

Basic Regularities of Assessing Ore Pulp Parameters in Gravity Settling of Solid Phase Particles Based on Ultrasonic Measurements

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The article describes the method of controlling the recovered grade based on measuring the intensity of volume ultrasonic oscillations and Lamb waves covering a fixed distance through the test medium and on a metal plate contacting the test medium at various time points of deliberate motion of ground materials.

The authors suggest a method of determining density of ground ore particles in the pulp periodically after isolating the pulp flow in the vertical part of the measuring vessel based on measuring attenuation change values in Lamb waves covering a fixed distance on a plate contacting the medium under study and high frequency volume ultrasonic oscillations that have come through it within a certain time period.

There are given dependencies of amplitudes of measuring channels based on volume ultrasonic oscillations and surface Lamb waves, size distribution according to solid phase pulp particles for various types of ores under study, a set of curves for determining the recovered grade with regard to various types of ores under study.

Keywords: settling; ultrasound; pulp; ore; Lamb waves.

1. Introduction

Available means of controlling qualitative and quantitative characteristics of ground materials do not meet modern requirements. A number of important chemical-mineralogical and physical-mechanical characteristics of the solid phase pulp including the recovered grade in ore crushing are not used for controlling the technological process.

To solve the mentioned tasks, we suggest using ultrasonic volume waves and Lamb waves. The principles and devices based on ultrasound application allow us to increase efficiency of ore crushing control, which is urgent for Ukraine’s economy nowadays. The method increases the recovered grade in concentrate using mining enterprises’ current capacity under conditions of energy resource deficit, reduces operational expenses, decreases the end product cost price and makes it competitive on the world market.

2. Literature review and problem statement

Reliable information on the process media characteristics is a key factor of increasing efficiency

of iron ore concentration processes (GUMANYUK, 1970; BRAZHNIKOV *et al.*, 1975; YAMSHIKOV, KO-ROBEYNIKOV, 1967; BRAZHNIKOV, 1975; MORKUN *et al.*, 2015a). The need to perform control of the solid phase pulp characteristics is also highlighted by uncertainty of process unit parameters (MORKUN *et al.*, 2015b; MORKUN, TRON, 2014; MORKUN, TCVIRKUN, 2014). Here, the most common method is application of controlled ultrasonic radiation that enables the required operating speed and measurement accuracy (BOGDANOVA *et al.*, 1989; VIKTOROV, 1981; LAMB, 1917; RZHEVSKIY, YAMSHCHIKOV, 1968; SEIP *et al.*, 1996).

Works (MORKUN *et al.*, 2015c; 2015d; MORKUN, MORKUN, 2018) note that application of ultrasonic methods to estimate parameters of the solid phase pulp particles allows considerable increase of efficiency of concentration control. The approach to measuring the speed of particles in the pulp flow suggested in (STENER *et al.*, 2016) is based on the acoustic backscatter method. The method is suggested for acquiring data on local concentration of particles from the spectral density of the back scattered signal. The performed experiments enable the conclusion on appli-

cability of the methods in actual technological processes.

In sound-wave propagating, fluctuations of the local medium volume are transferred to adjacent areas by elastic waves characterized by changes of the medium density. Principal correlations describing ultrasonic oscillations and waves in the medium follow from the medium state equation, the Newton motion equation and the continuity equation (BRAZHNIKOV, 1965).

Rayleigh waves possess comparatively small concentration of energy on the solid surfaces (BOGDANOVA *et al.*, 1989; VIKTOROV, 1981; LAMB, 1917). Love waves are of the similar nature. Unlike the above mentioned waves, they are horizontally polarized (RZHEVSKIY, YAMSHCHIKOV, 1968; SEIP *et al.*, 1996). However, there are several disadvantages in applying the above types of waves, severe dependency of wave propagation parameters on the propagation surface state being among them. In case of the surface defects, there appear reflection and scatter effects that complicate use of Rayleigh and Love waves in measurement systems.

Stoneley waves propagate in both liquid and solid semi-spaces (VIKTOROV, 1981). Like common volume ultrasonic oscillations, the wave component propagating in the liquid semi-space undergoes impacts of the same disturbing factors. In particular, there is a dependency of the attenuation ratio of the waves of this kind on bubble concentration in the pulp.

Non-linear processes of ultrasonic oscillation propagation in the heterogeneous medium are dealt with in (VANHILLE, CAMPOS-POZUELO, 2009). A number of studies have resulted in a mathematical model that describes the relationship between the acoustic field and solid particles oscillations in the medium under study using differential equations.

