

Research Paper

Evaluation of the Sedimentation Process in the Thickener by Using the Parameters of Longitudinal Ultrasonic Oscillations and Lamb Waves

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Water is widely used in the mining industry, particularly in mineral enrichment processes. In the process of magnetic separation or flotation of crushed ore, a concentrate (an enriched product), and tailings (a product with a low content of a useful component) are obtained. One of the main tasks of enrichment processes is the efficient use of water resources. This is achieved by reclaiming and subsequent reusing water contained in ore beneficiation products by extracting it in industrial thickeners. Optimizing this process makes it possible to reduce water usage in the mining industry, reduce costs of mineral enrichment processes, and address extremely urgent environmental protection problems. To evaluate the process of sedimentation of the solid phase in the pulp within the thickener, measurements of parameters of longitudinal ultrasonic oscillations and Lamb waves that have traveled a fixed distance in the pulp and along the measuring surface in contact with it are used. The proposed approach allows for the consideration of pulp density, particle size of the solid phase in the ore material and the dynamics of changes in these parameters in the thickener at the initial stage of the sedimentation process. Based on the obtained values, adjustments can be made to the characteristics of its initial product, leading to reduced water usage and minimized loss of a useful component.

Keywords: thickener; ultrasound; automatic control; modeling; parameter estimation.



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1. Introduction

In ore enrichment processes thickeners are used to separate, under the gravity action, a mixture of solid and liquid pulp phases into two products: a clarified aqueous solution in the overflow stream and a concentrated thick suspension in the underflow stream. Flocculants are also supplied to the system to increase the rate of solid particle sedimentation. As shown in several papers (BÜRGER *et al.*, 2013; SEGOVIA *et al.*, 2011; SMITH, n.d.), during the sedimentation process of particles of the solid phase in the pulp, several zones can be categorized (Fig. 1): 1 – particle sedimentation at a constant rate, 2 – variable rate of particle sedimentation, 3 – formation and compaction of the sediment.

The thickening process is controlled by changing the sedimentation parameters of crushed ore particles, which leads to increasing the transparency of the over-

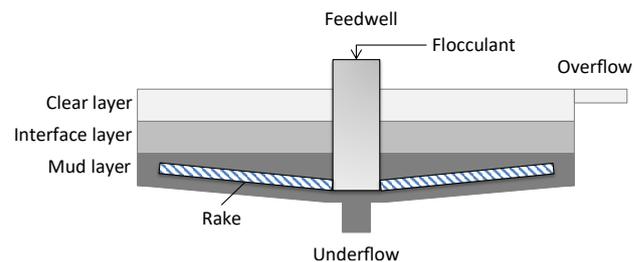


Fig. 1. Layers of the solid phase sedimentation in thickener.

flow (in order to achieve the minimum content of solid particles in the overflow) and increasing the density of the underflow product (in order to extract the maximum amount of solid particles). Control of the thickening process is usually achieved by adjusting the rate of release of the condensed product and adding a flocculant.

In the paper (Sinonine Tech, n.d.), it was demonstrated that the mechanism governing the solid phase particle sedimentation in the thickener is extremely complex. Different types of ore, particles size and variations in pulp concentration lead to diverse sedimentation characteristics. A higher rate of the sedimentation rate results in a shorter time for the pulp to remain in the thickener, otherwise the rate of the sediment layer growth turns out to be fast. This leads to the need to increase in the torque the thickener's rake drive motor, and, in extreme cases, to its overload and the shutdown of the thickener by the protection device. Conversely, a slow sedimentation rate requires that the pulp residence time in the thickener should be increased, otherwise the concentration of the solid phase in the unloaded material decreases, which leads to low dehydration efficiency and increases energy consumption for this process. It is concluded that the control of the performance of the thickener unloading slurry pump and the operational speed control of its drive motor in accordance with the current characteristics of the sedimentation process is of critical importance and central to optimizing the sedimentation process in thickeners.

In another work (Metso, 2017), the control of a thickener is considered from the perspective of measuring process characteristics and simple reaction to their changes. In the thickener, it is rather difficult to see or measure what is happening, and therefore the reaction time from the beginning of the deviation of any parameter to corresponding adjustments in process productivity and efficiency can be quite long. At the same time, the control of the thickener should take into account fluctuations in technological flow characteristics. This is achieved by regulating both the amount of flocculant supplied to the process and the speed of pumping out the thickener unloading product. Figure shows (in accordance with ISO 14617-6:2012) the proposed thickener control circuits: dosing of flocculant (MF – device for the flow measuring) depending on the mass flow rate of the initial material with feedback from the level of the sediment layer (LT – device for the level measuring) or the pressure of the sedimented material layer (PT – device for the pressure measuring), and the performance of the thickener discharge pump depending on either the concentration of the solid phase (DT – device for the density measuring) or the overflow turbidity. The torque of the rake drive motor (M) is also controlled to prevent overloading. In practice, thickened product pumps and flocculant dosing pumps must be controlled based on the measured parameters of the sedimentation process to achieve the thickener's desired operating point under various production scenarios and meet target quality indicators.

