Thickener Control on The Basis of Ultrasonic Measurements and Fuzzy Inference

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Abstract

Efficient water management in the mining and processing industry has become an important issue due to environmental and production issues. Increasing productivity of many ore concentrators calls for increased efforts to extract the maximum amount of water when separating solid and liquid phases. Thickeners work continuously creating a concentrated thickened product and draining water free of solid particles. This equipment belongs to significantly non-linear systems and practice reveals that standard feedback control is not effective in ensuring consistency of operations. At many enterprises, efficiency of thickeners is low as they use a large number of flocculants, overflows with high content of fine particles and highly variable characteristics of the thickened product. These problems are largely due to the lack of modern tools for automatic measurement of main characteristics of solid-phase slurry particles settling in thickeners.

The research aims to increase efficiency of thickening and desliming of iron ore concentration products and quality of magnetite concentrates by using ultrasonic methods to measure characteristics of solid-phase slurry particles settling in the thickener and fuzzy inference to determine the optimal flow rate of the thickened thickener product to stabilize its density.

Keywords

Thickener, ultrasound, automated control, fuzzy inference, modelling, parameter evaluation.

1. Introduction

Thickeners are used to separate under gravity the ore slurry into two products: clarified product in the overflow flow and concentrated thickened product. The settling process creates a zone at the bottom of the tank with a higher concentration of solids than in the inlet flow. The thickening process is typically controlled by adjusting its parameters, resulting in increased overflow clarity (to achieve a minimum solids content) and increased bottom product density (to maximize solids recovery).

Strategies based on a calibrated phenomenological model are used to solve the problem of controlling sludge levels and concentrations of thickened products. This model is used to not only simulate the process, but also adjust controllers. These results show that control structures with these two variables are difficult to adjust, but they provide a qualitative result. For example, a fuzzy strategy with 60 rules provides high performance, yet requires more efforts to adjust the controller. A time constraint provides a simple solution to simplify setting tasks, but requires two additional measurements – the feed rate and solids concentration in the input product. To study the effect of flocculant dosage and use of control strategies with a constraint-based model is quite promising.

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2. Related works

Article [1] investigates into flocculation of iron ore tailings in a thickener at the ore beneficiation plant. Dependences of flocculation efficiency (settling rate, turbidity and sediment volume) on flocculant dosage are obtained. However, use of exclusively chemical effects complicating operational control over thickening and desliming is its disadvantage. Work [2] presents dependences of increasing the residence time of particles due to the sediment layer depth and the sediment flow. Efficiency indices of thickening in the hydrocyclone are calculated. At the same time, the disadvantage of the paper is that it does not suggest methods of operational control of characteristics of ore particles, in particular their size.

Work [3] presents a modification of a known thickener model with a simple controller and a numerical scheme. The model predicts behaviour of the thickener at the time-varying settling rate of solids fed with the input product. The level of sediments appears to be a very sensitive variable with respect to changes in the particle settling rate. It is shown how the fixed state can be manually controlled by changing the two controlling variables Qu the amount of the thickened product Qu and the particle settling rate of the solid-phase slurry $kf(t)$ the latter being controlled by adding a flocculant to the feed flow. The actual values of controlling variables are determined from the working maps, which are compiled by numerical calculations of ordinary differential equations. This structure facilitates development of more complex controllers for the control system, but even a simple proportional controller significantly improves transient characteristics. The proposed model is based on the assumption of complete occlusion of suspended solids before entering the thickener and does not take into account interaction of particles during settling.

The research results of slurry dehydration the solid phase of which consists mainly of ultrafine particles are presented in [4]. This approach does not consider formation of controlling actions directly during the technological process to increase efficiency of thickening processes. In work [5] applies methods of computational fluid dynamics to optimizing design and performance of thickening operations. The authors use the model of balancing the number of particles. The approach requires additional research to form the information support of the control system of operational data on distribution of particles in the thickener and their physical-mechanical and chemical-mineralogical characteristics.

According to the results of fractional composition and magnetic analysis of iron ore concentrates of beneficiation plants of Kryvyi Rih basin [6], it is concluded that the causes of their dilution with silicate minerals are the following:

- unsatisfactory efficiency of the thickener in separating and removing poor aggregates and released non-metallic grains from the technological process prior to magnetic separation;
- extraction of grains of non-metallic particles and poor aggregates when forming magnetic flocs and lack of controlling actions to prevent this process in the thickener.

