DOI 10.2478/ama-2023-0047

FORMATION OF INFORMATION BASE FOR CONTROLLING SETTLEMENT OF SOLID-PHASE ORE SLURRY PARTICLES IN A THICKENER

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received 18 May 2022 , revised 25 February 2023 , accepted 1 March 2023

Abstract: Thickeners are process units that are often used at mining enterprises. There, they are involved in dehydration of mineral concentration products when water is removed from wet tailings containing metal concentrates. In mineral processing, large quantities of process water are used to separate different minerals from each other, so dehydration plays a major role in ore processing and preparation for concentration. This research aims to develop methods and tools of ultrasonic measurement of characteristics of settlement of solid-phase slurry particles and to assess their possible application to the automatic control system of the thickener to improve its efficiency.

Key words: thickener, ultrasonic, automatic control, modelling, parameter estimation

1. INTRODUCTION

The theory developed to date has provided the basis for designing, modelling and controlling industrial thickeners, where a product is a unit, an area, a concentration profile and the number of solids in the thickener [1–3].

However, mathematical models are useless if parameters of the corresponding equations cannot be determined experimentally. Knowledge of model parameters is necessary to form control and operation of mills, classifying units, flotation machines, magnetic separators (MS), equipment for separating solid and liquid phases, as well as the means of concentrate and tailings transportation. Synthesis of the thickener control is associated with certain problems due to their large time constants, non-linear characteristics, available disturbing influences and disturbances [4].

Quite a long period of slurry sampling for analysis in the existing control system for thickeners, as well as available disturbing influences due to changes in the flow rate, density and composition of the initial slurry do not enable maintaining slurry density in the discharge within technological regulations [5]. To overcome this drawback, the magnetic thickener control system is upgraded along the following lines:

- installation of a sensor on the slurry discharge to enable continuous measurement of density of the thickened slurry;
- development of an additional loop to control the density of the thickened slurry by changing its flow rate;
- development of a module for activating a magnetite level control loop or a slurry density stabilisation loop depending on the current technological situation.

The results of studying slurry dehydration with the solid phase composed mainly of superfine particles are presented in [6]. This approach does not consider formation of controlling actions directly during the process to increase the efficiency of thickening. In [7], to improve the design and efficiency of thickening, methods for calculating the fluid dynamics are used. The authors apply a balance model of the number of particles. The approach requires additional investigations to form an information support system for controlling operational data on the distribution of particles in the thickener and their physical–mechanical and chemical–mineralogical characteristics.

A method of measuring the ultrasound phase velocity and attenuation in slurries to evaluate their characteristics was considered in [8]. The results show that the phase velocity of ultrasonic waves increases with the number of fine particles in the slurry. Dispersion is due to the solid phase present and correlates with its mass fraction. The results of attenuation experiments show that it is possible to back-calculate the slurry properties by fitting the model to experimental data if size distribution of the solid-phase particles is known. It is concluded that it is difficult to determine the accuracy of these calculations and therefore more research in this area is needed.

When concentrating on flocculant solutions, the sand concentration varies significantly with and without displacement. In order to use the presented dependencies when controlling thickening and desliming, it is necessary to take into account the differences in characteristics of certain mineral and technological types of ore materials as well as contamination of ore particle surfaces [9]. Removal of high-dispersed impurities from process water by means of flocculation of iron ore particles was studied in [10]. The main aspects of chemical influence on thickening and desliming are indicated.

When controlling thickeners, fluctuations in the process flow should be considered [11]. This is achieved by changing both the amount of flocculant and the pumping rate of the bottom product. However, variations in the ore type cause relevant changes in the required flocculant dosage. It is noted that with the PID control loop, the amount of flocculant can be adjusted via a feedback from either the layer level or the turbidity of the overflow. Care is taken to ensure that the location of the flocculant injection point provides good flocculant dispersion. In some cases, it may be necessary to add some flocculant at several points, thus improving its contact with the medium. The density of the bottom product of the thickener is a function of the ability of solids to settle as well as the residence time in the thickener. Systems designed to adjust density according to the results of measuring this parameter tend to cause cyclic instability. It is concluded that the strategy of controlling the stock by regulating the pumped bottom product to maintain a constant mass provides consistently high density of the bottom flow.

