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DEVELOPMENT OF METHOD TO ASSESS SEPARATION PROCESS TAKING INTO ACCOUNT RHEOLOGICAL PROPERTIES OF MINERAL SLURRY

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DEVELOPMENT OF METHOD TO ASSESS SEPARATION PROCESS TAKING INTO ACCOUNT RHEOLOGICAL PROPERTIES OF MINERAL SLURRY

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This article considers the possibility of developing a methodology for assessing the separation process of gold-sulfide raw materials, taking into account the rheological characteristics of the mineral suspension. The object of the study is the ore of the Mayskoye deposit, which is subjected to fine crushing followed by cyanidation, so the consideration of rheological properties is the most important aspect of achieving the necessary enrichment performance. In the course of the research, using the object-oriented programming language Python 3.8, a program for calculating the empirical coefficients of the three-component rheological equation was developed. The resulting equation is the determinant for the shear stress within the suspension as a function of the velocity gradient. The developed program has been used to calculate coefficients of rheological equations for three variants of solid concentration in feed which correspond to the minimum, average and maximum for hydrocyclone used in the research (400 g/l, 500 g/l and 700 g/l respectively). Then, using the Ansys Fluent software, the multiphase classification modeling problem in the hydrocyclone was solved, resulting in shear rate profiles in the cross-section of the apparatus, from which the conditions necessary for the suspension to reach a fully dispersed state were concluded. It was determined that solid concentration 400 g/l is the optimum value that ensures maximum dispersion of the mineral slurry.

Key words: rheology, hydrocyclone, ansys fluent, Python, CFD modelling, gold sulfide ores

INTRODUCTION

These days, the availability of easy-to-process ores is steadily decreasing, resulting in the need to process ores that are classified as complex or low-grade, as well as, for example, ash and slag waste [1].

This results in new challenges for the enrichment industry, because often these types of ores must be subjected to a deeper grinding stage than conventional ores, or they contain organic carbon, which is one of the refractory factors [2]. It is also known that the presence of organic carbon, has a significant impact on the rheological parameters of mineral suspensions, as well as the content of clay minerals [3].

The mixing of a liquid continuous and a solid discrete medium creates a new continuous medium, a suspension, whose properties differ from the properties of the individual components [4].

The relationship between shear stress and shear rate is reflected by the flow curve (Fig. 1). Non-Newtonian suspensions are subdivided into pseudoplastic, Bingham, dilatant, and others, but most mineral suspensions exhibit pseudoplastic behavior. Speaking about Bingham suspensions it should be noted that there is a certain critical shear stress (τ_0) due to the presence of small particles or large molecules interacting with each other. This behaviour creates a weak solid structure that must be broken by overcoming the critical shear stress to make particles move with the liquid under viscous forces.

There are a large number of rheological models to describe the performance of such fluids, including Newtonian, Bingham, Herschel-Balkley, Cisco, Caro, and others [5].

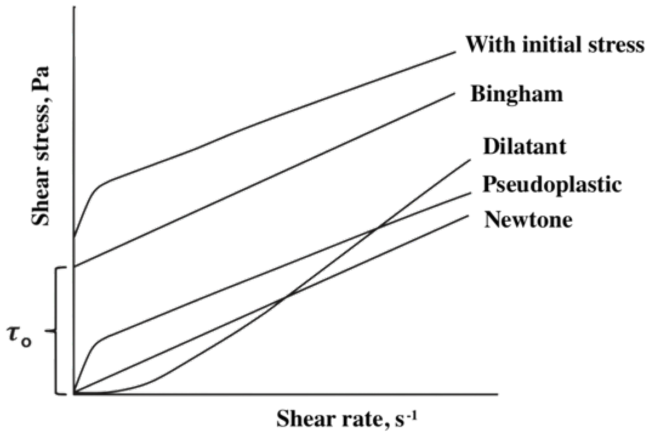

Figure 1: Flow curves for various fluids

It is generally accepted that the rheological parameters of mineral suspensions have a significant influence on enrichment processes, including grinding [5,6], transport [7] and flotation [8–10].