Article [7] proves that concentration of sands with and without displacement differs significantly during concentration of the flocculant solution. To apply the presented dependences to controlling thickening and desliming, it is required to consider differences in characteristics of individual mineral and technological varieties of ore materials, as well as contamination of ore particles. [8] considers removal of highly dispersed suspended solids from technological water in iron ore concentration. The disadvantage of this approach is application of chemical effects to thickening and desliming which complicates operational control of the processes.

In work [9] suggests maintaining constraints set by technological regulations for changing the following parameters in order to provide the optimal mode of thickener operation and subsequent technological stages of beneficiation:

- the level of sludge overflow in the thickener;
- the level of magnetite in the thickener tank;
- density of the thickened slurry in the thickener discharge.

In the existing automated control system (ACS), the overflow level is controlled automatically by changing the amount of water supplied to the feed chute of the thickener. The level of magnetite in the tank is measured by a magnetite level recorder RUM-3. The set level value is automatically maintained by regulating discharge of the thickened slurry.

Changes in thickened slurry discharge also significantly affect its density. The density value is determined by rapid laboratory analysis. However, a sufficiently long sampling period of the analyzed slurry and disturbing actions due to changes in the flow rate, density and composition of the initial slurry fed to the thickener do not guarantee maintenance of density in slurry discharge within technological regulations.

Article [10] proposes an evolutionary algorithm for synthesizing a neural network model by using data collected from an ore beneficiation plant. This approach requires additional research to form the information support of the system of optimizing concentration processes with operational data on their parameters.

Work [11] provides the results of systematic investigations into flocculation characteristics, settling and consolidation of ore tailings by using different polyacrylamide flocculants. The disadvantage of this approach consists in application of chemical effects to thickening and desliming which complicates operational control of the processes.

[12] investigates into slurry processing by ultrasound and its influence on electrochemical and flocculation processes to increase efficiency of settling processes. It is established that ultrasound can significantly improve concentration of the outflow, while its frequency and power are the most important factors. However, application of the above methods of ultrasonic effects to thickening when processing several mineral and technological varieties of ore requires additional research.

Article [13] proposes to use measurements of the phase velocity of ultrasound propagation and attenuation in slurries. The proposed method of calculating the phase velocity avoids ambiguity with the phase unfolding, if the medium is weakly dispersed. The results indicate that the phase velocity of ultrasound increases as the number of fine particles in the slurry grows. Dispersion occurs due to the available solid phase and correlates with its mass fraction. The results of the attenuation experiments show that it is possible to inversely calculate slurry properties by adjusting the model to the experimental data, if the size distribution of the solid phase particles is known. It is concluded that accuracy of these calculations is difficult to determine, and therefore, it requires further research in this area. It should be noted that the proposed method does not allow distinguishing the effect of the particle size of the solid phase caused by density of the medium on the measurement results. These circumstances cause errors in determining the nature of solid particles distribution in the thickener and, consequently, increase the useful component loss due to inconsistency of parameters of ore particles and the amount of input and output products of the thickener.

3. Proposed methodology

Technological processes of ore beneficiation plants involve multistage crushing and grinding of ore (Fig. 1) to prepare it for subsequent separation [14-16]. The operations are aimed at releasing ore aggregates and separating particles of different minerals from each other by reducing the grain size to 0.1 mm or less [16-17].

Fig. 1presents a flowchart of Ore Concentration Plant-1 (OCP-1) of the PJSC *Pivnichnyi GZK*.

The flowchart contains the following symbols:

γ=38.86 is the middling product/tailings yield in technological flows, %;

β=13.8/2.8 is $Fe_{tot/mag}$ content in the middling product, %;

ε=15.24 is the useful component release;

C=186.7 is the recycle (%).

The dashed line (–·–·) shows the points of water supply to the technological process.

Despite some differences in technological operations and beneficiation units, such a flow chart can be considered typical for most national GZKs.