The numerical model of ultrasound propagation in heterogeneous media presented in (TEJEDOR, VANHILLE, 2017) is based on the finite-volume and finite-difference methods. This approach enables solution of the Rayleigh-Plesset equation and the differential system formed by the wave equation. The obtained model considers a number of effects that emerge in the medium under study: attenuation, dispersion and non-linearity.

When simulating ultrasonic waves propagation in heterogeneous media (ZHANG, DU, 2015) suggests the approach that considers the non-uniform pressure field. The results of theoretical and experimental studies corroborate potential applicability of the approach.

Lamb waves are influenced by the above mentioned disturbing factors to a comparatively smaller degree than Love and Rayleigh waves (GUMANYUK, 1970; BRAZHNIKOV *et al.*, 1975; YAMSHIKOV, KOROBENNIKOV, 1967; BRAZHNIKOV, 1975). This along with the fact that Lamb waves are characterized by comparatively great concentration of energy en-

ables the conclusion of reasonability of studying Lamb waves propagation processes on the surface of a plate contacting the pulp. As Lamb waves are dispersive (DEBARNOT *et al.*, 2006) recommends using a sinusoidal emission signal.

The measurement method suggesting the use of such changed values of Lamb wave characteristics as a function of a liquid level value is presented in (SUBHASH, KRISHNAN, 2011). It should be noted that further studies are required to determine optimal measurement conditions.

The method of simulating local interaction at wave propagation in metal structures is treated in (LEE, STASZEWSKI, 2009). Application of the method is complicated by co-existence of at least two highly dispersed modes on any defined frequency.

Application of multimode Lamb waves as a means of nondestructive control is described in (RYDEN *et al.*, 2003). It is concluded that Lamb waves dispersion curves depend only on the plate parameters. At that, frequency and phase rates may be normalized relative to transverse wave velocity and thickness of the medium under study.

The method of simulating ultrasonic waves propagation in heterogeneous media is dealt with in (MORKUN *et al.*, 2014; SINCHUK *et al.*, 2017a; 2017b). To form controlled ultrasonic waves when controlling parameters of the ore pulp, it is suggested to apply phased arrays. Elaboration of the method and use of the obtained results of measurements for optimal control of concentration processes are presented in (LUTSENKO *et al.*, 2017a; 2017b).

3. Materials and methods

All iron ore concentrating plants classify ores (divide into grades) according to basic chemical-mineralogical and physical-mechanical properties (KOZIN, 2008). Division of this kind is used to plan and organize mining in the way that secure ore quality for the required period and therefore facilitates the choice and maintenance of the concentrating procedure and increases quality of the final product. However, identifying the type of the ore for concentrating still remains a problem.

Apparently, the key point of the problem solution is identification, analysis and classification of distinguishing features of various types of ores and minerals in them. Table 1 gives main distinguishing indicators of some minerals in iron ores.

In (KONDRATETS, KARCHEVSKA, 2011), ore is suggested to be divided into grades according to its density which is directly connected with the content of main minerals – magnetite, hematite, siderite and quartz.

This parameter can be determined on the basis of experimental works on the time of settling ground ore

Table 1. Distinguishing indicators of some minerals.

Name	Formula	Mass fraction of main components [%]	Density, ρ [kg/m ³]	Specific magnetic susceptibility, χ [m ³ /kg·10 ⁻⁷]	Hardness
Hematite (matite)	Fe ₂ O ₃	Fe = 69.9	5300	8.8–22	5–6
Goethite	FeOOH	Fe = 48.5	4300	3.2	5–5.5
Quartz	SiO ₂	Si = 46.6	2600	-0.02+0.1	7
Magnetite	FeFe ₂ O ₄	Fe = 72.3	4800–5200	8000 (4000–18000)	5.5–6
Pyrite	FeS ₂	Fe = 46.5	4900–5200	0.12	6–6.5
Pyrrhotine	Fe _{1-x} S	Fe = 58.8–61.8	4690	63–700	3.5–4.5
Siderite	Fe[CO ₃]	Fe = 48.3	3900	7.5	3.5–4.5

particles of the known size. Figure 1 exemplifies dependencies of the settling time of particles of various sizes and density to the depth of 0.3 m.

