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DETERMINATION OF THE PRESSURE FLOW PARAMETERS OF A STRUCTURED SUSPENSION

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Abstract. The subject of the research is the methods of calculating the parameters and flow regimes of structured suspensions, which have significant potential for substantial reduction in energy consumption and specific water consumption of all hydromechanization technologies used in mining enterprises. The main topic of the research is the stability of the suspension structure and uniform distribution of particles of its solid phase throughout the volume during pressure flow through the pipeline. The aim of the work is to establish dependencies on the relative radius that defines the flow area where the suspension structure is not destroyed, not only on the rheological characteristics of the suspension and hydraulic flow parameters but also on the gravitational and repulsive forces between the particles of the solid phase of the suspension, which have an ion-electrostatic and Van der Waals nature. It is established that forces having ion-electrostatic and Van der Waals nature lead to a decrease in the maximum value of the relative radius, at which the suspension structure is still preserved during its flow in the pipeline, since the addition that takes into account their influence is always positive and subtracted from the addition that takes into account the relationship between the initial tangential stress and the hydraulic frictional stress on the inner surface of the pipe. The range of existence of the addition that takes into account the influence of forces having ion-electrostatic and Van der Waals nature and the range of variation of its values at different values of the parameter of the energy interaction of particles of the solid phase of the structured suspension are investigated. It is established that the dependence of this addition on the distance between particles of the solid phase of the suspension is maximum. The magnitude and coordinates of the maximum depend on the parameter of the energy interaction of the solid phase particles. It is established that with an increase in the value of the parameter of the energy particles interaction of the suspension solid phase, the maximum value of the addition decreases, and the coordinate of this maximum increases.

Keywords: structured suspension, radius of undeformed flow core, ion-electrostatic forces, pressure flow, pipeline.

1. Introduction

Since the beginning of the 21st century, an increasing number of specialists consider the use of structured suspensions (SS) as the most promising option for modernizing the technology of processing minerals [1–7]. The implementation of technology using the SS is particularly relevant for the Dnipropetrovsk region, where the main mining and beneficiation enterprises of the country are located, and water consumption, before the destruction of the Kakhovka hydroelectric power plant, exceeded the corresponding indicator of local sewage resources by 55 thousand times per year per capita. [8–10]. The areas of implementation of such modernizations at mining and metallurgical enterprises touch upon almost all technological chains where pipeline transport is used. In the future, the transition to high-concentration hydraulic mixtures will significantly reduce the energy intensity and specific water consumption of all hydromechanization technologies, starting from pulp forming means, including the transportation of spills from the extraction site to the processing site, and ending with the disposal and storage of beneficiation wastes. That is, it is a prospect to reduce the consumption of technical water by the Central, Southern, and Northern mining and beneficiation enterprises, as well as by the Vilnohirsk mining and metallurgical plant. In addition, advanced approaches to the storage of beneficiation wastes at mining and beneficiation enterprises, which envisage their reprocessing and utilization, are already being designed based on the use of the SS

[8–11].

Results of the analysis of methods for calculating parameters and flow regimes of the SS, conducted based on scientific publications in domestic [1–18] and foreign [19–29] sources, indicate that known calculation methods were developed somewhat for different conditions than hydromechanization technologies in mining enterprises, thus requiring refinement and scientific justification.

Traditionally, methods of the SS hydromechanics were considered for flows of polymer solutions of various concentrations in chemical technologies [13, 14] or clay solutions in drilling and well cementing technologies [30–32]. A separate direction of the SS hydromechanics, which has been most intensively developed during the 20th century, is considered to be technologies for the production and transportation of water-coal fuel [1–7, 18, 33, 34]. Only at the turn of the 20th and 21st centuries did the first technologies of pressure hydrotransport of processing waste in the form of SS appear [8, 9, 15], and later technologies for the development of technogenic deposits and deposits formed in artificial reservoirs began to be developed [6, 35, 36].