Classification processes are no exception, in particular, classification using the hydrocyclone. Many works [5,11,12] are devoted to studying the influence of the rheology of mineral slurry on the separation process in the hydrocyclone. The complexity of understanding the rheology of the slurry in the hydrocyclone is due to the complexity of the flows being formed, and, therefore, many scientists have been working on this problem for many years [13–16].

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The viscosity of the medium affects the formation of the air column along the hydrocyclone axis. The effect of viscosity on separation in the hydrocyclone has been repeatedly confirmed by CFD modelling [17,18]. The efficiency of the hydrocyclone is quite sensitive to changes in the rheology of the mineral slurry: a relatively low viscosity value is preferable for optimum operation.

Gold-sulphide ores of Mayskoye deposit contain finely dispersed gold which signifies that there is a need for an ultrafine grinding process for sufficient intergrowth liberation. Further stages of mineral processing operations are highly influenced by the rheological properties of the slurry. In this regard, the development of gold-sulfide carbonaceous ore enrichment technology taking into account the rheological properties of mineral slurry is an important task, which can be solved through experimental and theoretical research, development of methods for assessing the separation process and the use of specialized software.

The development of existing and innovative technologies of enrichment of raw materials is impossible without the use of these tools, which leads to a wide range of computational instruments, the effectiveness of which is confirmed by the mass of works devoted to numerical and mathematical modelling [19–21]. Combining these tools in a unified approach makes it possible to develop a methodology for evaluating the separation process allowing the selection of optimum process parameters which is described in this article.

MATERIALS AND METHODS

In this paper, the influence of slurry rheology on the classification process in the hydrocyclone is considered using an experimental-theoretical approach, object-oriented programming and hydrodynamic simulation software. The scheme of conducting the study is shown in Fig. 2.

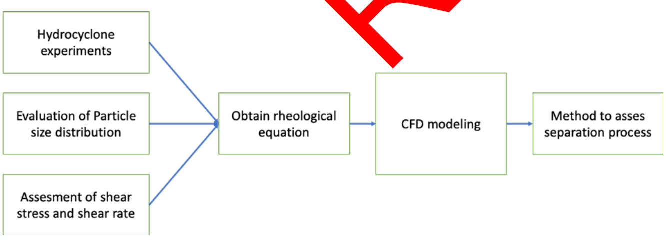

Figure 2: Scheme of experimental-theoretical research

For the experiments on the separation of the suspension, the setup is shown in Fig. 3 (a) was used. The unit is equipped with Rheotest RN 4.1 rotational viscometer to measure shear stress and shear rate of mineral slurry.

The experiment on the laboratory unit was conducted using gold-sulfide ore (particle size distribution shown in Fig. 4) of the Mayskoye deposit, which passed the grinding stage for 20 minutes.

The particle size distribution of the separation products and feed material was investigated using Malvern Mastersizer 2000 Hydro S laser diffraction particle size analyzer.

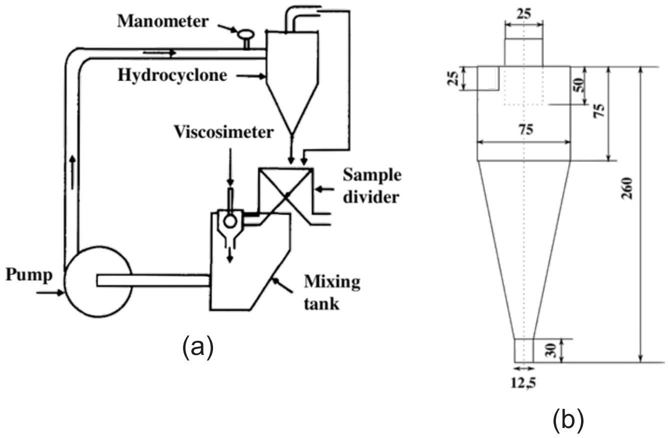

Figure 3: Installation of classification on the hydrocyclone: a) scheme of the installation; b) drawing of the hydrocyclone