However, as noted in the paper by OJEDA *et al.* (2014), conventional feedback control is ineffective for stabilizing the process when the properties of the raw material fluctuate significantly over time, primarily be-

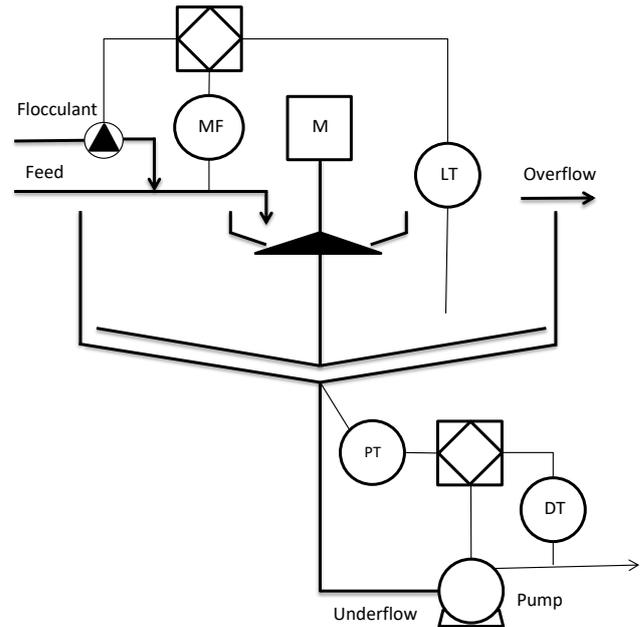


Fig. 2. General contours of the thickener control.

cause the dynamics of the process demonstrates high nonlinearity. This paper presents innovative approach based on an expert system for an industrial thickener with a diameter of 125 m and processing 13 000 m³/h of concentrate containing 27% solids. It is noted that the proposed expert system should be based on an information base encompassing all possible operating scenarios and real-time measurements of the main technological variables.

Thus, the control of sedimentation process variables is crucial for the effective operation of a thickener. In the study conducted by ZUZUNAGA *et al.* (2018), attention is paid to three important control parameters within the thickening technological process: pulp flow speed at the thickener inlet, thickened product flow speed at its outlet, and clarified water flow into the overflow. These measurements have certain problems that can potentially affect the ability to accurately determine the flow rate: pipe size, the medium density in the flow, pump type, the involved air, access to the pipe, etc. Taking these factors into consideration is important for obtaining reliable measurement results that can serve as an indirect indicators of the efficiency of the thickening process.

Currently, the evaluation of the sedimentation process of crushed ore particles entering the thickener relies on the recognition of sediment level and the boundary between different media (MORKUN *et al.*, 2014b; 2014c; 2015b; KANSAI Automation Co., n.d.; SMITH, n.d.). This assessment characterizes the dynamics of particles with specific concentration and sizes in the pulp. Since these estimates are used to regulate the density of the discharge product and the flow of flocculant, inaccurate measurement of these pa-

rameters can lead to water entering into the thickener discharge, solid particles entering the overflow or problems with flocculation. All these problems, in turn, lead to additional costs associated with increased flocculant consumption or the need for reprocessing of ore pulp.

There are several methods of measuring sediment levels and media interfaces in thickeners: manual core sampling (manual core sampling), measurement of hydrostatic pressure, buoyancy-based system, ultrasonic measurements with fixed position ultrasound, mechanical lowering sample analyzers – mud diver (SMITH, n.d.).

Taking core samples manually is a complex, risky, and time-consuming test. When used in combination with a thickener rake torque measurement, this method can actually be used to estimate the sediment level. However, it does not yield high accuracy of estimation. Depending on the rheology of the sediment, the torque and reservoir pressure do not always align. Moreover, this method also requires frequent maintenance.

The float method can incur high operational costs. Floats also often leak and fill with substances they are meant to float in, and as a result they sink. It is not easy to maintain their operational filling with the required liquid density. The boundary of media separation is difficult to detect using this method, especially when the difference in density between the layers can be very small (Markland Specialty Engineering Ltd., n.d.).