The initial studies already revealed that the most significant difference in the flow of the SS compared to the flow of low-concentration hydraulic mixtures, in which viscoplastic effects are not manifested, is the absence of a critical flow regime. Most SS, unlike other types of hydraulic mixtures, can exist in a stable state without the destruction of the structure with a uniform distribution of solid phase particles throughout the volume for several days. Historically, two approaches have emerged in studies of the SS stability and flow regimes. The first, oriented towards pressure flows of the SS, uses the relationship between the initial tangential stress and the hydraulic frictional stress on the inner surface of the pipe to determine the radius of the undeformed flow core. The second approach considers the coagulation of solid phase particles of the SS under the action of gravitational and repulsive forces having an ion-electrostatic and Van der Waals nature, the so-called stability theory of lyophobic colloids by Derjaguin – Landau – Verwey – Overbeek (DLVO). The second approach was initially developed for the stationary SS, such as water-coal fuel, which can be transported in tanks or other containers. Subsequently, it was used to model the process of SS deposition in pipelines during emergency shutdowns. Later, it began to be used to assess the stability of the suspension structure during its flow.

Both of these approaches have certain advantages and disadvantages. The first approach allows determining the boundary between areas in the cross-section of the pipeline where the suspension structure is preserved and destroyed. However, this approach takes into account only the pressure drop, geometric parameters of the pipe, and initial tangential stress, ignoring the influence of viscosity, particle size, and density, as well as their ion-electrostatic properties. The second approach takes into account the influence of ion-electrostatic and Van der Waals forces on the stability of the suspension structure and allows determining the concentration of the solid phase that disrupts the stability of the suspension structure. However, it does not take into account the rheological characteristics of SS and hydraulic parameters of the process and, in general, does not allow determining the boundaries of structure destruction during flow in the pipeline.

Experimental studies of pressure flow of SS in pipelines indicate that the valuesof the radius of the undeformed flow core obtained within the framework of the first approach cannot be applied at very small values and values close to unity [13, 14, 23]. The methods limit these intervals, considering that in the first case, the turbulent regime has already been realized, and in the second case, the laminar regime has already begun.

Thus, the purpose of the study is to establish dependencies on the relative radius defining the flow area where the suspension structure is not destroyed, simultaneously from the relationship between the initial tangential stress and the hydraulic frictional stress on the inner surface of the pipe and from the gravitational and repulsive forces between the solid phase particles of the SS, having an ion-electrostatic and Van der Waals nature.

2. Research Methods

According to the results obtained within the DLFO theory, the destruction of suspension structure, accompanied by the uneven distribution of solid phase particles throughout the suspension volume, occurs when the following condition is met [1, 12, 15–17]:

$$\frac{r^2 \rho_s \Delta U^2}{36 \varepsilon_n \varphi_\delta^2} > \ln\left(1 + \mathrm{e}^{-y}\right) - \frac{E}{y}, \tag{1}$$

$$E = \frac{A\chi}{24\pi\varepsilon_n \varphi_\delta^2}, \qquad y = \chi h, \qquad \Delta U = U(s+\eta) - U(s), \qquad s = \frac{r_T}{R}, \qquad \eta = \frac{h}{R},$$

where χ is the inverse Debye radius, typically $1 \cdot 10^{-8}$ m in most cases; E is the parameter of energy interaction of solid phase particles in SS; ε_n is the absolute dielectric permeability of the liquid phase of SS, $7.26 \cdot 10^{-10}$ F/m; r is the radius of solid phase particles in SS, m; φ_δ is the potential of a diffusing particle of the double electric layer on the surface of solid phase particles in SS, V; h is the distance between solid phase particles in the SS, m; ρ_s is the generalized density of solid phase particles in the SS, kg/m^3; R is the radius of the pipeline, m; y is the dimensionless distance between solid phase particles in SS, m; η is the relative distance between solid phase particles in SS; r_T is the current value of the radius, m; s is the relative current radius; A is the Hamaker constant, J; ΔU is the difference in velocities of motion of two particles under consideration relative to each other, m/s; U is the velocity of any solid phase particle in SS, m/s.

While investigating the inequality (1), scientists have used various approaches to calculate the difference in velocities of motion of two particles relative to each other [1–36]. Analyzing the results of their research published in scientific journals, the following methodologies can be generalized.

The first group of methods assumes that the distribution of the SS velocity across the flow is described by the logarithmic law, corresponding to developed turbulent flow, thus there exists a sliding velocity of solid phase particles relative to the liquid, which is proportional to the hydraulic size of these particles. In the second group of methods, the distribution of the SS velocity across the flow is described by the logarithmic law corresponding to developed turbulent flow, but the existence of the sliding velocity of solid phase particles relative to the liquid is not taken into account. In the methods belonging to the third group, it is postulated that the solid phase particles in the SS collide with the liquid phase, leading to the emergence of aerodynamic resistance forces on each of them, which are determined by methods of experimental aerohydrodynamics or hydrodynamics at low Reynolds numbers.

