V}\right\}, \tag{5}$$

$$\chi_2 = \int_0^\infty \frac{4}{3}\pi R^3 F(R)\, dR, \tag{6}$$

In the most cases the pulp solid phase particle size distribution function is based on the log-normal distribution and for the gas bubbles it's can be determined by experiments.

On the base of ultrasonic vibration experimental measurements it is possible to formulate the signal with the following equation [7]

$$S_1 = \ln\frac{A_0}{\langle A_\nu(z)\rangle}, \tag{7}$$

According to the eq. (2), the signal can be presented with the following equation

$$S_1 = \frac{W_\tau}{\chi_2}V(1-\eta_2) + \frac{W_l}{\chi_1}V(1-\eta_1), \tag{8}$$

This signal depends on the pulp solid phase volume fraction and particle size distribution function. Fig. 1 shows the dependence of the signal from the ultrasonic frequency for solid particles with lognormal distribution (curves 1-4). Curve 5 corresponds to the dependence of the signal only in the presence of gas phase with the volume fraction $W_l = 10^{-4}$. It is clear from the figure that the influence of gas phase on the S_1 becomes slight for the ultrasound frequency $\nu > 1$ MHz.

It is caused by resonance character of the ultrasonic waves attenuation on the gas bubbles.

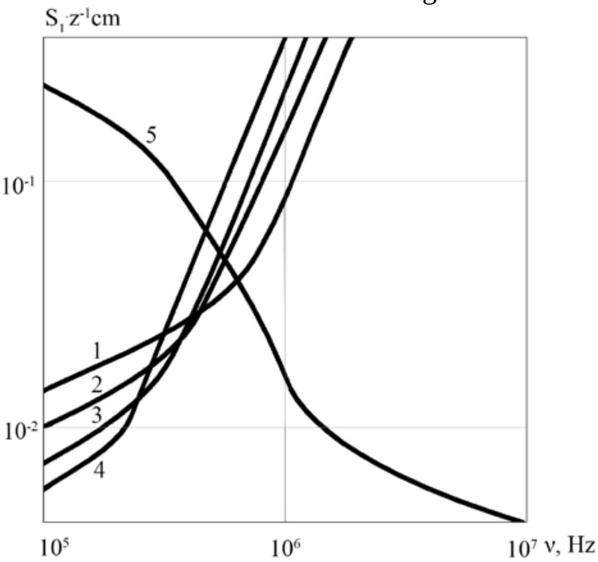

Figure 1 The dependence of the signal $S_1 \cdot z^{-1} = f(\nu)$ from the ultrasonic frequency: (curves 1- 4) - for solid particles with lognormal distribution; (curve 5) - only in the presence of gas phase with the volume fraction $W_l = 10^{-4}$.

To form the required gas bubble size distribution function, which would coincide with the pulp solid phase particle size distribution in the flotation process, it is proposed to affect on the pulp flow with high-energy ultrasonic wave with given frequency and amplitude, resulting in a gas bubbles concentration change, and redistribution of their size. Character of redistribution depends on the size of the bubbles themselves, the frequency and amplitude of the incident radiation. Increasing the frequency and amplitude to the values at which the transition cavitation starts, bubble size will decrease due to crushing of larger bubbles. When decreasing the amplitude and frequency the bubbles will rise due to coalescence of smaller bubbles.

To account for the gas pressure in the bubble, and pressure varying in the liquid, the viscosity and surface tension it is advisable to use a cavitation bubble dynamics equation of Rayleigh-Plesset in which the driving pressure *Pi(t)* given as a short pulse [8]

$$\ddot{R}\left(1-\frac{\dot{R}}{c}\right)+\frac{3}{2}\dot{R}^2\left(1-\frac{\dot{R}}{3c}\right)=\frac{P(t)}{\rho}=\frac{1}{\rho c}\frac{d}{dt}\left[RP(t)\right] \quad (9)$$

$$P(t)=\left(P_0+-\frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^{3\gamma}-\frac{2\sigma}{R}-P_0+P_i(t)-\frac{4\mu\dot{R}}{R} \quad (10)$$

where P_0 – is static pressure in the liquid, $R(t)$ – is current bubble radius, R_0 – is initial bubble radius, $P_i(t)$ – is pressure in the incident wave, σ – is surface tension, μ- is dynamic viscosity of the fluid, ρ – is density of the liquid, c – is speed of sound in the fluid (water σ = 0.07 N/m, μ = 0.001 N·s/m^2, $\rho = 10^3$ kg/m^3, c = 1500 m/s), γ – is adiabatic exponent of gas in the bubble (air γ = 1.33). The initial conditions are given as, (t = 0) = 0.

To initiate appropriate processes, due to the extreme nature of cavitation in liquids, it is necessary not only to form a certain amplitude and frequency of oscillations, but also to maintain their optimal values when changing the medium parameters and the impact of factors such as: changing the temperature of the medium and the material of the piezoelectric transducer, the damping action of the medium.