Ultrasonic devices based on the measurement of the signal's transit time to reflective surfaces capture the sediment level effectively, provided the medium does not weaken the probing signal's energy before it reaches the sediment layer. However, when using this method, it is difficult to detect the layer of interest, especially if its boundary is not clearly defined (MORKUN *et al.*, 2014b; 2014c; KANSAI Automation Co., n.d.).

A mud diver is an automated device that mechanically lowers a probe into a thickener. This probe can use various measurement methods (for example, optical, ultrasonic, etc.) to determine the depth of layers in the reservoir in real-time (PLA Process Analysers, n.d.). The dives of the mud diver are synchronized with the rotation of the thickener's rake, which prevents entanglement of the probe in the rake arms. Additionally, mud divers are usually equipped with a washing station that cleans the probe after each dive, preventing its contamination. However, this method cannot ensure the efficiency and continuous data acquisition necessary for the operation of automatic thickener control systems. Moreover, like all mechanical devices, mud divers require high maintenance costs.

Therefore, for effective thickener control, it is essential to obtain operational information about the process of sedimentation of particles of the solid phase in the pulp. Having such an estimate applied to its ini-

tial stage allows one to predict the characteristics of final product. The assessment of this process should be based on measurements of the dynamics of changes in the concentration of the solid phase within the pulp and the size of its particles at a certain depth of the thickener.

The objective of this research is to develop methods for gathering information about the ore pulp thickening process in an industrial thickener. This information allows to improve the quality of control, ensuring the desired concentration of the solid phase in the final product, and ultimately reducing production costs. Existing automatic control systems for industrial thickeners are characterized by prolonged response dynamics to disturbing influences and extended transient processes. In contrast, the proposed method of ultrasonic control of the process of sedimentation of crushed ore particles in the thickener is based on measuring the concentration of solid-phase particles and their size in the initial stage of sedimentation. This enables obtaining highly accurate forecast of final product characteristics.

2. Proposed methodology

In the mining industry, water is widely used in hydrometallurgical and mineral enrichment processes (GOLIK *et al.*, 2015a; 2015b; MORKUN *et al.*, 2017). In the beneficiation based on the magnetic separation method, ore particles are ground to a size that is approximately equal to that of the useful component size, which consequently allows the magnetic separator to extract the valuable component from the ore pulp. Before entering the crushing unit, the ore is mixed with water and brought to the optimal size in several stages before being fed into the magnetic separator. Each of these stages includes the following essential technological operations: grinding, classification, and magnetic separation (MORKUN *et al.*, 2015a; SHUKLA, 2021).

In the process of magnetic separation, two products are obtained: concentrate and tails, which are then sent to dehydration systems (ARJMAND *et al.*, 2019; GARM-SIRI, UNESI, 2018; TRIPATHY *et al.*, 2021).

Figure 3 presents a technological diagram of the beneficiation process at the Northern Mining and Beneficiation Plant in Kryvyi Rih, Ukraine (MORKUN *et al.*, 2015a). In this figure, the following symbols are used: mill denotes the ball mill (a technological apparatus for reducing the size of ore particles) and numbers denote the stages of ore particle separation (1 – first stage, 2 – second stage, 3 – third stage, 4 – fourth stage); MS denotes the magnetic separator (a technological apparatus for separating ore particles according to their magnetic properties), while sizer (classifier), H/c (hydrocyclone) and T-r (thickener) are technological apparatus for separating ore particles based on their size.

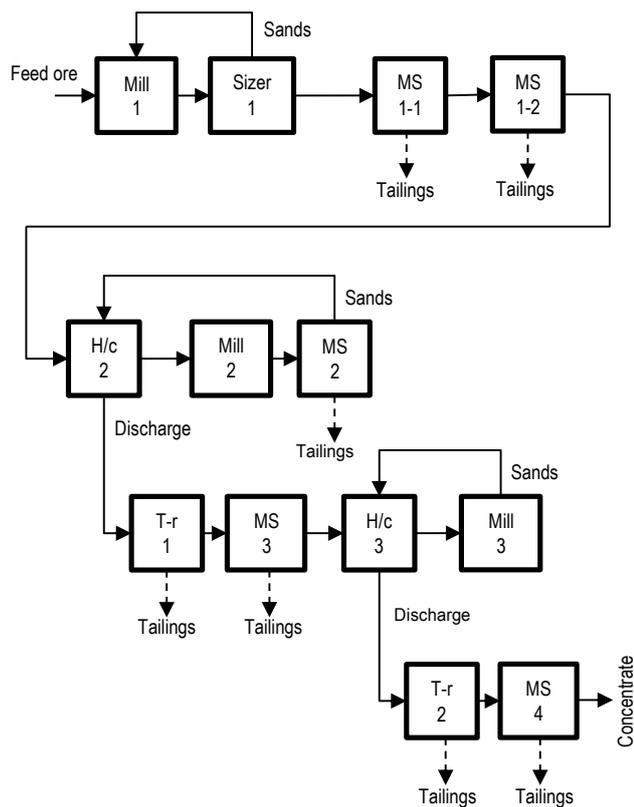


Fig. 3. Technological scheme of the iron ore beneficiation process.