In the general case, when particles of the ore material differ in several (n) physical properties and at the same time they contain (m) components to be considered, fractional composition is evaluated by n-dimensional functions considering separation characteristics [18-19]. The yield of the i-th product is determined by the formula:

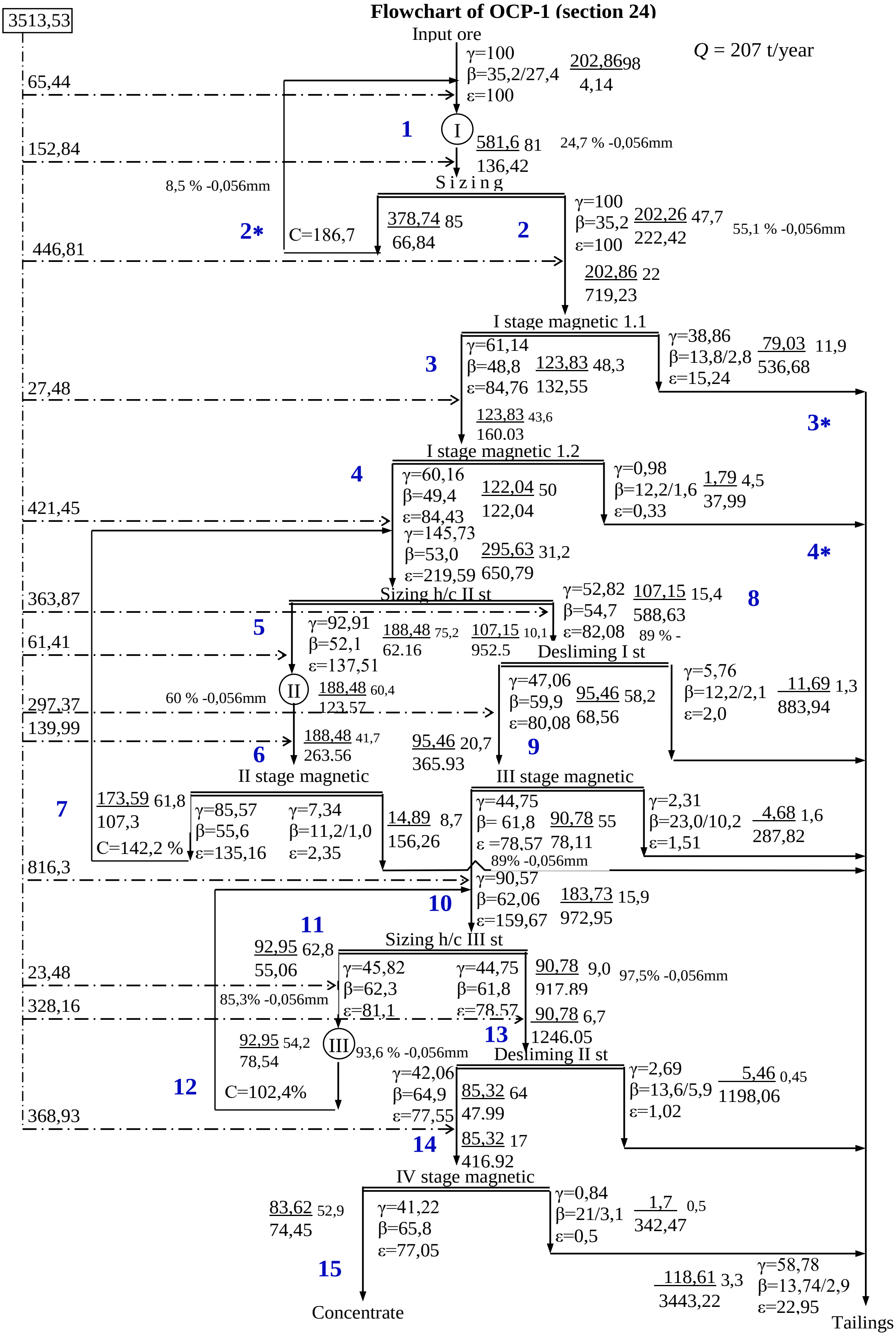

Figure 1: Flowchart of the iron ore concentration line with control points of solid-phase slurry characteristics

$$\overline{\gamma_i} = \int \cdots_{\Omega} \int K_i\,(\xi_1, \ldots, \xi_n)\gamma_{in}\,(\xi_1, \ldots, \xi_n)d\xi_1, \ldots, d\xi_n \tag{1}$$

the j-th component content in the i-th product is

$$\overline{\beta_{\iota J}} = \frac{1}{\overline{\gamma_\iota}} \int \cdots_{\Omega} \int \beta_j\,(\xi_1, \ldots, \xi_n)k_i\,(\xi_1, \ldots, \xi_n)\gamma_{in}(\xi_1, \ldots, \xi_n)d\xi_1, \ldots, d\xi_n \tag{2}$$

where Ω is the n-dimensional space of changed physical properties of the ore material.