For this purpose, the ultrasonic effect with specific amplitude and frequency, in the working area of flotation machine, at each current moment is generated. This allows to obtain the desired gas bubble size distribution function in the pulp flow.

To solve this task, let's form the control action based on the dynamic effects of high-energy ultrasound using phased array technology, which have many advantages compared to conventional single-element transducers is proposed.

The main feature of ultrasonic phased array technology - computer-controlled driving pulses amplitude and phase of the individual piezoelectric elements in multi-element transducer. Piezoelectric excitation is performed such a way that to control the parameters of the ultrasound beam, for example, angle, focal length, focal spot size.

The acoustical pressure of the array was calculated by modeling every element of the array as an independent simple source and summing the contribution of each simple source at each point in the field. The acoustic pressure *p(x,y,z)* at a specific point *(x,y,z)* in the field due to a simple source was calculated using the Rayleigh-Sommerfeld equation [9]

$$p_i(x,y,z)=\sqrt{\frac{2W\rho}{cA}}\left(\frac{fS}{d}\right)e^{\left\{\left(\varphi-\frac{2\pi d}{\lambda}\right)i-d\alpha\right\}} \quad (11)$$

where W - is total acoustical power output from the array, ρ – is density of the medium, c – is speed of sound in the medium, A – is active transducer aperture, f – is frequency, S – is area formed by source, d – is distance from the source to the point *(x, y , z)*, φ – is phase of oscillation, λ – is wavelength, and α – is attenuation in the medium.

The active aperture (the total length of the array) is calculated by the following formula [10]

$$A=n\cdot e+g\cdot(n-1), \quad (12)$$

where A - is active aperture; g – is gap between nearest elements; e – is width of one element (typically $e < \lambda / 2$); n – is number of elements.

The net pressure due to all the elements was determined by summing the effects of each simple source:

$$P_{net}(x,y,z)=\sum_{i=1}^{n}p_i(x,y,z) \quad (13)$$

The net power deposition at point (x,y,z) was the result of the attenuation [11]

$$q(x,y,z)=\frac{\alpha P_{net}^2(x,y,z)}{\rho c}, \quad (14)$$

The phase of each element of the array was determined by

$$\varphi_i=\frac{360°}{\lambda}\left(d_i-d_0\right)-360°n, \quad (15)$$

where φ_i is phase of element i in degrees, d_i is distance from the center of element i to the focus, d_0 is the focus depth, n is an integer used to maintain $0 <= \varphi_i <= 360°$.

3. Results

The phased array configuration (size) used in the simulation with software and hardware tools package TAC (Transducer Array Calculation) is presented on Fig. 2 [12].

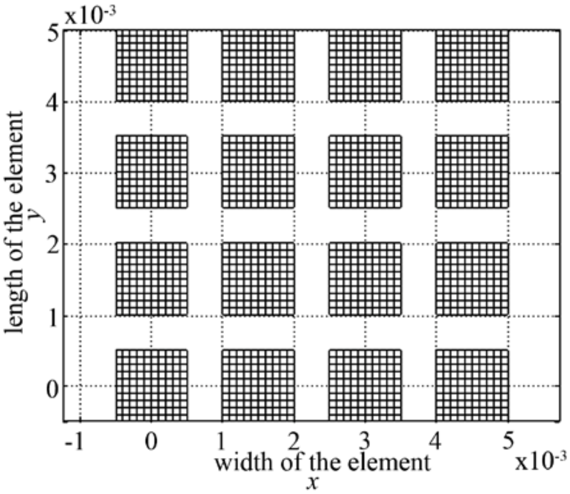

Figure 2 16-element phased array

The 16-element transducer acoustic pressure field in the focal plane *xz* at y = 0,01 m is presented on Fig. 3.

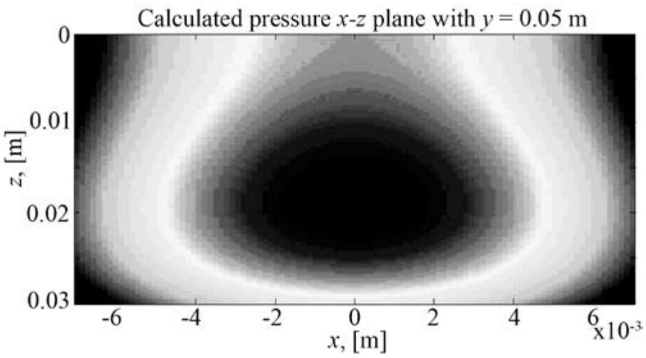

Figure 3 Acoustic pressure field in the focal plane x-z.