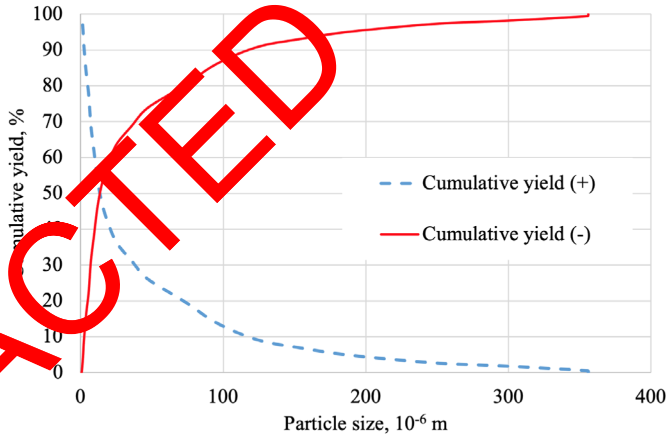

Figure 4: Feed particle size distribution

Numerical Simulation

Numerical modelling of the hydrocyclone was performed using Ansys Fluent software, which is based on the finite element method (FEM).

The Reynolds stress model was chosen as the turbulence model in this paper, in which the transport equations (1) are solved for individual Reynolds stresses $\overline{u_i' u_j'}$ [22].

$$\frac{\partial}{\partial t}\left(\rho\overline{u_i' u_j'}\right)+\frac{\partial}{\partial x_k}\left(u_k\rho\overline{u_i' u_j'}\right)=\varphi_{ij}+P_{ij}+D_{T,ij}+D_{L,ij}-\varepsilon_{ij}+F_{ij} \quad (1)$$

To describe the gas-liquid interaction, the Volume of Fluid model was used, in which the interface between the phases is traced by solving the continuity equation for the volume fraction of one (or more) phases. For the q-th phase, this equation has the following form (equation (2)):

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right)+\nabla\cdot\left(\alpha_q\rho_q\vec{V}_q\right)=S_{a_q}+\sum_{p=1}^{n}\left(\dot{m}_{pq}-\dot{m}_{qp}\right)\right] \quad (2)$$

where $\dot{m}_{pq}$ – mass transfer from phase p to phase q, a $\dot{m}_{qp}$ – mass transfer from phase q to phase p.

Also important is the description of fluid motion in the hydrocyclone. The general equation of motion of the mineral slurry can be derived from the well-known equation of fluid dynamics in stresses:

$$\rho\frac{d\bar{v}}{dt}=\rho\bar{F}+divP \quad (3)$$

where ρ – fluid density; $\bar{v}$ – absolute flow velocity vector; t – time; $\bar{F}$ – vector of mass forces; P – stress tensor in the liquid.

The deviatoric part of the tensor can be represented by the shear stress function, which in turn can be described by the rheological equation reflecting the dynamics of internal structural transformations in mineral suspensions and making it possible to determine the shear stress depending on velocity gradients. Then the equation can be rewritten, taking into account the decomposition into parts in the form:

$$\rho\frac{d\bar{v}}{dt}=\rho\bar{F}\text{-}grad\ p+div\left(\sum_{k=1}^{n+1}\varphi_k e^{-t_k\dot{\gamma}_{ij}}+\mu\dot{\gamma}_{ij}\right) \quad (4)$$

where p – average hydrostatic pressure in the stream; φ – coefficient of the rheological equation; μ – dynamic viscosity coefficient; γ_{ij} – shear rate.

Equation (4) is a modified Navier-Stokes equation with a term - $\Sigma_{k=1}^{n+1}\varphi_k e^{-t_k\dot{\gamma}_{ij}}$ taking into account properties of mineral suspension and can be taken as an equation of motion in vector form. In general, this term is described by equation (5):

$$\tau=A_1e^{-\alpha_1\dot{\gamma}}A_2e^{-\alpha_2\dot{\gamma}}+\mu_T\dot{\gamma} \quad (5)$$

where μ_T – coefficient of dynamic viscosity of the dispersed suspension. This equation is the determinant for the shear stress within the suspension as a function of the velocity gradient. It includes the shear stress, the stress characterizing the internal strength of the structure and the viscosity stress of the dispersed suspension. The graphical interpretation of the equation is shown in Fig. 5.