A control strategy based on measuring density and the flow rate of the feed product, density and the flow rate of the thickened product to maintain the amount of solid materials at the input, output and directly in the thickener by adjusting the pump performance was suggested in [12]. The following controlled variables are either corrected or limited: density of the thickened product, the drive torque and the level of solids stock in the thickener. This implements the following control logic. If the outflow is smaller than the inflow, the pump capacity will not increase until density is such that the upper torque limit or the maximum solids stock in the thickener is reached. If the outflow is greater than the inflow and the outflow density is lower than the required one, the pump capacity will be reduced provided the torque limit is in the safe operating range and the amount of solids is below the upper limit.

Conventional control of the thickener is based on single-loop auto-control systems with PI-controllers (control of the bottom product pumping, the density-dependent flow rate of the thickened product) [13]. However, practice shows that this control architecture is not optimal for controlling a process of slow and complex dynamics. Depending on the process flowchart used at a plant, different objectives can be set to optimise the thickener capacity: the target density of the bottom product is used to ensure optimal solids content in the tailings pond, the efficient drainage rate for the mill, and so on. The target slurry level is used to obtain optimal thickener loading without overloading the drive. The pressure at the thickener bottom is used as an indicator of the solids stock. This helps the system determine whether the high layer level is the result of a decrease in the settling rate or an increase in solids concentration. In some cases, the target torque is used as an indicator of acceptable rheology of the bottom flow.

While ensuring optimal control of solids percentage in the flow, keeping all relevant variables within acceptable limits is what many authors are striving for when forming a control strategy for thickeners [14–16].

However, in any control strategy, it is good to have as much information as possible about the values of the important variables. In the case of the thickener, several values can be measured, for example, torque of the rake drive, the layer level, pressure at the thickener bottom, in/outflow rates and percentage of solids in the flows. Additional measurements also allow for more effective control strategies [17].

This research is aimed at the formation of an information base for controlling the settlement of solid-phase ore slurry particles in a thickener by determination of such characteristics as dynamics of slurry density and particle size distribution of its solid phase at the initial stage of ground ore settlement in the thickener. This approach will allow to consider the nature of the size distribution of solid-phase particles of the ore material in the thickener, and determine the characteristics of the output product in the thickener in accordance with the parameters of ore particles settlement, which as a result will reduce the loss of the useful component in the iron ore concentrate.

2. PROPOSED METHODOLOGY

Process lines of concentration usually consist of several successive stages, each of which includes the following main operations: grinding, classification/sizing and magnetic separation. The operations are aimed at ore aggregate release and separation of particles of various minerals from each other by reducing the size of mineral grains to 0.1 mm or less.

Fig. 1 depicts a concentration flowchart at the ore concentration plant of the Northern Mining and Concentration Plant in Kryvyi Rih MS, hydrocyclone (H/c), thickener (T-r). Despite some differences in the operations and concentration units, the flowchart can be considered typical for most mining and concentration plants of Ukraine.