Let's consider the forming of gas bubble size distribution using phased array technology. When using this approach, the gas bubbles are subjected to elements of the phased array, which having different characteristics. Numerically this effect can be expressed as a weighted sum of the individual bubble size distributions generated by each element of array.

$$f(x) = \sum_{j=1}^{N} a_j \cdot f_j(x), \qquad (16)$$

with

$$\sum_{j=1}^{N} a_j = 1, \quad 0 \le a_j \le 1, \quad j = 1.2, ..., N, \qquad (17)$$

where N - is the number of array elements, α_j – are weights which can be regarded as the probability of sampling bubbles generated from *j*-element of array.

$f_j(x)$ - is the bubble size density distribution function generated from *j*- element of array.

After receiving a series of sound velocity and attenuation measurements in a bubbly medium with a set of frequencies covering the range of interest, the inverse problem is to determine the bubble size distribution corresponding to the obtained measurements. A series of tests using various combinations of air and water flow rate through the pump was carried out.

Identification of the obtained dependences at the stage of experimental research was carried out using the software MATLAB 7.0 [13]. Fuzzy Logic Toolbox package, which is part of MATLAB, contains a set of GUI modules that provide the stage of structural identification in the dialog mode. At this stage the number of inputs and outputs of the model are specified by the number of terms and the types of membership functions, the knowledge base is formed. Fuzzy Logic Toolbox package for Sugeno models automates the stage of parametric identification. The setting of Sugeno type fuzzy model is convenient to carried out in a dialog mode using the GUI module *anfisedit*. The setting is made using the ANFIS technology (Adaptive Network based Fuzzy Inference System) It is editor of Matlab 7.0. ANFIS package. The editor automatically synthesizes data from experimental neuro-fuzzy network, which can be considered as one of the varieties of Takagi-Sugeno type fuzzy logic output [14].

Setting is an iterative procedure for finding the parameters of membership functions that minimize the differences between the actual and the desired behavior of the model. As adjusting the method of backpropagation or its combination with the method of least squares is used. Fuzzy Logic Toolbox can automatically synthesize data from a fuzzy knowledge base for Sugeno type model. For this purpose the two algorithms - gridpartition and subtractive clustering are used. At the output of the first algorithm the knowledge base containing all sorts of rules is obtained. As a result of the subtractive clustering the rules corresponding to regions of greatest concentration data are generated.

The experiments were performed using either a single frequency range, or an average of 100 for the series of experiments. In this case, the program considers the values of *u* and *v* for each series (Fig. 4), and then generates a curve of average values *u(f)* and *v(f)*, and displays the average number of bubbles. These sizes and the amount of bubbles considered to be uniformly distributed in the volume between the two transducers. This volume is used to deduce the bubble size distribution per unit of volume in test liquid [15,16]

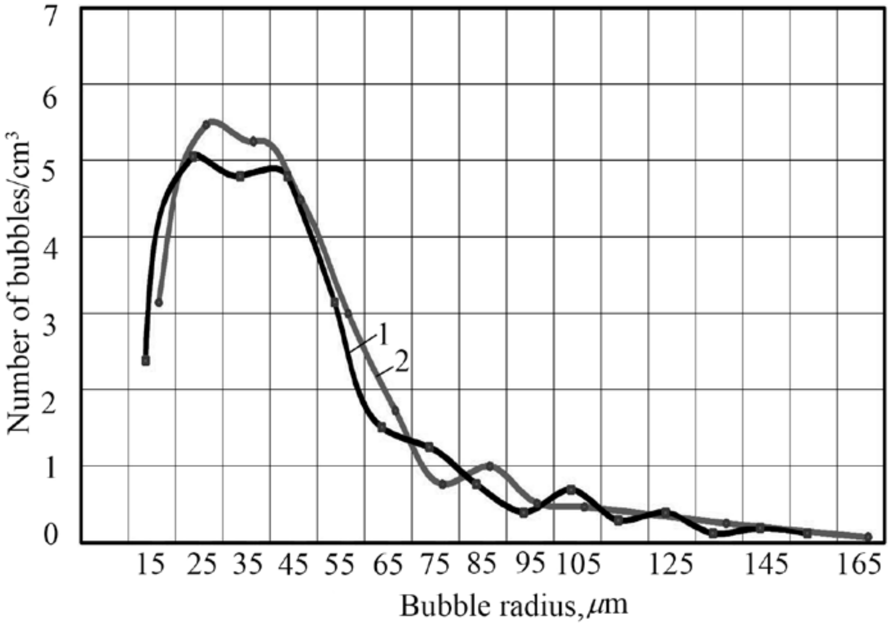

Figure 4 Bubble size distribution: 1- initial; 2 - resulting.

Conclusions. Simulation results of the high energy ultrasound impact on the pulp solid and gas phases allow to form the required gas bubble size distribution function, which will coincide with the pulp solid phase particle size distribution in the flotation process**.**

Thus, the proposed flotation control method based on ultrasonic phased array technology allows to implement efficient control of the iron ore pulp solid and gas phases composition, improve the quality of the concentrate and the efficiency of the beneficiation process.

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