However, none of the methods listed above takes into account the features of the SS flow in the layer between the inner surface of the pipeline and the undeformed flow core. The first two methods consider the conditions of non-rod flow regime, when flow cores no longer exist. Meanwhile, a laminar regime is observed in the flow with a flow core in the annular layer. The third method is more adapted to the flow through a bulk mass of solid particles, where the probability of structure destruction is very low.

Given the above, the article proposes the following research methodology. When investigating inequality (1), consider that the flow of the Bingham-Shvedov medium occurs around a circular pipeline in the rod regime. Calculate the difference in velocities of motion of two solid phase particles relative to each other using known dependencies under the condition that the distance between particles is determined by the action of forces with ion-electrostatic and Van der Waals nature, and the sliding velocity of solid phase particles relative to the liquid is absent. Substitute the obtained dependency for the difference in velocity of two solid phase particles into inequality (1) and rewrite it in the form of constraints for the relative current radius.

3. Theoretical or experimental part

As mentioned above, in determining ΔU previous researchers used a logarithmic velocity profile, which does not correspond to the conditions in the layer between the inner surface of the pipeline and the undeformed flow core. A number of experts who studied the peculiarities of non-Newtonian fluid flow in pipelines note that if we consider the destruction of suspension structure during the SS flow in the pipeline, then the velocity distribution in the layer near the pipeline surface will correspond to the following dependency [1, 13, 14]:

$$U(s)=\frac{R\tau_w}{2\mu}\left(1-s^2-2(1-s)a\right), \tag{2}$$

$$a=\frac{\tau_0}{\tau_w}, \qquad \tau_w=\frac{\Delta pR}{2L},$$

where τ_w is the tangential stress of hydraulic friction on the inner surface of the pipe, Pa; μ is the dynamic viscosity coefficient of the liquid phase of SS, kg/m/s; a is the relative radius of the undeformed flow core; τ_0 is the initial tangential stress of SS, Pa; Δp is the pressure difference at the beginning and end of the pipeline, Pa; L is the length of the pipeline, m.

Using equation (2), the difference in velocities of motion of two solid phase particles, after neglecting the square of the relative distance between solid phase particles, can be calculated by the following formula:

$$\Delta U = \frac{\eta R \tau_0}{\mu} - \frac{\eta R \tau_w}{\mu} s. \tag{3}$$

Considering jointly equations (1) and (3), after corresponding transformations, we obtain a condition under which the destruction of suspension structure occurs during the SS flow in the pipeline:

$$s < s_*, \tag{4}$$

$$s_* = a - \frac{\mu}{\eta R \tau_w} \sqrt{\ln\left(1 + \mathrm{e}^{-y}\right) - \frac{E}{y}} \sqrt{\frac{36 \varepsilon_n \varphi_\delta^2}{r^2 \rho_s}}, \tag{5}$$

where s_* is the maximum value of the relative radius at which the suspension structure is still preserved during the SS flow in the pipeline.

Condition (4) indicates that when the values of the relative radius exceed s_*, the SS flow occurs with the destruction of its structure, and the suspension itself, according to rheological characteristics, corresponds to ordinary viscous fluid. As seen from formula (5), the maximum value of the relative radius at which the suspension structure is still preserved during SS flow in the pipeline consists of two additions: the first addition is the known in the theory of hydrodynamics of non-Newtonian fluids relative radius of the undeformed flow core, which takes into account the relationship between the initial tangential stress and the hydraulic frictional stress on the inner surface of the pipe, and the second addition takes into account the influence of gravitational and repulsive forces between solid phase particles, which have ion-electrostatic and Van der Waals nature.

Considering that the second addition of formula (5) contains two square root expressions and one positive multiplier, it can be concluded that the forces having ion-electrostatic and Van der Waals nature lead to a reduction in the maximum value of the relative radius at which the suspension structure is still preserved during SS flow in the pipeline. To assess the impact of this factor, let's rewrite the formula in the following form:

$$s_* = a(1 - \Delta), \tag{6}$$

$$\Delta = \delta(x)E_0, \quad \delta = x\sqrt{\ln\left(1+\mathrm{e}^{-\frac{E}{x}}\right)-x}, \quad x = \frac{E}{y}, \qquad E_0 = 452\frac{\mu\varphi_\delta^3}{A\tau_0}\sqrt{\frac{\varepsilon_n^3}{r^2\rho_s}}, \quad (7)$$

where Δ is the relative decrease in the maximum value of the relative radius at which the suspension structure is still preserved during SS flow in the pipeline, under the action of forces with ion-electrostatic and Van der Waals nature; δ is the parameter of the influence of the distance between particles on the maximum value of the relative radius at which the suspension structure is still preserved during the SS flow in the pipeline; x is the effective dimensionless distance between solid phase particles of SS.