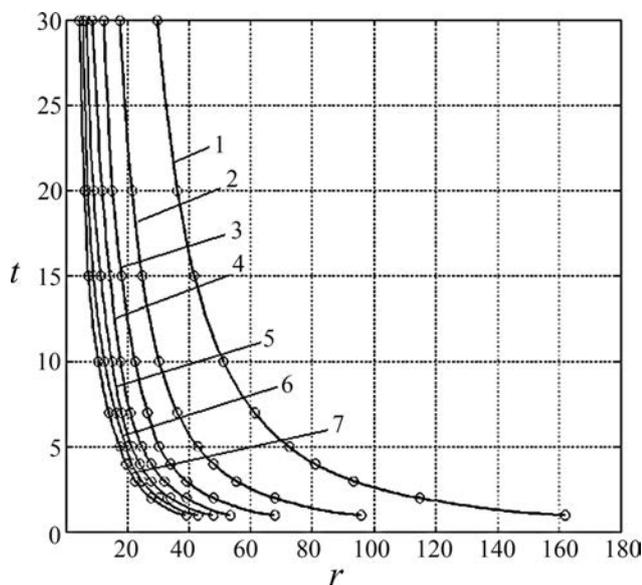


Fig. 1. Settling time of particles of various sizes and density to the depth of 0.3 m (ground ore particles density): 1 – 1350 kg/m³; 2 – 2000 kg/m³; 3 – 3000 kg/m³; 4 – 4000 kg/m³; 5 – 5000 kg/m³; 6 – 6000 kg/m³; 7 – 7000 kg/m³.

4. Summary and conclusions

Let us consider a method of controlling the recovered grade based on measuring the intensity of volume ultrasonic oscillations and Lamb waves covering a fixed distance through the medium under study and on the plate contacting the test medium at various time points of deliberate motion of ground materials.

As indicated above, such motion of ground material can be conditioned by the action of dynamic effects of high-power ultrasound, centrifugal forces, etc. Let us consider gravity settling of ground material particles in a measuring vessel after instantaneous isolating of a section in the pulp flow.

The settling rate of solid phase particles depends both on their size and density. To describe these processes it is necessary to introduce a two-dimensional density distribution function $f(R, \rho_s)$, which depends on two variables – R (the radius of particles) and ρ_s (their density). It is obvious that the value of $f(R, \rho_s) dR d\rho_s$ determines the fraction of solid-phase particles, the radii of which range from R to $R + dR$ with their densities ranging from ρ_s to $\rho_s + d\rho_s$.

The initial controlled material is a suspension with uniformly mixed particles. A simplified scheme of installation realizing this method is shown in Fig. 2. Ultrasonic radiators 1, 3 and receivers 2, 4 are located below the level of suspension 5 at depth h . While settling, particles leave the area controlled by ultrasonic waves, and therefore, signal amplitudes will change over time.

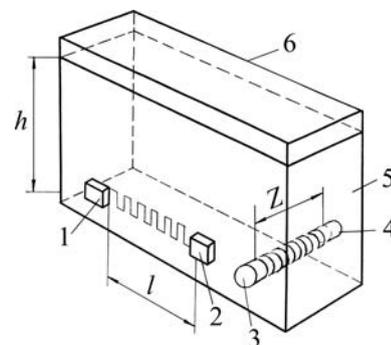


Fig. 2. Installation scheme: 1, 3 – radiators of ultrasonic waves; 2, 4 – receivers of ultrasonic waves; 5 – a test suspension; 6 – a measuring vessel.

The time dependency of the amplitude for high-frequency volume waves will be determined by

$$A_v(t) = A_{0v} \exp \left\{ -n_o Z \int_{\rho_s \min}^{\rho_s \max} d\rho_T \cdot \int_0^{R(t, \rho_s)} \sigma(\nu, R) f(R, \rho_s) dR \right\}, \quad (1)$$

where A_{0v} is the wave amplitude in pure water; n_0 is the initial particle concentration; Z is the distance between the radiator and the receiver; $\rho_{s \min}$, $\rho_{s \max}$ are boundary values of particle density; $\sigma(v, R)$ is the attenuation section of the ultrasonic wave with frequency v on the particle of radius R .

The particles of ρ_s density, the radii of which are greater than $R(t, \rho_s)$, settled below the measurement level h by the time t and left the controlled area. When the Stokes law is satisfied in particle settling, this value is found by

$$\tilde{R}(t, \rho_s) = \sqrt{\frac{9\eta h}{2g(\rho_s - \rho_0)t}}, \quad (2)$$

where η is liquid viscosity; ρ_0 is liquid density.