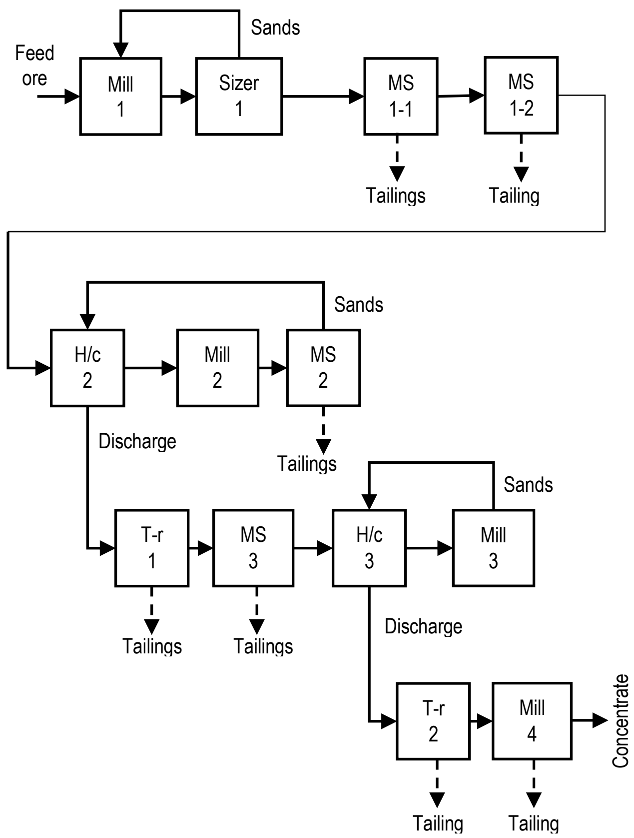


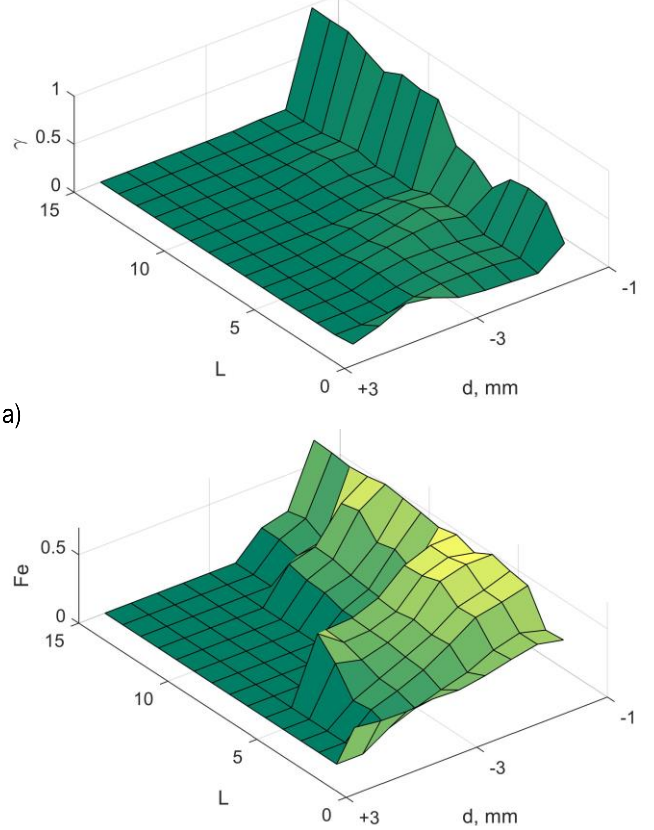
Fig. 1. Concentration flowchart at the ore concentration plant of the Northern GZK

To assess the quantity of mineral products, besides distribution of mineral particles γ (ξ) by fractions with different physical properties ξ, the indicator of distribution of useful components β (ξ)

DOI 10.2478/ama-2023-0047

is generally used as well. γ(ξ) and β(ξ) allow to perform a quantitative evaluation of ore materials. Separation characteristics f ε (ξ) are used to quantify the efficiency of process devices.

Surfaces of indicators of released ore sizes and the content of the useful component in them, which are distributed along the concentration line (control points 1...15 in Fig.1), are presented in Fig. 2 (a) and (b).



a)

b)

Fig. 2. Indicators distributed along the concentration line: (a) the yield of sizes of the solid-phase slurry; (b) the total Fe content in the intermediate product

The thickener is an integral part of the ore concentration line and the results of its operation directly affect qualitative and quantitative indices of products obtained.