The main internal control influences in the beneficiation line, presented in Fig. 3, are water flows into technological units. In Figs. 4 and 5, examples of obtained qualitative-quantitative dependencies that characterize the influence of this parameter on the technological process are presented.

The dependence of the output of the -0.044 mm grain size class on the flow of water to technological units distributed along the enrichment line is presented in Fig. 4. Here, L denotes the measuring point numbers after the technological devices (1 – mill 1; 2 – sizer, etc.).

The dependence of the mass fraction of iron in the industrial product on the water flow to the technological units is presented in Fig. 5.

The slurry enters the dirt separators at the first stage (point 8), where the solid phase is crushed to a fineness of 91% in the -0.074 mm class. In the dirt separators at the second stage (point 13) the fineness reaches 98% in the -0.074 mm class. Under these conditions, the measurement error for the concentration of the solid phase in the pulp at a level of 0.5–1.5 m from the surface of the pulp in the desludger is 1.8–2.1%, and the concentration of the control size class -0.074 mm showed a deviation in the range of 1.5–1.7% compared to the results of laboratory analysis.

The technological process of ore beneficiation (Fig. 4) involves the pulp entering the thickener, where the solid phase is crushed to expose the ore joints (MORKUN *et al.*, 2014a).

According to the proposed method, a measuring module is placed in the thickener, which enabling for conducting ultrasonic measurements using longitudinal ultrasonic oscillations and Lamb waves. The measuring module placed in the upper part of the thickener vertically along the depth of the thickener. It can function as either a stationary or mobile unit.

First, a reference liquid, in this case, water, is supplied to the measuring module. In the measuring module, high-frequency ultrasonic vibrations are formed and travel a fixed distance in it. The obtained results

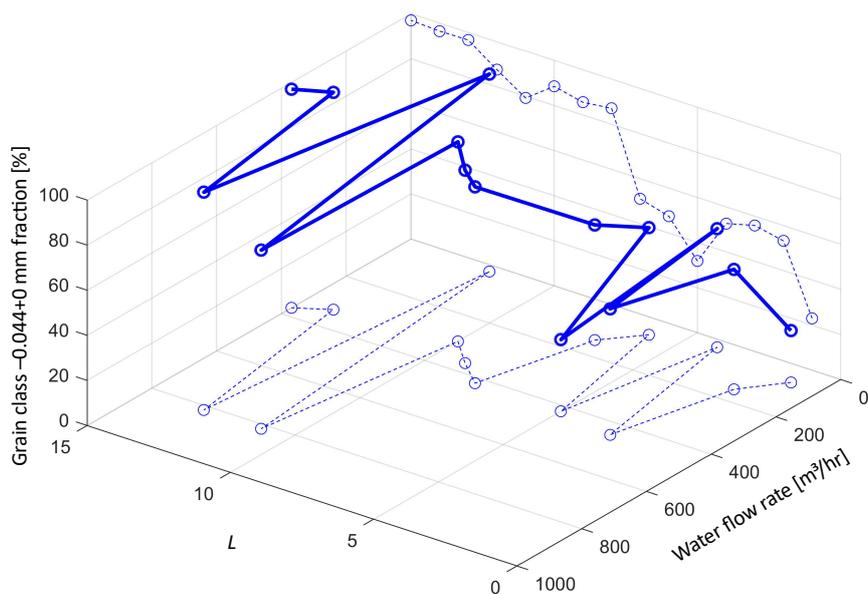


Fig. 4. Output of the grain size class -0.044 mm depending on the water flow to the technological units: the solid line represents a distributed function; the dashed lines are projections on coordinate planes.