Researchers in the field of the DLFO, when studying the dynamic sedimentation stability of the SS, use equation (4) to assess the possibility of suspension structure breakdown, considering it for the respective distances between two solid phase particles [1, 12–14, 16, 17]. Thus, the dependence of the interaction force between two particles on the distance between them has two extrema and two equilibrium points. The smallest in absolute value is the distance at which the maximum force interaction is realized, determining the onset of the coagulation process leading to the disruption of SS homogeneity [12, 16, 17]

$$y^* = 1.721E^{0.503}, \qquad x^* = 0.581E^{0.497}, \quad (8)$$

where y^* – is dimensionless distance, corresponding to the maximum interaction force between particles.

The next point is the point of stable equilibrium, at which the interaction force between particles equals zero, corresponding to the stable state of the SS [12, 16, 17]

$$y'' = 2.473\cdot\lg\left(\frac{4.162}{E}\right), \qquad x'' = \frac{0.404E}{\lg\left(\frac{4.162}{E}\right)}, \quad (9)$$

where y'' is dimensionless distance, corresponding to the point of stable equilibrium.

Following is the minimum of the interaction force between two particles, corresponding to the beginning of the coagulation process due to the manifestation of thixotropic properties [12, 16, 17]

$$y^{**} = 1.162\cdot\ln\left(\frac{21.041}{E}\right), \qquad x^{**} = \frac{0.374E}{\lg\left(\frac{21.041}{E}\right)}, \quad (10)$$

where y^{**} is dimensionless distance, corresponding to the minimum interaction force between particles.

At greater distances, there is a point of unstable equilibrium, near which any deviation causes the disruption of the SS homogeneity [12, 16, 17]

$$y' = 1.575E, \qquad x' = 0.635, \tag{11}$$

where y' is dimensionless distance, corresponding to the point of unstable balance.

For each of these special points of formula (8)–(11), conditions (4) can be considered or the values of quantities can be computed using formulas (5)–(7).

4. Results and discussion

The analysis of the formulas presented above allows us to draw the following conclusions. Obviously, physically realistic are the values of δ, that ensure the existence of the following condition:

$$\Delta \le 1,$$

which limits the parameter dependent on the distance between solid particles

$$\delta \le \delta_*, \tag{12}$$

$$\delta_* = zE, \tag{13}$$

$$z = \frac{\tau_0 r}{6\chi\mu\varphi_\delta}\sqrt{\frac{\rho_s}{\varepsilon_n}},$$

where δ_* is the assumed value of the parameter influencing the distance between particles on the maximum value of the relative radius at which the suspension structure is still preserved during SS flow in the pipeline; z is the parameter taking into account the influence of rheological characteristics of SS.

Taking into account the requirements of satisfying inequality (12), it is necessary to investigate the first of the dependencies (7) in the interval of the argument's variation (Figure 1) and compare this interval with the values calculated by formulas (8)–(11).

Comparing the interval of variation of the parameter x, depicted in Figure 1, with the maximum value of the interaction force between two solid phase particles among themselves from the special points of the force interaction (11), we can conclude that they coincide well. From the graphs presented in Figure 1, it is also evident that the dependence of the parameter influencing the distance between particles on the maximum value of the relative radius at which the suspension structure is still preserved during SS flow in the pipeline has an extremum on the interval of variation, the magnitude and coordinate of which depend on the value of the parameter of energy interaction of solid phase particles (Figures 2, 3):

$$W = 0.2181 - 0.4128E - 0.6477E^2, \quad Y = 0.0329 + 1.2426E + 6.5662E^2, \quad (14)$$

where W is the maximum value of the parameter influencing the distance between particles on the maximum value of the relative radius at which the suspension structure is still preserved during the SS flow in the pipeline; Y is the dimensionless distance between solid phase particles corresponding to the extremum of the function (12).