In [1,17] it is shown that the automatic control system (ACS) of the thickener should enhance its efficiency, namely: stabilise thickening indicators, form concentration of the thickened product taking into account process requirements, reduce the flow rate of flocculant considering torque limitations and properties of the transported slurry. The control system performs continuous correction of process parameters on the basis of their promptly measured characteristics. The optimal operating conditions of the thickener are determined by steady-mode characteristics, and the ACS is used to stabilise its operation at the selected values of process variables.

In the thickening process, we can distinguish the following variables by output: concentration of the thickened product and the settlement level; adjustable variables: the volume flow rate of the thickened product and the flocculant flow rate; parameters: the function of solids density and effective solids pressure; and disturbances: granulometric composition, density of the feed product and its flow rate. In practice, the following measurements are available: density of feed and thickened products, the settlement level, bottom pressure, torque, overflow turbidity, and pumping current of the thickened product.

Fig. 3 presents main processes associated with the thickener operation; i.e. flocculation, which results from adding flocculants to the slurry, and settlement of its solid phase [1].

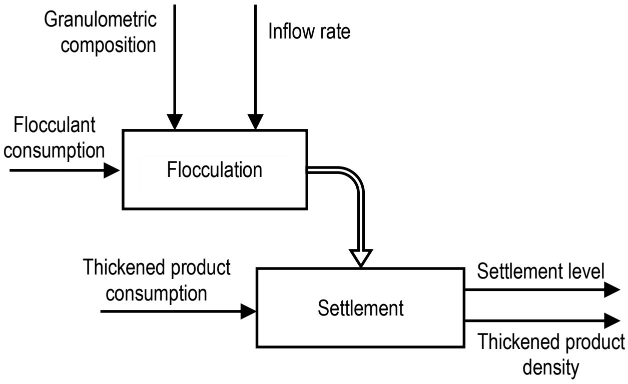


Fig. 3. Diagram and main variables of the thickening process

Various mathematical models of the thickening process of ore raw materials were suggested in [18–20]. For example, the internationally accepted phenomenological model describes slurry compaction in the thickener based on the degenerate parabolic differential equation of the second order [21–22]:

$$\frac{\partial\varphi}{\partial t}+\frac{\partial}{\partial z}\left(q\varphi+f_{bk}(\varphi)\right)=\frac{\partial}{\partial z}\left(\frac{f_{bk}(\varphi)\sigma_c'(\varphi)\,\partial\varphi}{\Delta\rho\varphi g}\right) \quad (1)$$

where (*z, t*) are the vertical upward spatial coordinate and time, φ is the volume fraction of solids, q(t) is the volume flow rate (volume of the thickened product per unit area of thickeners), $f_{bk}(\varphi) - \varphi v_s(\varphi)$ is Kinch solid flow density, where $v_s(\varphi)$ is the initial rate of the concentrated product settling, φ, $\sigma_c(\varphi)$ is effective pressure of solids representing compressibility of sediments, $\Delta\rho = \rho_s - \rho_f$ is a difference in solid-liquid density and g is acceleration of gravity.

The above and other proposed models prove that availability of information on the actual behaviour of solid-phase particles of the slurry during its settlement allows for significant simplification of slurry control formation.

We propose a method of forming control over thickening based on assessing changes in slurry density and particle size distribution of its solid phase in the initial settlement stage in the thickener, which makes it possible to predict the characteristics of the thickened product and thereby counteract high inertia of the system. For this purpose, the characteristics of ultrasonic waves passing through the controlled volume of the slurry settling in the thickener are measured [8, 23–25].

Let us denote the intensity of the ultrasonic signal passing a fixed distance in the slurry as [26]

$$\xi = I_0 \exp\left\{-\frac{1}{V}\sum_{i=1}^{k}\sigma(r_i)Z\right\} \quad (2)$$

where $\sigma(r_i)$ is a cross section of ultrasound attenuation on particles of the radius r_i.