An example of comparing the useful component content in a certain grain-size class to the yield of this class distributed along the technological beneficiation line is presented in Fig. 2

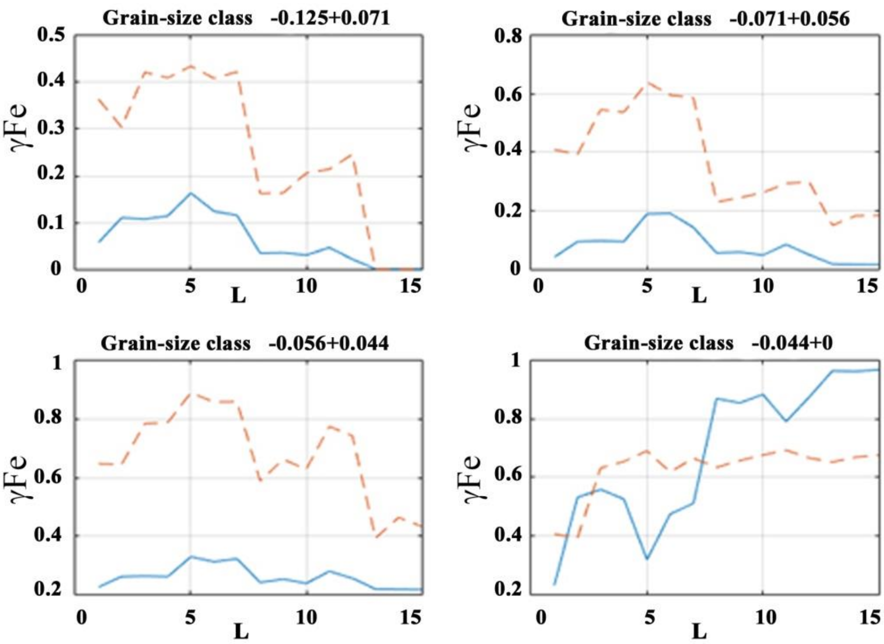

Figure 2: Useful component content of a particular grain size class and the yield of this class distributed along the technological line

The analysis results of phases and composition of iron ore concentrates presented in [6,18] convincingly show a dependence of magnetic separation on efficiency of the desliming process, which, in turn, proves relevance of developing and implementing control parameters, technical devices and automatic desliming control systems to increase its efficiency.

The grain size distribution of solid-phase slurry particles and changes under the influence of various factors have a particular impact on the efficiency of various technological operations of the ore beneficiation process [19-21].

To determine the phase and fractional composition of the slurry, it is advisable to use ultrasonic measurement methods [22-25]. The attenuation value and the ultrasonic propagation velocity are used as measured parameters. Attenuation of ultrasonic oscillations propagating in the ore slurry during its free settling in the thickener is determined by both the particle size and density of the medium. These factors condition components of ultrasound scattering and absorption in the ore slurry.

In order to separate the effect of solid-phase particle size caused by medium density on the results of ultrasonic attenuation measurements, it is proposed to use a separate measuring channel, which evaluates the scattering component in the total ultrasonic attenuation coefficient.

It is convenient to use the approach proposed in [24] to evaluate ultrasonic scattering on liquid-suspended particles. The kinetic equation, the solution of which is the function $I_\lambda(\vec{r}, \overrightarrow{\Omega})$ can be obtained by considering the energy balance in the elementary volume of the phase space

$$\overrightarrow{\Omega} = \nabla I_\lambda(\vec{r}, \overrightarrow{\Omega}) = -\Sigma(\lambda) I_\lambda(\vec{r}, \overrightarrow{\Omega}) + \int d\Omega'\, \Sigma_s(\overrightarrow{\Omega}' \to \overrightarrow{\Omega}) I_\lambda(\vec{r}, \overrightarrow{\Omega}') + S_\lambda(\vec{r}, \overrightarrow{\Omega}) \tag{3}$$

where $\Sigma(\lambda) = \Sigma_{-}(\lambda) + \Sigma_S(\lambda)$; $S_\lambda(\vec{r}, \overrightarrow{\Omega})$ is a function of ultrasonic source radiation density which determines the average amount of energy radiated per unit time by a unit phase volume.