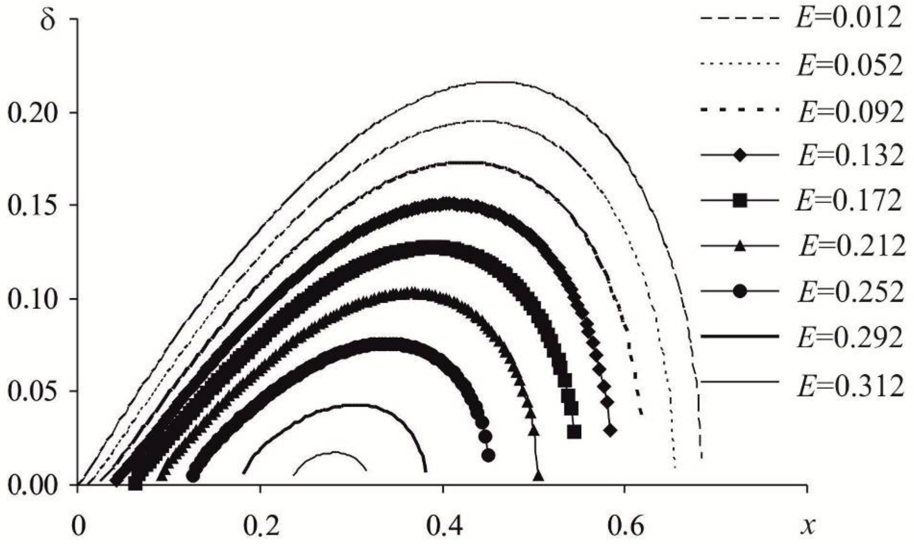

Figure 1 – Dependence of the parameter δ on the value of x for various values of the parameter of energy interaction of solid phase particles of the SS 2

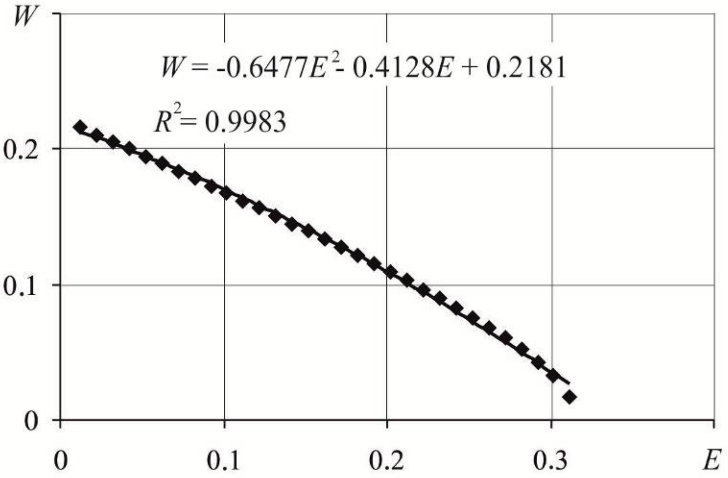

Figure 2 – Dependence of the maximum value of the parameter W on the value of the parameter of energy interaction of solid phase particles of the SS

From Figure 2 and Figure 3, it can be concluded that the curve passing through the extrema of the function (7), with precision typical of engineering calculations, is approximated by a linear function (Figure 4):

$$W = 0.2129 - 0.1827y,$$

where y is the dimensionless distance between solid phase particles SS, corresponding to the interval of variation of the parameter x.

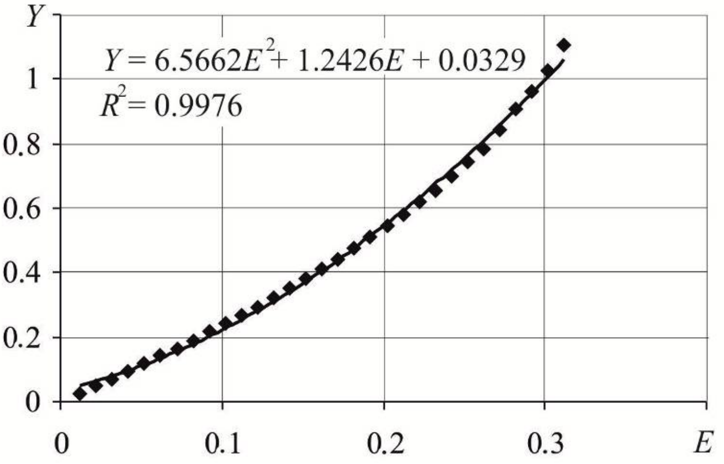

Figure 3 – Dependence of the relative distance between solid phase particles of the SS, corresponding to the maximum value of the parameter δ, on the value of the parameter of energy interaction