Dispersion of this value is determined by the expression

$$D_{\xi} = M(\xi - <\xi>)^2 = M(\xi^2 - 2\xi <\xi> + <\xi>^2) = M\xi^2 - <\xi>^2 \quad (3)$$

Considering that

$$\xi^2 = I_0 \exp\left\{-\frac{2}{V}\sum_{i=1}^{k}\sigma(r_i)Z\right\} \quad (4)$$

we obtain

$$M\xi^2 = \sum_{k=0}^{\infty} M\left(\frac{\xi^2}{k}\right)F(k) \quad (5)$$

Mathematical expectation of the value for the fixed number of particles *k* of the ground material in the controlled volume makes:

$$M\left(\frac{\xi^2}{k}\right) = \left[\int_0^{\infty} e^{\frac{2}{V}\sigma(r)Z}F(r)dr\right]^k = \eta_1^k \quad (6)$$

$$M(\xi^2) = \sum_{k=0}^{\infty}\frac{\eta_1^k \bar{N}^k e^{-\bar{N}}}{k!} = e^{-\bar{N}(1-\eta_1)} \quad (7)$$

$$M(\xi^2) = I_0^2 \exp\left\{-nV(1 - \int_0^{\infty} e^{-\frac{2}{V}\sigma(r)Z}F(r)dr)\right\} \quad (8)$$

The average value of the signal passing through the controlled volume of the slurry V is

$$<\xi> = I_0 \exp\left\{-nV(1 - \int_0^{\infty} e^{-\frac{1}{V}\sigma(r)Z}F(r)dr)\right\} \quad (9)$$

We substitute the determined values into expression (3)

$$D\xi = I_0^2 \exp\left\{-nV(1 - \int_0^{\infty} e^{-\frac{2}{V}\sigma(r)Z}F(r)dr)\right\} - -I_0^2 \exp\left\{2nV[1 - \int_0^{\infty} e^{-\frac{1}{V}\sigma(r)Z}F(r)dr]\right\} \quad (10)$$

Let us represent summands of the obtained expression in the form of

$$\int_0^{\infty} F(r)e^{-\frac{2}{V}\sigma(r)Z}dZ \approx \int_0^{\infty} F(r)[1 - \frac{2}{V}\sigma(r)Z + \frac{4\sigma^2(r)Z}{2V^2}]dZ \quad (11)$$

$$\int_0^{\infty} F(r)dr \cdot e^{-\frac{1}{V}\sigma(r)Z} = 1 - \frac{Z}{V}\int_0^{\infty}\sigma(r)F(r)dr + \frac{Z^2}{2V^2}\int_0^{\infty} F(r)\sigma^2(r)dr \quad (12)$$

Dispersion of the signal passing through a layer of the slurry of thickness Z is determined from the expression

$$D\xi = I_0^2 \exp\left\{-nV\left(1 - 1 + \frac{2Z}{V}\int_0^{\infty}\sigma(r)F(r)dr - \frac{2Z^2}{V^2}\int_0^{\infty}\sigma^2(r)F(r)dr\right)\right\} - I_0^2 \exp\left\{-2nV\left(1 - 1 + \frac{Z}{V}\times \int_0^{\infty}\sigma(r)F(r)dr - \frac{Z^2}{2V^2}\int_0^{\infty}\sigma^2(r)F(r)dr\right)\right\} = I_0^2 \exp\left\{2nZ\int_0^{\infty}\sigma(r)F(r)dr\right\}\times\left[\exp\frac{2nZ^2}{V}\int_0^{\infty}\sigma^2(r)F(r)dr - \exp\frac{nZ^2}{V}\times\int_0^{\infty}\sigma^2(r)F(r)dr\right] \quad (13)$$

Let us introduce the designation

$$\psi = \exp\left\{\frac{nZ^2}{V}\int_0^{\infty}\sigma^2(r)F(r)dr\right\} \quad (14)$$

Then

$$D\xi = I_0^2 \exp\left\{2nZ\int_0^{\infty}\sigma(r)F(r)dr\right\}[\psi^2 - \psi] \quad (15)$$