Phase coordinates are variables r and Ω, the elementary phase volume is determined by the product $d\vec{r} \cdot d\vec{\Omega}$. This equation denotes the following: the change in ultrasonic beam intensity with the direction Ω at the point $\vec{r}$ is primarily due to its weakening-absorption and scattering (the first term of the right part); secondly – the scattering of the energy flow, which previously had the direction $\vec{\Omega}'$, towards $\vec{\Omega}$ (the second term in the right part), and finally, due to the energy coming into this beam from sources (the last term of the right part). Equation (3) is reduced to the integral equation

$$I_\lambda(\vec{r}, \vec{\Omega}) + \int d\vec{r}' \int d\vec{\Omega} \sum\nolimits_s (\vec{\Omega}' \to \vec{\Omega}) \frac{e^{-\tau(\vec{r}', \vec{r}, \lambda)}}{|\vec{r} - \vec{r}'|} \times \delta \left[\vec{\Omega} - \frac{\vec{r} - \vec{r}'}{\vec{r} - \vec{r}'} \right] I_\lambda(\vec{r}', \vec{\Omega}') + I_\lambda^0(\vec{r}, \overrightarrow{\Omega}) \tag{4}$$

where $\tau(\vec{r}', \vec{r}, \lambda) = \sum(\lambda) |\vec{r} - \vec{r}'|$, $\delta(\cdot)$ is the Dirac delta function.
$I_\lambda^0(\vec{r}, \vec{\Omega}) = \int_0^\infty S_\lambda(\vec{r} - \xi \, \vec{\Omega}, \vec{\Omega}) \, e^{-\tau(\xi, \lambda)} d\xi$ is a free term of integral equation (4), which determines intensity of the scattered ultrasonic wave; $\xi = |\vec{r} - \vec{r}'|$.

In this case, additional data is obtained by measuring amplitude (intensity) of scattered ultrasonic oscillations by additional receiver 3 (Fig. 3).

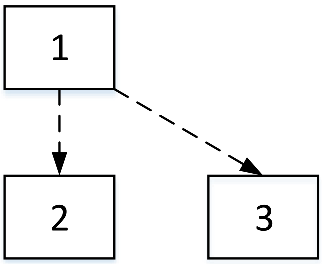

Figure 3: Measuring channel with the additional receiver for evaluating ultrasonic wave scattering

The amplitude of scattered ultrasonic oscillations measured by receiver 3 is described in some approximation by the following expression

$$A_s = KN \left[\int_o^{r_m} F(r) \sigma_s(v, r) dr \right] A_o \, exp \left[-NZ \int_o^{r_m} F(r) \sigma_s(v, r) dr \right] \tag{5}$$

where K is the coefficient considering the geometric factors of the measuring system;
Z is the distance passed by the ultrasound from radiator 1 to receiver 3 in accordance with the geometry of the measuring channel;
N is the number of particles in the effective controlled volume (V) of the slurry;
$\sigma(v, r)$ is the ultrasound attenuation cross section of the frequency v on a spherical solid particle of the radius r;
$F(r)$is the size distribution function of the solids of the slurry.

It is assumed that the directional cones of the radiator and the receiver intersect and therefore the parameters of waves scattered only in the central area of the controlled medium are measured.

Receiver 2 measures the amplitude of the wave passing through the controlled medium which is determined by the expression

$$A_v = A_o \, exp \left[-NZ \int_o^{r_m} F(r) \sigma(v, r) dr \right] \tag{6}$$

where A_0 is the amplitude of the ultrasonic wave in pure water.

According to the results of measurements A_s, A_v and A_0, a signal is formed

$$S = \frac{A_s}{A_v \, \ln(A_0 / A_{v)}} = \frac{K}{Z} \frac{\int_o^{r_m} F(r) \sigma_s(v, r) dr}{\int_o^{r_m} F(r) \sigma(v, r) dr} \tag{7}$$

This signal depends only on the particle size distribution, which means that its value can condition particle size distribution of the medium under study.

When using this method, the choice of ultrasonic frequency should depend upon commensurability of absorption and scattering coefficients, i.e.

$$\sigma_v \approx \sigma_s$$

Thus, ultrasound frequency should not be too high, as in this case, the information about the particle size is lost, yet it can not be too small either, because at low frequencies there is no scattering of waves on particles. For particle sizes of ground materials, which are characteristic of beneficiation, the above condition is met within the frequency range (3-8)$\cdot 10^5$ Hz.

4. Results

The amplitude-frequency characteristic of the signal reflected from the reflector of ultrasonic oscillations depends on distribution of solid-phase particles of the ore slurry during their free settling with parameters determined by both the particle size and slurry density.

The proposed ACS of thickener 1 (Fig. 4) contains waveguides 2, 3, 4 with radiating piezoelectric transducer 5 and receiving piezoelectric transducers 6, 7 mounted on them. Master generator 8 at the command of computing control unit 9 generates a trigger pulse of normalized amplitude and duration, which through logic circuit OR 10 enters the input of controlled generator of electromagnetic sinusoidal oscillations 11 which is turned on for the period of pulse duration.