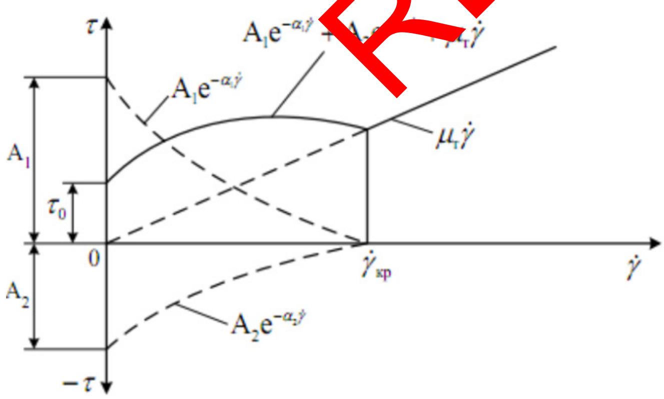

Figure 5: Graphical interpretation of the mineral suspension rheological equation

The part of the curve between 0 and γkp reflects the anomalous viscosity, which is caused by the presence of structured flow. Above the shear rate threshold, the suspension obeys the laws of motion of a Newtonian fluid. This modification of the Navier-Stokes equation was applied to the classification problem in the hydrocyclone in the Ansys Fluent software.

Calculation of the coefficients of the rheological equation was carried out using the developed program in Python 3.8 [23] (Fig. 6).

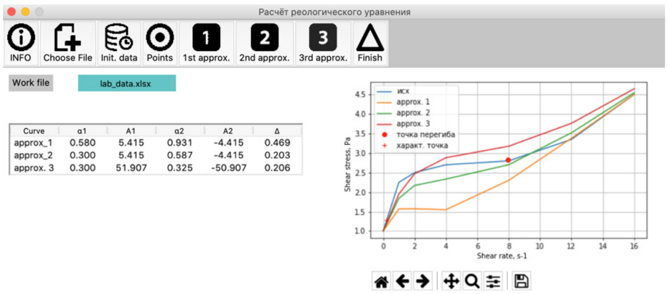

Figure 6: Interface of the developed program

The initial data for calculations are the data obtained by a viscometer - shear rate and shear stress. The principle of operation of the program (Fig. 7) consists of consecutive approximations of the theoretical curve to experimental data, which results in a set of curves, from which, based on statistical conclusions the one that best describes the original data is selected.

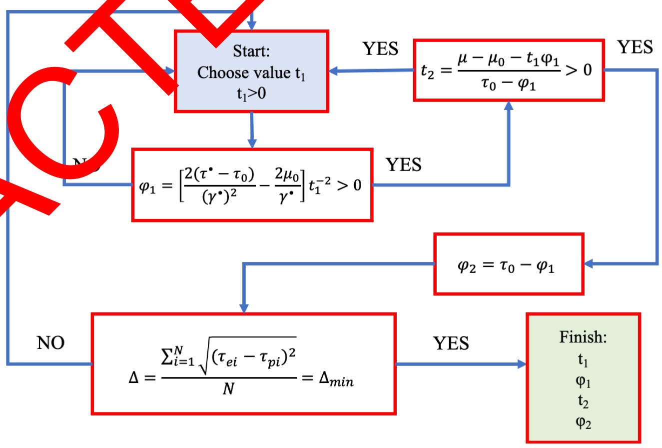

Figure 7: Calculation algorithm of the coefficients of the rheological equation

RESULTS AND DISCUSSION

Taking into account the technological properties of laboratory hydrocyclone unit and Mayskoye deposit ore, three variants of solid concentration have been chosen to investigate the influence of rheological parameters of mineral suspension on the classification process. Since the purpose of the paper is the development of a separation process assessment technique, the chosen concentrations correspond to the minimum, average and maximum value of solid content in the feed for hydrocyclones.