However, particle settling in a real suspension differs much from gravity settling of particles in a liquid, for which formula (2) is valid. When settling is hindered, the ascending flow of liquid displaced by the substantial mass of settled particles becomes significant. The walls exert an impact on this and particles collide with each other. There are suggested many formulae to consider constrained motion of particles (GRINMAN, BLYAKH, 1967). Most researchers find a ratio between the velocity of the constrained v and the free settling v_0 as follows

$$K_{\text{constr}} = \frac{v}{v_0}. \quad (3)$$

The simplest description of the coefficient K_{constr} is suggested by Finkey by means of volume concentration (fraction) of solid particles in the pulp

$$K_{\text{constr}} = W = V_s/V, \quad (4)$$

where V_s is the volume of solid phase particles contained in the pulp (suspension) volume V .

Further analysis will be carried out in this approximation. It should be noted that the volume concentration of solids will vary in the course of time. Therefore, considering time dependency and particle size distribution, K_{constr} can be presented as

$$K_{\text{constr}} = W(t) = n_0 \int_{\rho_{s \min}}^{\rho_{s \max}} d\rho_s \int_0^{\tilde{R}(t, \rho_s)} f(R, \rho_s) \cdot \frac{4}{3} \pi R^3 dR. \quad (5)$$

As can be seen in (5), the coefficient K_{constr} also depends on the same value of $\tilde{R}(t, \rho_s)$ enabling an equation to determine it.

Indeed, considering the dependency of the settling velocity on particle concentration, we can state that

$$\tilde{R}(t, \rho_s) = \sqrt{\frac{9\eta h}{2g(\rho_s - \rho_0)tK_{\text{constr}}}}, \quad (6)$$

or in approximation (5), equation (6) can be reduced to an integral equation in the form of

$$\begin{aligned} \tilde{R}^2(t, \rho_s) \cdot \int_{\rho_{s \min}}^{\rho_{s \max}} d\rho_s \int_0^{\tilde{R}(t, \rho_s)} f(R, \rho_s) \frac{4}{3} \pi R^3 dR \\ = \frac{9\eta h}{2g(\rho_s - \rho_0)n_0 t}. \end{aligned} \quad (7)$$

The analysis reveals that for Eq. (7), the Lipschitz condition is satisfied. Therefore, it can be solved by the method of successive approximations.

The time dependency of the Lamb waves amplitude is found by

$$\begin{aligned} A_L(t) = A_{0L} \exp \left\{ -\frac{n_0 C_v l}{\rho_{wm}} \int_{\rho_{s \min}}^{\rho_{s \max}} d\rho_s (\rho_s - \rho_0) \right. \\ \left. \cdot \int_0^{\tilde{R}(t, \rho_s)} dR f(R, \rho_s) \frac{4}{3} \pi R^3 \right\}, \end{aligned} \quad (8)$$

where A_{0L} is the amplitude of a Lamb wave passing along wall l with pure water present; l is the distance between the radiator and the receiver; ρ_{wm} is density of the wall material of the measuring vessel; C_v is the value depending on the Lamb wave frequency.

Based on the results of measuring the ultrasonic oscillation amplitude, two signals can be generated and they will be time dependent as well. For the Lamb waves channel

$$\begin{aligned} S_L(t) = \ln \left(\frac{A_{0L}}{A_L(t)} \right) = \frac{n_0 C_v l}{\rho_{wm}} \int_{\rho_{s \min}}^{\rho_{s \max}} d\rho_s (\rho_s - \rho_0) \\ \cdot \int_0^{\tilde{R}(t, \rho_s)} dR f(R, \rho_s) \frac{4}{3} \pi R^3, \end{aligned} \quad (9)$$

and for the high-frequency channel

$$\begin{aligned} S_v(t) = \ln \left(\frac{A_{0v}}{A_v(t)} \right) = n_0 Z \int_{\rho_{s \min}}^{\rho_{s \max}} d\rho_s \\ \cdot \int_0^{\tilde{R}(t, \rho_s)} \sigma(v, R) f(R, \rho_s) dR. \end{aligned} \quad (10)$$

Both signals depend on the initial concentration of suspended solid particles n_0 and the regularity of their distribution by size and density $f(R, \rho_s)$. To reduce the influence of these parameters to the extent possible, we will form a signal through differential values of (9) and (10), i.e.