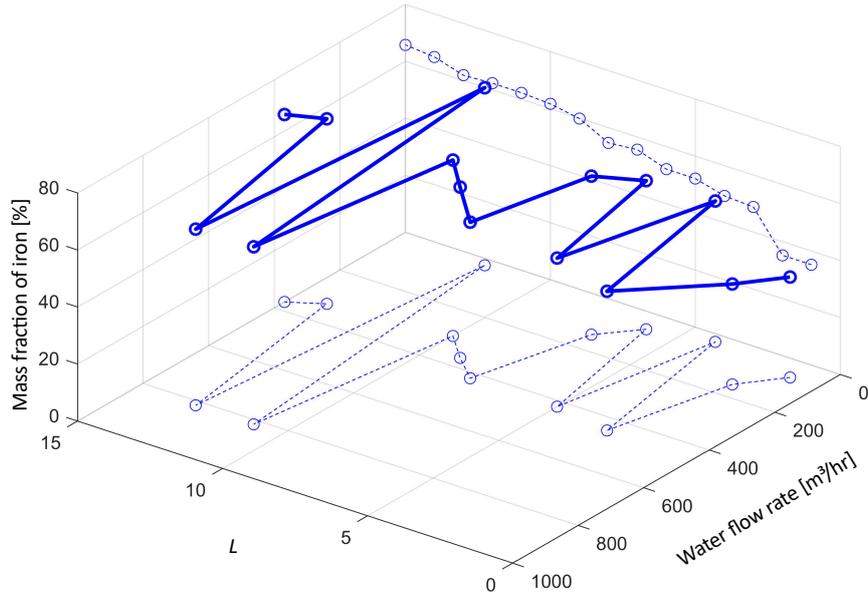


Fig. 5. The mass fraction of iron in the industrial product depending on the water flow to the technological units: the solid line is a distributed function; the dashed lines are projections on coordinate planes.

measure the attenuation of the intensity of high-frequency ultrasonic vibrations serving as reference (basic). In the operational state, an ore suspension flow is formed in the measuring chamber of the thickener. This flow generates high-frequency ultrasonic vibrations that travel a fixed distance when there is a flow of ore suspension in the measuring chamber. For high-frequency ultrasonic vibrations that have traveled a fixed distance throughout the flow of water and ore suspension, the ratio of ultrasound intensities S_1 is determined:

$$S_1 = \ln \frac{I_{B1}^{\text{vol}}}{\langle I_{v1}(z) \rangle}, \quad (1)$$

where I_{B1}^{vol} is the intensity of high-frequency bulk ultrasonic waves that have traveled a fixed distance z throughout the water flow, z is a fixed distance of the ultrasonic waves travelling throughout the water flow, and $\langle I_{v1}(z) \rangle$ is the intensity of high-frequency bulk ultrasonic waves that have traveled a fixed distance z throughout the flow of ore suspension.

The equation for $\langle I_{v1}(z) \rangle = I_{B1}^{\text{vol}}$ is:

$$\langle I_{v1}(z) \rangle = I_{B1}^{\text{vol}} \exp \left(-\frac{W \cdot z}{\varkappa} \int_0^{r_m} \sigma(v_1, r) F(r) dr \right), \quad (2)$$

where $\varkappa = \int_0^{r_m} \frac{4\pi r^3}{3} F(r) dr$, $F(r)$ is the distribution function of solid-phase particles in the ore suspension based on their size r , r_m is the maximum size of solid-phase particles in the ore suspension, and $\sigma(v_1, r)$ is the attenuation cross-section of high-frequency bulk ultrasonic waves with frequency v on a particle of size r .

The size $\sigma(v, r)$ for any frequency bulk ultrasonic waves is determined by the sum of absorption cross-

sections $\sigma_s(v, r)$ and scattering $\sigma_c(v, r)$ ultrasound (MORKUN *et al.*, 2014b; 2019):

$$\sigma(v, r) = \sigma_c(v, r) + \sigma_s(v, r) \quad (3)$$

In the high-frequency region ($v_1 \geq 5 \cdot 10^6$ Hz), the attenuation of ultrasound is primarily caused by the scattering of ultrasonic waves on the solid-phase particles: $\sigma(v_1, r) \approx \sigma_c(v_1, r)$. Therefore, the attenuation formed in the frequency region $v_1 \geq 5 \cdot 10^6$ Hz is determined by the size and concentration of the solid phase particles in the ore suspension.

In (MORKUN *et al.*, 2019) it was concluded that Lamb waves can be used to obtain a value proportional only to the concentration of the solid phase. In the metal plate, which is a component of the measuring module, Lamb waves are formed, which propagate along its entire length. In this case, the attenuation coefficient of ultrasonic Lamb waves that have traveled a fixed distance along the metal plate is determined by the expression:

$$\alpha = \left[(1 - W) \frac{\rho_w}{\rho} + W \frac{\rho_s}{\rho} \right] C_v, \quad (4)$$

where W is the mass concentration of the solid phase in the suspension, while ρ_w , ρ_s , ρ are the specific densities of water, solid phase particles, and the material of the metal plate. In Eq. (4), the value C_v does not depend on the parameters of the surrounding environment whose parameters are controlled, and is a function of the wave numbers of ultrasonic Lamb waves, including both longitudinal and transverse waves of the metal plate material.