In the particular case, for different values of solids content in the slurry (400 g/l; 500 g/l; 700 g/l), three equations ((6), (7) and (8) respectively) of the form (5) were obtained using the developed program that utilizes the algorithm presented on Figure 7. These equations describe the relationship between shear stress and shear rate in suspension.

$$\tau=5,415e^{0,580\gamma}\text{-}4,415e^{0,931\gamma}0,281\gamma \quad (6)$$

$$\tau=3{,}120e^{0{,}441\gamma}-2{,}190e^{0{,}881\gamma}\,0{,}602\gamma \quad (7)$$

$$\tau=2{,}919e^{0{,}901\gamma}-1{,}989e^{0{,}765\gamma}\,0{,}712\gamma \quad (8)$$

These equations theoretically describe the dynamics of internal transformations in the pulp and were used as rheological equations in further modelling of the classification process in the hydrocyclone using the Ansys Fluent software.

The following boundary conditions were set in Ansys Fluent:

Table 1: Boundary conditions

Parameter	Value
Inlet velocity	2,28 m/s
Outlet pressure	101325 Pa
Number of phases	2
Turbulence intensity	5%

The calculation of the hydrocyclone model in the Ansys Fluent software was performed in several stages. The first stage was the calculation in Steady State mode, i.e., independent of time. Using the Reynolds stress model at this stage, a stable pattern of pressure in the apparatus profile was obtained (Fig. 8 (a)).

Then followed the Transient calculation step, which is directly dependent on time. During 10^4 iterations with a time step of 10^{-4} s, the internal air column is formed (Figure 8 (b)) as a result of the reduced pressure along the axis. In the model, this is described in the form of the Backflow Volume Fraction boundary condition on the overflow and underflow outlets.

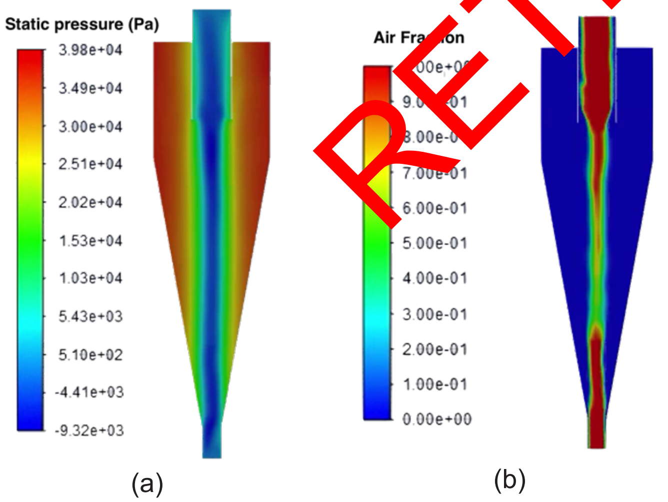

Figure 8: Calculation of the multiphase flow problem in Ansys Fluent:

a) pressure distribution; b) air core formation

At the third stage of calculation, the particle trajectories were calculated. The particle size distribution of the hydrocyclone feed is specified by the Rosin-Rammler distribution (equation (9)) in the Ansys Fluent software.

$$Y_d=e^{-\left(d/49\right)^{0{,}853}} \quad (9)$$

where Y_d – mass fraction of particles, d – particle size.

The calculation results of the hydrocyclone model for various viscosity values are shown in Fig. 9-11.

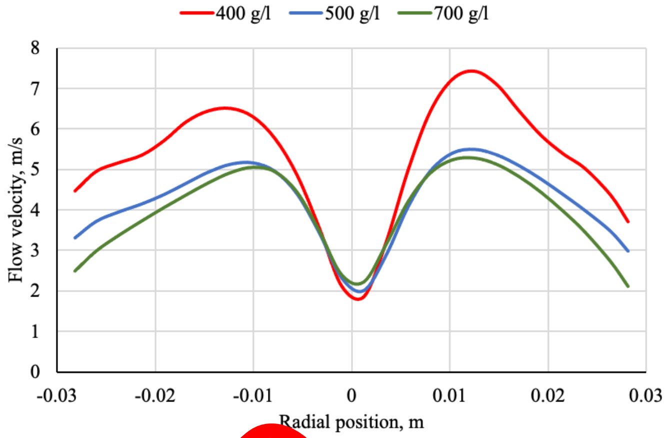

Figure 9: Velocity distribution in the upper part of the hydrocyclone at different viscosity values