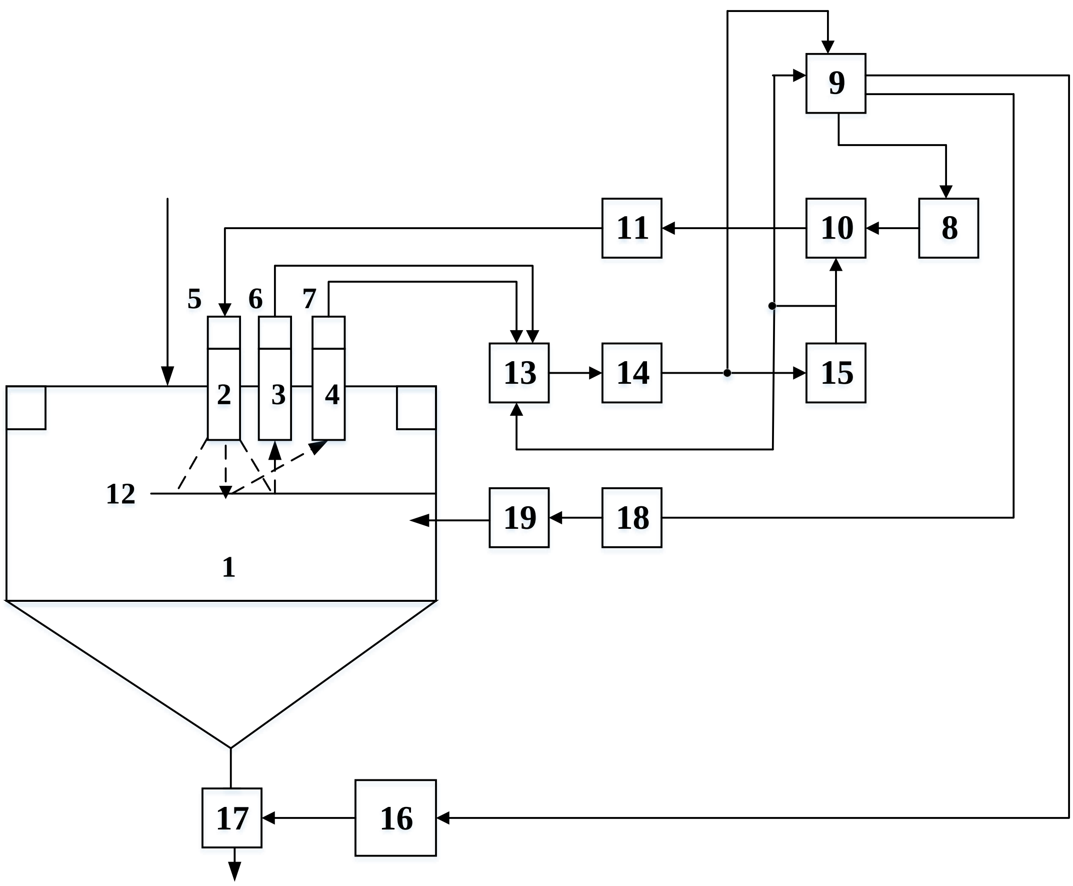

Figure 4: Ultrasonic control-based ACS of the thickener

The train of ultrasonic oscillations is formed by radiating piezoelectric transducer 5 and is radiated through waveguide 2 in the direction of ultrasonic wave reflector 12 in thickener tank 1. Reflected ultrasonic oscillations are fed to receiving amplifier 14 through waveguides 3, 4, receiving piezoelectric transducers 6, 7 and selection unit 13. Thus, two signals are formed at the output of receiving amplifier 14, the amplitude of one of which is A_{ν} and that of the other – A_s. In computing and controlling unit 9, values of S are calculated to characterize particle size distribution of the studied medium.