The intensity of Lamb waves is measured after they travel a certain distance along a metal plate. The in-

tensity of Lamb waves that have traveled a fixed distance through a metal plate l_n ($n = 1, 2, 3, \dots, m$) can be determined by the expression:

$$I_{nL} = I_{0L} \exp\left(-\left[(1-W)\frac{\rho_w}{\rho} + W\frac{\rho_s}{\rho}\right]C_v l_n\right), \quad (5)$$

where I_{0L} and I_{nL} are the intensity of Lamb ultrasonic waves emitted and the intensity of Lamb ultrasonic waves after they have traveled the distance l_n ($n = 1, 2, 3, \dots, m$), respectively.

If the metal plate is in contact with pure water, then the intensity of ultrasonic Lamb waves in this case is:

$$I_{nBL} = I_{0L} \exp\left(-\frac{\rho_w}{\rho}C_v l_n\right). \quad (6)$$

It follows from Eqs. (5) and (6):

$$I_{nL} = I_{nBL} \exp\left(-\frac{WC_v l_n}{\rho}(\rho_s - \rho_w)\right), \quad (7)$$

that is, the intensity of the received signal is determined by the concentration of the solid phase of the ore suspension and the length of the measurement section l_n ($n = 1, 2, 3, \dots, m$) – the length of the segment of the metal plate along which the Lamb waves have travelled.

According to the proposed method, the value S_2 is calculated as:

$$S_2 = \ln \frac{I_{nBL}}{I_{nL}} = W_n \frac{(\rho_s - \rho_w)}{\rho} C_v l_n. \quad (8)$$

Thus, the value S_2 is determined exclusively by the solid-phase concentration of the ore suspension at a certain depth of the thickener and uniquely characterizes its changes during the sedimentation process. The schematic for measuring changes in the solid-phase concentration of the ore suspension during its sedimentation in the thickener is shown in Fig. 6. To generate and shape ultrasonic waves, as well as to receive, amplify, filter, and select their frequency and timing, we use the corresponding sub-units of our self-designed “Pulsar” ultrasonic granulometer. All other components are standard units of computerized automated process control systems employed in ore beneficiation plants.

The ratio of values S_1 and S_2 characterizes the granulometric composition of the controlled medium:

$$S = \frac{S_1}{S_2} = \frac{z \cdot \rho}{l C_v \kappa (\rho_s - \rho_w)} \int_0^{r_m} \sigma(v, r) F(r) dr. \quad (9)$$

The size S depends only on the size distribution of solid particles, which means that it unambiguously determines the concentration of the controlled particle size class of the solid phase in the thickener’s controlled zone.

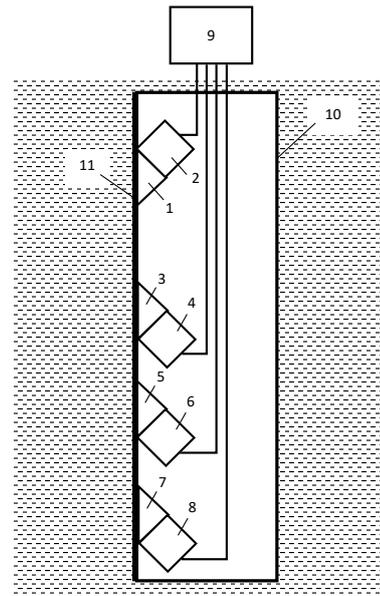


Fig. 6. Scheme for measuring changes in the solid-phase concentration of the ore suspension during its sedimentation in the thickener: 1, 3, 5, 7 – prisms that form an ultrasonic signal; 2, 4, 6, 8 – piezo transducers; 9 – control unit; 10 – measuring module; 11 – measuring surface.

Therefore, the proposed method makes it possible to determine the concentration of the solid-phase concentration and the content of crushed material particles in the control size class, enabling an assessment of the sedimentation process of the solid-phase pulp particles in the thickener.

3. Results

Tests of the measuring system, implementing the proposed method, were carried out at the ore beneficiation factory to verify its metrological and operational characteristics under real industrial conditions. The tests were conducted in two stages. During the first stage, the installation, adjustment, and calibration of the measuring system was carried out in relation to the technological process of the beneficiation factory. In the second stage, the metrological and operational-technical characteristics of the measuring system were determined. To record the metrological characteristics, measurements were taken of the solid-phase concentration and the content of the controlled size class (-0.074 mm) in the precipitated product, with simultaneous sampling for sieve analysis. Measurements were carried out at the minimum, nominal, and maximum consumption of the thickener’s input product. The estimation of the measurement error for both the solids content in the pulp and the content of the controlled size class was made by comparing the readings of the measuring system with the results of a carefully performed sieve analysis of the samples.