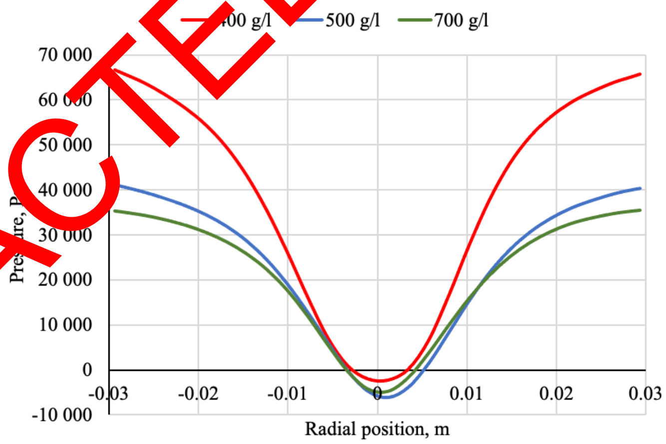

Figure 10: Pressure distribution in the upper part of the hydrocyclone at different viscosity values

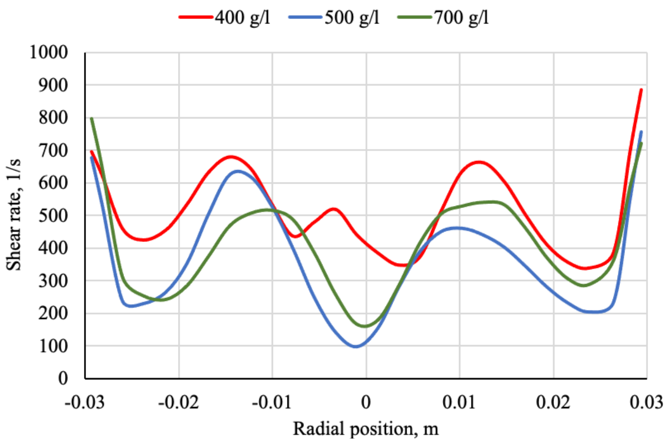

Figure 11: Distribution of shear rates

Based on the statistical data presented in Table 2, we can conclude about the optimal viscosity value at which the necessary velocity profile is formed.

With a minimum standard deviation, the solid content of 400 g/l in feed is optimum because it ensures that the

Table 2: Statistical parameters of shear rate distributions

Parameter	400 g/l	500 g/l	700 g/l
Mean value, s^{-1}	523,791	380,557	419,911
Standard deviation	134,699	173,211	158,942
Minimum value, s^{-1}	339,266	97,994	165,287
Maximum value, s^{-1}	885,536	757,120	796,984
Critical shear rate, s^{-1}	281	602	712

shear rate in the flow reaches a value greater than the critical one, which is determined by the three-component rheological equation. Under such conditions, the maximum dispersion of the mineral slurry is achieved, and thus a more accurate separation into size classes, which in turn has a positive effect on further beneficiation processes such as cyanidation and flotation.

CONCLUSIONS

As a result of experimental-theoretical research, the rheological equation of mineral suspension depending on the content of solids in the slurry was clarified. For this purpose, a program in Python 3.8 language was developed, which allows calculating the empirical coefficients of the rheological equation. Then, using the Ansys Fluent software, the problem of gold-sulfide raw material classification in the hydrocyclone was set and solved based on a series of full-scale experiments and modification of the Navier-Stokes equation in accordance with the rheological equation derived earlier.

Statistical analysis of slurry flow in hydrocyclone in terms of shear rate showed that the optimal content for the particular case is 400 g/l, which results in maximum dispersion of mineral slurry of this type. Thus, the method of evaluation of the mineral suspension separation process taking into account its rheological properties was developed and tested.

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