$$S(t) = \frac{\Delta S_v(t)}{\Delta S_L(t)}, \quad (11)$$

where

$$\Delta S_v(t) = S_v(t + \Delta t) - S_v(t),$$

$$\Delta S_L(t) = \Delta S_L(t + \Delta t) - S_L(t).$$

In this case, the signal $S(t)$ will be determined as follows

$$S(t) = \frac{C \int_{\rho_{s \min}}^{\rho_{s \max}} d\rho_s \int_{\tilde{R}(t, \rho_s)}^{\tilde{R}(t+\Delta t, \rho_s)} dR \sigma(v, R) f(R, \rho_s)}{\int_{\rho_{s \min}}^{\rho_{s \max}} d\rho_s (\rho_s \rho_0) \int_{\tilde{R}(t, \rho_s)}^{\tilde{R}(t+\Delta t, \rho_s)} dR f(R, \rho_s) \frac{4}{3} \pi R^3}. \quad (12)$$

If Δt is small, the internal integrals over R can be replaced by approximated expressions as $\Delta \tilde{R}(t, \rho_s) = \tilde{R}(t + \Delta t, \rho_s) - \tilde{R}(t, \rho_s)$ is also small. In this case

$$S(t) \approx \frac{\frac{Z \rho_{wm}}{C \nu l} \int_{\rho_{s \min}}^{\rho_{s \max}} d\rho_s a^*}{\int_{\rho_{s \min}}^{\rho_{s \max}} d\rho_s b^*}, \quad (13)$$

where

$$a^* = F(t, \rho_s) f(\tilde{R}(t, \rho_s), \rho_s) \alpha(v, \tilde{R}(t, \rho_s)) \tilde{R}^3(t, \rho_s),$$

$$b^* = f(\tilde{R}(t, \rho_s), \rho_s) \tilde{R}^3(t, \rho_s) F(t, \rho_s) (\rho_s - \rho_0),$$

$$\alpha(v, R) = \frac{\sigma(v, R)}{\frac{4}{3} \pi R^3},$$

$$F(t, \rho_s) = \left[\frac{9 \eta h t}{g} + (\rho_s - \rho_0) n_0 \tilde{R}^3(t, \rho_s) \cdot t^2 \int_{\rho_{s \min}}^{\rho_{s \max}} d\rho_s f(\tilde{R}(t, \rho_s)) \frac{4}{3} \pi R^3(t, \rho_s) \right]^{-1}.$$

Using the mean value theorem in the integrals of (12), we can write

$$S(t) = \frac{C \alpha(v, \tilde{R}(t, \rho_s^*))}{(\rho_s^{**} - \rho_0)} \frac{\int_{\rho_{s \min}}^{\rho_{s \max}} d\rho_s F(t, \rho_s) f(\tilde{R}(t, \rho_s), \rho_s) \tilde{R}^3(t, \rho_s)}{\int_{\rho_{s \min}}^{\rho_{s \max}} d\rho_s F(t, \rho_s) f(\tilde{R}(t, \rho_s), \rho_s) \tilde{R}^3(t, \rho_s)} = \frac{C \alpha(v, \tilde{R}(t, \rho_s^*))}{(\rho_s^{**} - \rho_0)}, \quad (14)$$

where ρ_s^* and $\rho_s^{**} \in [\rho_1, \rho_2]$.

For the frequency $\nu = 5$ MHz and particle radii $R \geq 50 \mu\text{m}$, the value $\alpha(v, R)$ does not depend on the

particle density. Therefore, if we select a certain time interval (operating range), for which $\tilde{R}(t, \rho_s^*) \geq 50 \mu\text{m}$, the generated signal will depend on some average density of suspension particles of a certain size. The density of these particles can give us data on the recovered grade. As shown in (13), the formed signal depends implicitly on the magnitude $\tilde{R}(t, \rho_s)$, which, in its turn, is determined by solving (7). Since this equation includes the values n_0 and $f(R, \rho_s)$, $S(t)$ will also depend on these values.

Therefore, as far as this method of determining of the recovered grade is concerned, there are some limitations associated with the requirement to control a strictly determined amount of the material and the content of the particle size class.

As the signal $S(t)$ is a differential value, it is necessary to smooth measurement results to form it. The smoothed dependences of high-frequency and Lamb channels amplitudes are shown in Fig. 3.

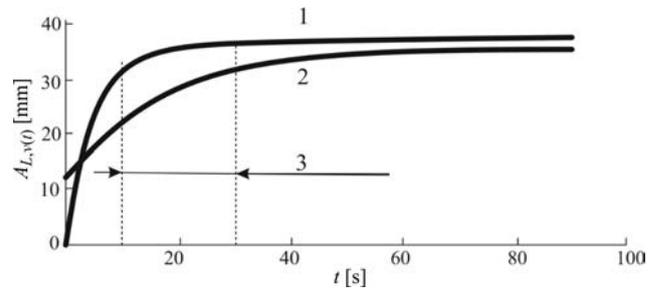


Fig. 3. Smoothed time dependencies of the signal change: 1 – the high-frequency signal; 2 – the Lamb signal; 3 – the measuring range.