The analysis of the obtained results is of interest concerning the ratio of the values between equipment error and the error in the measurement method itself. As it was shown above, the operation of the measuring system relies on determining the characteristics of ultrasonic vibrations propagating in the controlled volume of the pulp and in the plate in contact with it. This device generates two main signals S and S_2 , which characterize the measured technological parameters. Due to the fact that pulp is a randomly inhomogeneous medium in which there are fluctuations in both the number and size of crushed ore particles, along with density variations in the controlled volume of the pulp, the signals generated by the measuring system are also subject to fluctuations. These factors are the primary causes of the inaccuracy in the ultrasonic measurement method used to determine pulp parameters.

Let η be the value characterizing the granulometric composition of the pulp, i.e., the mass fraction of solid particles whose sizes are smaller (or larger) than a given value, for example, 0.074 mm. Fluctuations in the above-mentioned physical quantities lead to scattered values η by size $\Delta\eta$, which, as the analysis showed, can be determined by the expression:

$$\begin{aligned} \Delta\eta = & K \frac{1}{S_2} \left(\left[\exp \left\{ \frac{\overline{W}V_1}{\aleph} (1-\lambda)^2 \right\} - 1 \right] \right. \\ & + S^2 \left[\exp \left\{ \frac{\overline{W}V_2}{\aleph} (1-\theta)^2 \right\} - 1 \right] \\ & \left. + S^2 \theta^2 \left(\frac{\Delta\rho_s}{\overline{\rho}_s - \rho_w} \right)^2 \right)^{\frac{1}{2}}. \end{aligned} \quad (10)$$

Here, the magnitude

$$K = \left| \frac{d\eta}{dS} \right|$$

characterizes the sensitivity of the measurement method. The size η can be represented as a linear or quadratic dependence on the signal S generated by the device based on the measurements results. As the tests showed, this dependence in the working range is linear and can be presented in the form:

$$\eta = a_0 + a_1 S,$$

where the coefficients a_0 and a_1 are determined by the method of least squares based on the results of the sieve analysis of the samples and the readings of the device.

In this case, the sensitivity of the measurement method is given by:

$$K = \left| \frac{d\eta}{dS} \right| = |a_1|.$$

Taking into account Eq. (9), the signal S generated by the measuring system is determined by the expression:

$$S = \frac{V_1(1-\lambda)}{V_2(1-\theta)}, \quad (11)$$

where

$$\lambda = \int_0^{\infty} F_{\eta}(r) dr \exp \left[-\frac{\sigma(v,r)z}{V} \right],$$

and $\sigma(v,r)$ is the full frequency ultrasound scattering cross-section v on a particle of radius r , and V_1 , V_2 , z are the values characterizing the geometric parameters of the measurements.

The signal S_1 generated by the measuring system is determined by the equation:

$$S_2 = \frac{\overline{W}V_2}{\aleph} (1-\theta), \quad (12)$$

where \overline{W} is the mean value of the volume fraction (concentration) of the solid in the controlled volume V of the pulp; $\theta = \exp \left\{ -\frac{\aleph}{V_2} (\overline{\rho}_s - \rho_w) C_v l \right\}$; $F_{\eta}(r)$ is the size distribution function of particles at a certain mass fraction of the size class η ; $\overline{\rho}_s$ is the average pulp density; C_v is the constant value; l is the length of the measuring plate; \aleph is the distribution function of particles of the solid phase in the ore suspension by size.

Using some approximations and transformations, Eq. (10) can be reduced to a simpler form:

$$\Delta\eta = KS \sqrt{\frac{\aleph}{\overline{W}} \left(\frac{1}{V_1} + \frac{1}{V_2} \right) + \frac{\theta \Delta\rho_s^2}{(\overline{\rho}_s - \rho_w)^2}}. \quad (13)$$

It should be noted that complete a priori information for calculating the value $\Delta\eta$ according to Eq. (13) is not available, but these data can be obtained indirectly.

Let us first focus on the determination of the measurement error of the mass fraction of the solid in the pulp β :

$$\beta = bS_2, \quad (14)$$

where b is the coefficient determined by experimental data. Equation (14) describes the dependence of the results of evaluation measurements with specific values of the concentration of the solid phase of the pulp, obtained as a result of laboratory analysis of selected pulp samples, i.e., it actually scales the measurement results and converts them into a commonly used concentration scale.