In (9), we decompose the integrand into a series. Leaving three terms of this series, we obtain

$$<\xi> = I_0 \exp\left\{-nV\left(1 - 1 + \frac{Z}{V}\int_0^{\infty}\sigma(r)F(r)dr - \frac{1}{2}\frac{Z^2}{V^2}\int_0^{\infty}\sigma^2(r)F(r)dr\right)\right\} = I_0 \exp\left\{-nZ\int_0^{\infty}\sigma(r)F(r)dr\right\}\sqrt{\psi} \quad (16)$$

Let us determine the relative value

$$\frac{\sqrt{D\xi}}{<\xi>} = \frac{I_0 \exp\left\{-nZ\int_0^{\infty}\sigma(r)F(r)dr\right\}\sqrt{\psi^2 - \psi}}{I_0 \exp\left\{-nZ\int_0^{\infty}\sigma(r)F(r)dr\right\}\sqrt{\psi}} = \sqrt{\psi - 1} \quad (17)$$

We present (14) as

$$\psi = \exp\left\{\frac{WZ^2}{V}\cdot\frac{\int_0^{\infty}\sigma^2(r)F(r)dr}{\int_0^{\infty}4/3\pi r^3 F(r)dr}\right\} \quad (18)$$

We determine the logarithm of this value as

$$\log\psi = \frac{WZ^2}{V}\cdot\frac{\int_0^{\infty}\sigma^2(r)F(r)dr}{\int_0^{\infty}4/3\pi r^3 F(r)dr} \quad (19)$$

We introduce the designation

$$\frac{\sqrt{D\xi}}{<\xi>} = \sqrt{\psi - 1} = a \quad (20)$$

Then $\psi = 1 + a^2$

Considering that $\sqrt{\psi} \approx 1$, we obtain

$$<\xi> = I_0 \exp\left\{\frac{-ZW\int_0^{\infty}\sigma(r)F(r)dr}{\int_0^{\infty}4/3\pi r^3 F(r)dr}\right\} \quad (21)$$

and thus

$$\ln\frac{I_0}{<\xi>} = ZW\frac{\int_0^{\infty}\sigma(r)F(r)dr}{\int_0^{\infty}4/3\pi r^3 F(r)dr} \quad (22)$$

We determine the characteristic function

$$S' = \frac{\ln\psi}{\ln I_0/<\xi>} = \frac{Z}{V}\frac{\int_0^{\infty}\sigma^2(r)F(r)dr}{\int_0^{\infty}\sigma(r)F(r)dr} \quad (23)$$

The last expression reveals that the value S′ is a function of the solid particle size in the slurry. Thus, by measuring the parameters I0 , <ξ>, Dξ and calculating the parameter S′, we can assess particle size distribution of the slurry settled in the thickener.

3. RESULTS

The amplitude–frequency characteristic of the signal reflected from the ultrasonic oscillation reflector in the slurry depends on the distribution of solid-phase particles of the ore slurry during their free settlement, whose parameters are determined by both the particle size and slurry density [27, 28].

The proposed ACS of thickener 1 (Fig. 4) contains waveguide 2 with piezoelectric transducer 3 mounted. Driving oscillator 4 on command from computing-control unit 5 generates a trigger pulse of normalised amplitude and duration, which through the OR logic circuit 6 goes to the input of controlled electromagnetic sinusoidal oscillator 7 switched on for the duration of the pulse. A train of ultrasonic oscillations is formed by piezoelectric transducer 3 and through waveguide 2 is radiated in the direction of ultrasonic wave reflector 8 in the tank of thickener 1. The reflected ultrasonic oscillations via waveguide 2, piezoelectric transducer 3 and selection unit 9 arrive at the receiving amplifier 10. Thus, at the output of receiving amplifier 10, the signal coming from ultrasonic wave reflector 8, the amplitude–frequency characteristic of which is

DOI 10.2478/ama-2023-0047

determined in analyzer 11, is formed. In computing-control unit 5 the value S characterising granulometric composition of the medium under study is calculated.