5. Discussion of results

The countdown starts when signals change. According to $\tilde{R}(t, \rho_s^*) \geq 50 \mu\text{m}$, the temporal operating range of the measurements was chosen within 10–30 s. In this range, according to Eq. (11), the signal $S(t)$ was formed.

Figure 4 shows the time dependency of this signal for various controlled materials with approximately the same particle size distribution regularity (Fig. 5).

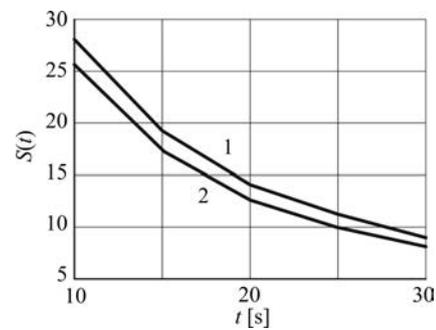


Fig. 4. Time dependency of the generated signal for various ore types: 1 – $\rho_s = 2.98 \text{ g/cm}^3$; 2 – $\rho_s = 3.02 \text{ g/cm}^3$.

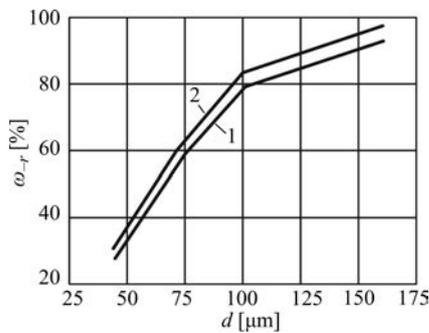


Fig. 5. Cumulative curves of ore types under study:
 1 – $\rho_s = 2.98 \text{ g/cm}^3$; 2 – $\rho_s = 3.02 \text{ g/cm}^3$.

A set of graduated curves for determining the recovered grade η is presented in Fig. 6. Each curve corresponds to a specific time point in the operating measurement range, with which the particle size range of the measured particles can be compared. In this case, the specified range of 10–30 s corresponds to the particles with the average radius of $\sim 45\text{--}60 \mu\text{m}$. For dependencies of the signal $S(t)$ shown in Fig. 5, the recovered grade determined by the graded curves of Fig. 6 corresponds to $\eta = 59.6$ and 66% for the first and second types of ores respectively. These values correspond to average values found according to the three time points – 15 s, 20 s and 30 s.

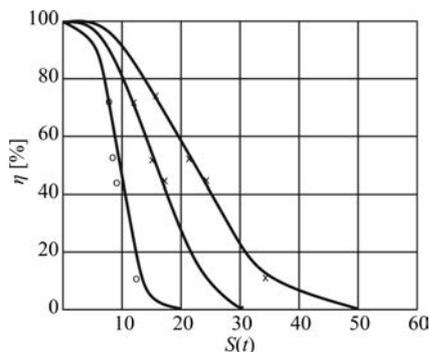


Fig. 6. Calibration dependency of the recovered grade for various time points: 1 – $t = 15 \text{ s}$; 2 – $t = 20 \text{ s}$; 3 – $t = 30 \text{ s}$.

The above control method assumes the presence of a certain amount of the test material of certain particle size distribution. The measurements taken by this method are not absolute. Therefore, it is necessary to conduct some preliminary studies for the various ore types to obtain graded curves.

6. Summary and conclusions

The authors suggest a method of determining density of ground ore particles in the pulp periodically after isolating the pulp flow in the vertical part of the measuring vessel based on measuring attenuation change values in Lamb waves covering a fixed distance on a plate contacting the medium under study, and

high frequency volume ultrasonic oscillations that have come through it within a certain time period.

There are given dependencies of amplitudes of measurement channels based on volume ultrasonic oscillations and surface Lamb waves, size distribution according to solid phase pulp particles for various types of ores under study, a set of curves for determining the recovered grade with regard to various types of ores under study.

The obtained model and the dynamic curve of the gravity settling of ground ore particles enables formation of quantitative characteristics of the process (settling rate, pressure at certain levels) and products (quantity, density etc.) of discharge, sands and sediments on the settler bottom. This provides a database for determining an optimal separation characteristic of a technological unit during the concentration process.

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