The error of this magnitude $\Delta\beta$ in general, it can be presented in the form:

$$\Delta\beta = \beta \sqrt{\frac{\aleph}{\eta \overline{W} V_2} + \frac{\theta \Delta\rho_s^2}{(\overline{\rho}_s - \rho_w)^2}}. \quad (15)$$

It follows from Eqs. (13) and (15) that the error in measuring the granulometric composition $\Delta\eta$ can be expressed due to the measurement error of the mass fraction of the solid $\Delta\beta$:

$$\Delta\eta = KS \sqrt{\left(\frac{\Delta\beta}{\beta} \right)^2 + \frac{\aleph}{\overline{W} V}}. \quad (16)$$

The analysis showed that

$$\frac{\kappa}{\overline{WV}} \ll \left(\frac{\Delta\beta}{\beta} \right)^2,$$

therefore, it is possible to obtain an even simpler expression for estimating the error value $\Delta\eta$:

$$\Delta\eta \approx KS \frac{\Delta\beta}{\beta} = |\eta - a_0| \frac{\Delta\beta}{\beta}. \quad (17)$$

In the process of experimental studies, pulp samples were taken at fixed points along the depth of the thickener. Samples were collected into a measuring container and then processed using proven laboratory methods. The volume and mass concentration of the solid phase of the pulp, its density, as well as the content of the control size class -0.074 mm were determined. The determination of the granulometric composition of crushed ore in the pulp was carried out by the dry sieve method, i.e., by sieving through a set of standard sieves with holes of normalized sizes: +3, 3+1, 1+0.5, 0.5+0.25, 0.25+0.125, 0.125+0.074, 0.074+0.056, 0.056+0.044, 0.044+0. The density of the crushed material was determined by the pycnometer method. Samples were analyzed with a density ranging from 1050 to 1550 kg/m³, with a fineness class of -0.074 mm ranging from 30 to 98% and a crushed ore density ranging from 1900 to 4500 kg/m³. The results of industrial tests testify to the fact that the uncertainty in determining the mass fraction of solids $\Delta\beta$ makes up $\sim 2\%$. This value is used as the initial value for calculating the value $\Delta\eta$ according to Eq. (17), and the results are given in Table 1.

Table 1. Calculation results $\Delta\eta$.

$\eta_{-0.074}$ [%]	50	55	60	65	70
$\Delta\eta$ [%]	1.6	1.4	1.2	1.0	0.7

Therefore, the accuracy of measuring the granulometric composition of the pulp at the thickener's depth depends on the size range of the measurements. With a high mass fraction of the controlled size class (65% or more), the uncertainty of the measurement method is approximately 1%. However, as the mass fraction of the controlled size class decreases to 50% and below, the method's uncertainty doubles.

Based on the results of the conducted tests, it can be concluded that the error values associated with the measurement method and the instrument's error in the measuring system itself are practically comparable. In the actual operational conditions of the processing plant, it is possible to ensure the measurement of the controlled technological parameters with an uncertainty ranging from 1 to 2%.

The proposed method for estimating pulp density and particle size of its solid phase in the initial stage of

the sedimentation process allows to implement thickener control based on the MPC (model-predictive control) algorithm and, for example, a widespread phenomenological model (BARTH *et al.*, 2016; BETANCOURT *et al.*, 2014; BÜRGER *et al.*, 2019). It is also possible to use expert control systems based on fuzzy rules, and other algorithms for optimal control of a thickener (CHAI *et al.*, 2014; TAN *et al.*, 2015; XU *et al.*, 2015; ZHANG *et al.*, 2016).

According to the industrial test results of the automatic control system of the thickener using ultrasonic control means, it was determined that its use as part of the automatic control system of the processes of iron ore enrichment at the Northern Iron Ore Beneficiation Works can lead to a reduction in water consumption by 3.5% and a decrease in iron-magnetite losses by 0.6–0.7%.

4. Conclusion

To evaluate the sedimentation process of the solid phase of the pulp in the thickener, measurements of longitudinal ultrasonic oscillations and Lamb waves that have traveled a fixed distance in the pulp and on the measuring surface in contact with it were used.

As a result of industrial tests of the measuring system, the following was established: the proposed method ensures stable measurement of the content of solid and the controlled size class of crushed materials, with measurement errors not exceeding the specified technological parameters $\pm 2\%$.

Since all calculations in the proposed automatic control method are carried out based on measurements relative to the characteristics of water, which serves as the reference substance, the results obtained are resilient against various disturbing factors that reduce the accuracy of measurements of the solid-phase parameters in the ore suspension.

The proposed approach allows to take into account pulp density, particle size of the solid phase in the ore material and the dynamics of changes in these parameters in the thickener at the initial stage of the sedimentation process. Based on these obtained values, adjustments can be made to the characteristics of the initial product, leading to a reduction in water consumption by 3.5% and a decrease in the loss of the useful component by 0.6–0.7%.

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