Pulse generator 15 on the signal from receiving amplifier 13, through logic circuit OR 10 restarts controlled generator of electromagnetic sinusoidal oscillations 11. The frequency of the pulses formed in this way is a function of distance to reflector 12 of ultrasonic waves and the ultrasonic propagation velocity.

$$f = \nu /2d \tag{8}$$

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

In liquid media, ultrasound propagates in the form of volume rarefaction-compression waves, and the process occurs adiabatically, i.e. the change in temperature in the sound wave does not have time to equalize. The adiabatic speed of sound is determined by the pressure transfer rate:

$$C = \sqrt{\left(\frac{dP}{d\rho}\right)_s} \tag{9}$$

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

The ultrasound velocity can also be expressed in the following form:

$$C = \sqrt{\frac{K_{\alpha\partial}}{\rho}} = \sqrt{\frac{1}{\beta_{\alpha\partial}}} = \sqrt{\frac{\gamma}{\beta_{u з} \cdot \rho}} \tag{10}$$

where $K_{\alpha\partial}$ is an the 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
$\beta_{u з} = \gamma \cdot \beta_{\alpha\partial}$ is isothermal compressibility
$\gamma = \frac{C_p}{C_\nu}$ is a ratio of heat capacities at constant pressure and volume.

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

In order to increase noise immunity of the measurement results, the frequency of pulses generated by master generator 8 is selected to be an order of magnitude less than that of circulating pulses. Therefore, with no reflected signal, for example, in case of a foreign object entering the control plane, master generator 8 after some time restarts controlled generator of electromagnetic sinusoidal oscillations 11 and the system resumes.

On the basis of the calculated value *f*, computing control unit 9 by means of actuator 16 and executive organ 17 regulates consumption of the thickened product of thickener 1 to stabilize its density.

In the task of determining the optimal flow rate of the condensed product of the thickener to stabilize its density, the vector of parameters of the membership functions of the terms of the input variables and the vector of coefficients of linear functions in the conclusions of the rules are formed based on the measured values of the flow rate of the input pulp flow, the characteristics of the density and fineness of the pulp at a fixed depth of the thickener. The procedure for forming these dependencies is carried out in ANFIS (Adaptive Neuro-Fuzzy Inference System) - the editor of the Matlab package. ANFIS - editor automatically synthesizes a neuro-fuzzy network from experimental data, which can be considered as one of the varieties of fuzzy inference of the Takagi-Sugeno type.

Practical approbation of the developed theoretical, algorithmic and software and hardware solutions was carried out on pilot plants and on the experimental base of the laboratory of ultrasonic measurements of the Krivoy Rog National University. The experimental plant is based on an

Advantech IPPC-7157A industrial panel computer equipped with PCI boards for data acquisition and storage. The connection diagram of individual devices is shown in fig. 5.

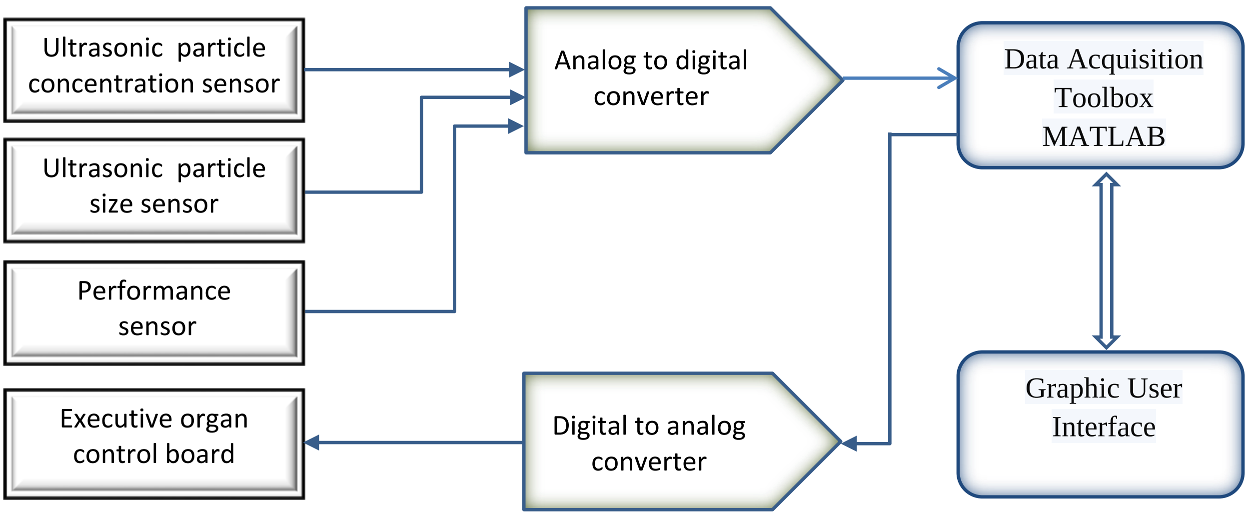

Figure 5: Block diagram of the experimental plant

The structure of the TS 3508 model is shown in fig. 6. The implementation of the logical operation AND (andMethod) was carried out by the method of product (prod), the logical operation OR (orMethod) - by the method of probabilistic OR (probor). The implementation of the implication (impMethod) is performed by the minimum method (min), and the operations of combining membership functions of the output variable (aggMethod) - by the maximum method (max). For defuzzification (defuzzMethod), the weighted average method (wtaver) was used.