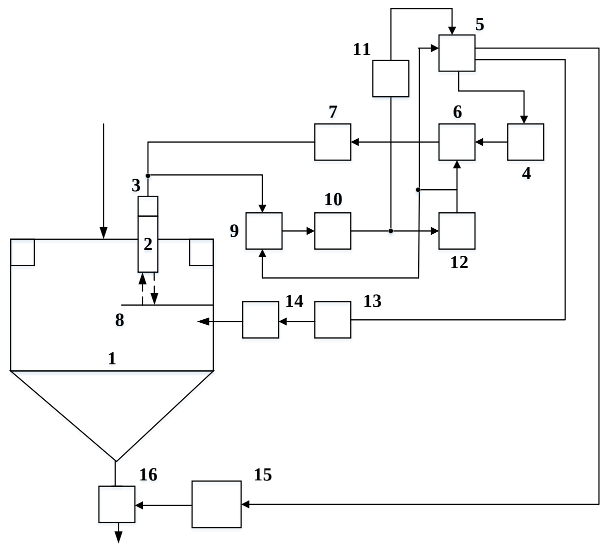


Fig. 4. Ultrasound-based ACS of the thickener. ACS, automatic control system

Pulse former 12 receiving a signal from receiving amplifier 10 through OR logic circuit 6 again starts controlled electromagnetic sinusoidal oscillation generator 7. The frequency of the formed pulses *f* is a function of the distance to ultrasonic wave reflector 12 of and the velocity of ultrasonic wave propagation in the studied medium:

$$f = \nu /2d \quad (24)$$

where ν is the velocity of ultrasonic wave propagation and *d* is the distance from waveguide 2 to ultrasonic wave reflector 12 in thickener tank 1.

In liquid media, ultrasound propagates as volume rarefaction-compression waves and the process is adiabatic, that is, the temperature in the sound wave has no time to equalise [29]. The adiabatic sound velocity is determined by the pressure transmission velocity:

$$C = \sqrt{\left(\frac{dP}{d\rho}\right)_s} \quad (25)$$

where *P* is pressure in the material, ρ is density of the material and s indicates that the derivative is taken at constant entropy.

The ultrasound velocity can be expressed in the following form:

$$C = \sqrt{\frac{K_{\alpha\partial}}{\rho}} = \sqrt{\frac{1}{\beta_{\alpha\partial}}} = \sqrt{\frac{\gamma}{\beta_{из}\cdot\rho}} \quad (26)$$

where $K_{\alpha\partial}$ is an adiabatic comprehensive compression module; $\beta_{\alpha\partial} = \frac{1}{K_{\alpha\partial}} = \frac{1}{\rho}\left(\frac{\partial\rho}{\partial P}\right)_s$ is adiabatic compression; $\beta_{из} = \gamma \cdot \beta_{\alpha\partial}$ is isothermal compressibility; and $\gamma = \frac{C_p}{C_v}$ is a ratio of heat capacities at constant pressure and volume.

Thus, given the invariability of distance *d* from waveguide 2 to ultrasonic wave reflector 12 in thickener tank 1, the frequency *f* is determined by the ultrasound propagation velocity, which, in turn, depends on the density of the controlled medium *ρ*.

To increase noise immunity of the measurement results, the frequency of pulses generated by driving oscillator 8 is selected by an order of magnitude less than the repetition rate of circulating pulses. Therefore, without a reflected signal, for example, in case of a foreign object in the control plane, after some time driving oscillator 8 again starts controlled electromagnetic sinusoidal oscillations generator 11 and the system resumes its operation.