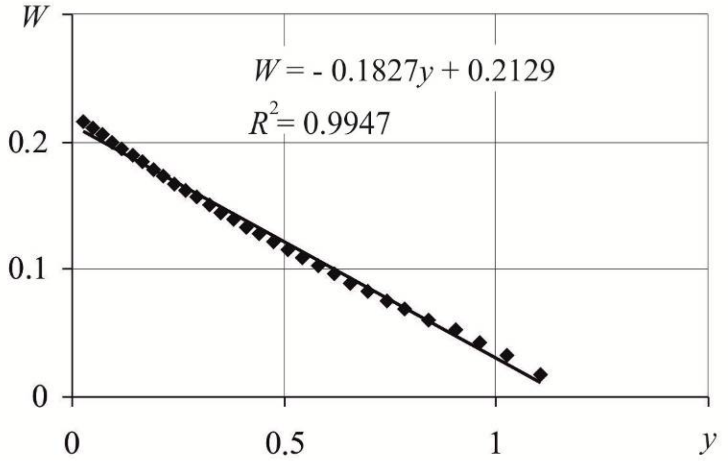

Figure 4 – Dependence of the maximum value of the parameter δ on the relative distance between solid phase particles of SS

Obviously, if the value of δ_* does not exceed the value of W, then condition (12) is satisfied throughout the interval of variation of the parameter of energy interaction of solid phase particles of SS. That is, in this case, the flow region with a disrupted suspension structure will exist and will not occupy the entire cross-sectional area. Therefore, considering simultaneously formulas (12)–(14), after appropriate transformations, we obtain the following constraint on the value of E, compliance with which ensures condition (12) (Figure 5):

$$E_* \le E,$$

$$E_* = 0.663\left(\sqrt{1+1.123z+1.355z^2} - 0.481 - 1.164z\right),$$

where E_* is the minimum possible value of the parameter of energy interaction of solid phase particles of the SS, which ensures the presence of a flow region with a disrupted suspension structure, with an area smaller than the area of the pipeline (Figure 5).

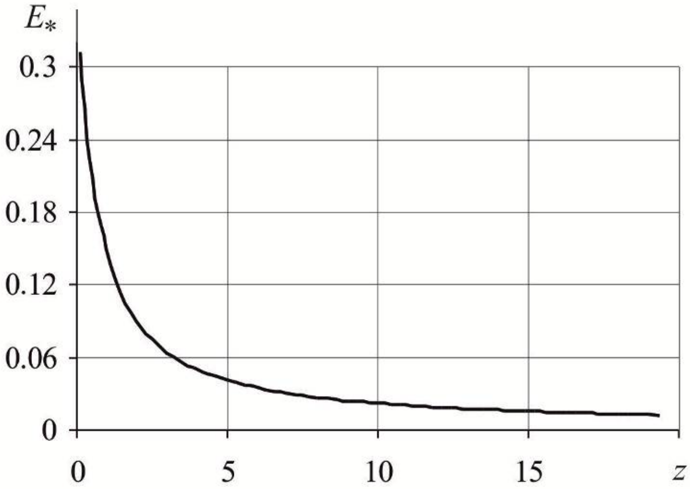

Figure 5 – Dependence of the minimum possible value of the parameter of energy interaction of solid phase particles of the SS on the parameter taking into account the influence of the rheological characteristics of the SS

According to formula (6), the influence of forces with ion-electrostatic and Van der Waals nature on the relative radius at which the suspension structure is still preserved during its flow in the pipeline can be neglected if

$$10x\sqrt{\ln\left(1+\mathrm{e}^{-\frac{E}{x}}\right) - x} \le zE. \tag{15}$$

Inequality (15) is substantially nonlinear, making it impossible to obtain a solution in analytical form, and it is also parametric, which significantly complicates its investigation by numerical methods.

5. Conclusions

The article investigates the influence of forces with ion-electrostatic and Van der Waals nature on the relative radius at which the suspension structure is still preserved during its flow in the pipeline, taking into account the peculiarities of processes occurring in the layer between the inner surface of the pipeline and the undeformed flow core.