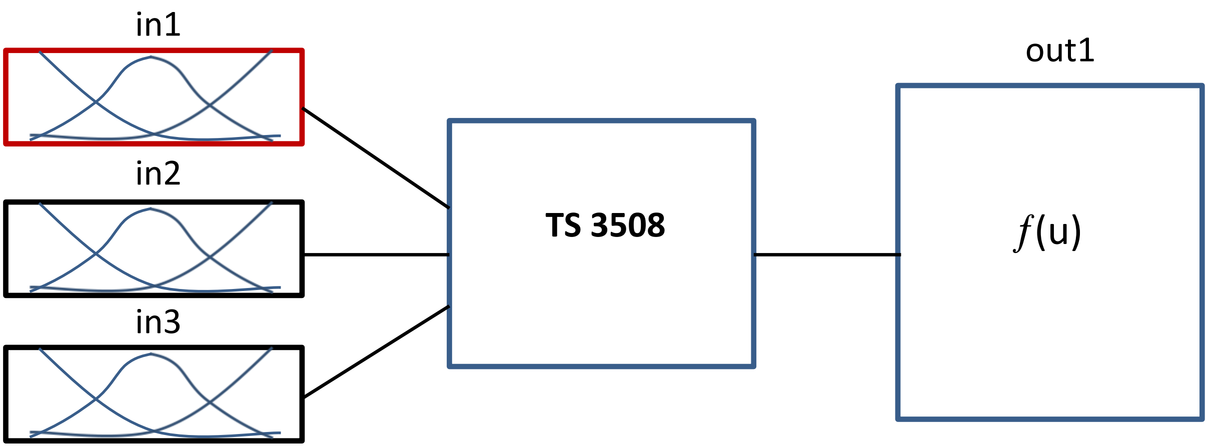

Figure 6: Structure of the TS 3508 model

Thus, by means of fuzzy logical inference, in accordance with the algorithm used, the optimal flow rate of the condensed product of the thickener is determined.

The calculated values of S are used to control the settling rate of solid-phase particles by controlling the amount of supplied flocculant through actuator 18 and controlling element 19.

Defined parameters allow maintaining productivity of the desliming process in accordance with ore slurry characteristics without losing the useful component. Due to obtained operational information about characteristics of solid-phase slurry particles already at its initial settling stage, it is possible to reduce transient duration in the ACS.

According to the results of industrial testing of the ultrasonic control-based ACS of the thickener, it is established that its use within the TP ACS of iron ore raw material concentration at mining enterprises of Kryvyi Rih iron ore basin will reduce Fe_{mag} losses by 0.6% - 0.7%.

5. Conclusions

It is shown that on the basis of the Takagi-Sugeno fuzzy inference and the results of ultrasonic measurements, an optimal control of the ore pulp desliming process can be formed. To form the optimal flow rate of the condensed product of the desludger and stabilize its density, the vector of parameters of the membership functions of the terms of the input variables and the vector of coefficients of linear functions in the conclusions of the rules are formed on the basis of the measured values of the flow rate of the input pulp flow, the characteristics of the density and fineness of the pulp at a fixed depth of the desludger. The procedure for forming these dependencies is carried out in ANFIS (Adaptive Neuro-Fuzzy Inference System) - the editor of the Matlab package. The control of the settling rate of particles of the solid phase of the pulp is carried out by changing the amount of flocculant supplied using a similar algorithm. This channel is considered as an additional opportunity to improve the quality of deslimer control for ore materials characterized by highly heterogeneous physical-mechanical and chemical-mineralogical properties.

The proposed approach allows considering the nature of grain-size distribution of solid-phase particles of the ore material in the thickener, establishing characteristics of its output products in accordance with parameters of ore particles settling and thereby reducing useful component losses by 0.6%- 0.7%. Determining already at the initial settling stage such characteristics as dynamics of changes in density of the solid-phase slurry and its particle size distribution enables considering fluctuations in parameters of the technological flow, this being achieved by changing both the amount of flocculants and the pumping rate of the underflow.

6. References

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