Taking into account the applied approach and the formed information base, the control algorithm for the thickener can be formulated as an optimisation problem [15, 30–32]:

$$\min = \int_{t_k}^{t_{k+\Delta k}} (W_x(\tilde{x}(t) - x_{SS})^2 + W_u(u(t) - u_{ss})^2)dt \quad (27)$$

where the state equation looks like

$$\tilde{x}(t) = f(\tilde{x}(t)) + g(x(t))u(t) \quad (28)$$

where $\tilde{x}$ is the forecast value of *x*; *k* is the time horizon; W_x, W_u - вага is weight.

The *u*-function minimising the optimisation problem should be in the set of piecewise continuous functions (with the sampling time which is the time difference between two steps t_k and t_{k+1}) [33]. The steady-state input u_{SS} corresponds to the steady-state x_{SS}.In the context of the thickener model, it is clear from the above equation that the state vector *x* coincides with the vector ϕ in the model [34, 35].

Computing-control unit 9 based on the calculated value *f* through actuator 13 and operating member 14 regulates the flow rate of thickened products in thickener 1 to stabilise their density.

The calculated values of *S′* are used to control the rate of solid-phase particles settlement by controlling the amount of flocculant by means of actuator 15 and regulator 16. Fig. 5 shows the calculated dependence of the parameter *S′* on the content of the 74 μm class in the solid phase of the slurry settling in the thickener.

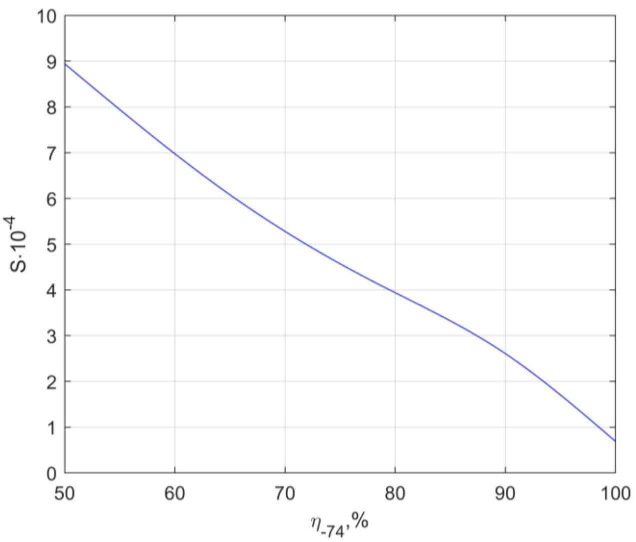


Fig. 5. Granulometric composition of the medium on the content of the 74 μm class in the solid phase

The specified parameters allow maintaining the efficiency of the thickening process in accordance with the characteristics of the ore slurry without losing the useful component. Due to obtaining operational information about the characteristics of the settlement of the solid phase particles of the ore slurry already at its initial stage, it is possible to reduce the duration of transient processes in the ACS.

According to the results of industrial tests of the ACS for the thickener control on the basis of ultrasonic control devices, it is found that the use of this system within the iron ore concentration ACS at mining enterprises of Kryvyi Rih iron ore basis will reduce the loss of Fe_{mag} by 0.6%–0.7%.

4. CONCLUSIONS

Determination of such characteristics as dynamics of slurry density and particle size distribution of its solid phase at the initial stage of ground ore settlement in the thickener allows us to take into account fluctuations in the parameters of the process flow. This is achieved by controlling both the amount of flocculants and the pumping rate of the bottom product.

The ACS based on the obtained information and modern software and hardware tools makes it possible to overcome slow dynamics of the response to control actions and cross-impacts of controlled variables. To achieve optimal efficiency of the thickening processes, their ACS should be formed as modules of the hierarchical control structure of the entire technological process of ore concentration.

The proposed approach allows us to consider the nature of size distribution of solid-phase particles of the ore material in the thickener, and determine the characteristics of the output product in the thickener in accordance with the parameters of ore particles settlement, thus reducing the loss of the useful component by 0.6%–0.7%.

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Funded by the Alexander von Humboldt Foundation.

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