The dependence of the relative radius, beyond which the SS flow occurs with disruption of its structure, and the suspension itself, in terms of rheological characteristics, corresponds to ordinary viscous fluid. Unlike known formulas, the obtained dependence consists of two terms: the first term is a well-known relative radius of the undeformed flow core in the theory of non-Newtonian fluid hydrodynamics, which takes into account the relationship between the initial tangential stress and the hydraulic frictional tangential stress on the inner surface of the pipe, and the second term takes into account the influence of gravitational and repulsion forces between solid phase particles of SS, which have ion-electrostatic and Van der Waals nature.

It is proved that the forces of ion-electrostatic and Van der Waals nature lead to a decrease in the maximum value of the relative radius at which the structure of the suspension is still preserved during the flow of the SS in the pipeline, since the term that takes into account their influence is always positive and subtracted from the term that takes into account the ratio of the initial tangential stress and the tangential stress of hydraulic friction on the inner surface of the pipe

The region of existence of the additive that takes into account the influence of forces of ion-electrostatic and Van der Waals nature and the interval of change in its values at different values of the parameter of energy interaction of SS solid phase particles are investigated. It was found that the dependence of this term on the distance between the particles of the SS solid phase has a maximum. The magnitude and coordinates of the maximum depend on the parameter of energy interaction of SS solid phase particles. It has been established that with an increase in the value of the parameter of energy interaction of particles of the SS solid phase, the maximum value of the term decreases, and the coordinate of this maximum increases.

The practical significance of the results obtained is to clarify the value of the radius of the undeformed core of the SS flow, which allows using the Bingham equation to obtain more realistic parameters of hydraulic transport of iron ore beneficiation waste in the form of the Bingham-Shvedov medium, and to reduce the consumption of technical fluid by mining and beneficiation enterprises by increasing the concentration of transported hydraulic mixtures

REFERENCES

1. Krut, O.A. (2002), *Vodovuhilne palyvo* [Hydrocarbon fuel], Naukova dumka, Kyiv, Ukraine.

2. Dyakun (Slobodiannykova), I.L. (2014), *Povyshenie effektivnosti energeticheskoy pererabotki uglya* [Increasing the efficiency of energy pro-cessing of coal], Naukova dumka, Kyiv, Ukraine.

3. SvItliy, Yu.G. and Krut, O.A. (2010), *GidravlIchniy transport tverdih materIalIv* [Hydraulic transport of solid materials], ShIdniy vidavnichiy dIm, Donetsk, Ukraine.

5. Svitliy, Yu.G. and Biletskiy, V.S. (2009), *GidravlIchniy transport* [Hydraulic transport], ShIdniy vidavnichiy dIm, Donetsk, Ukraine.

6. Kyrychko, S.M. (2016), “Substantiation of parameters of processes of hydromechanization of mining works at use of hydromixtures of high concentration”, Ph.D. Thesis, Geotechnical and mining mechanics, M.S. Poljakov Institute of Geotechnical Mechanics under NAS of Ukraine, Dnipro, Ukraine.

7. Shvornykova, G.M. (2010), Reduction of energy costs for the transportation of hydrocarbon fuel by improving the processes and modes of operation of hydrotransport systems, Ph.D. Thesis, Mining, Volodymyr Dahl East Ukrainian National University, Lugansk, Ukraine.

8. Blyuss, B., Semenenko, Ye., Medvedieva, O., Kyrychko, S. and Karatayev, A. (2020). Parameters determination of hydromechanization technologies for the dumps development as technogenic deposits, *Mining of Mineral Deposits*, vol. 14(1), pp. 51-61, https://doi.org/10.33271/mining14.01.051

9. Medvedieva, O.O., Semenenko, Ye.V. and Medianyk, V.Yu (2021), “Determination of parameters of hydromechanization processes for Kryvbas mining and processing plants”, *Gornyiy zhurnal Kazahstana*, no. 12. pp. 17–22.

10. Bubnova O.A. (2019) “Prediction of changes in the state of the geological environment in the mining region”, E3S Web of

Conferences, *International Conference Essays of Mining Science and Practice*, Dnipro, Ukraine, June 25-27 2019, Volume 109. DOI: https://doi.org/10.1051/e3sconf/201910900009

11. Samoilyk, V.G. (1992), "Development of technology for obtaining the solid phase of water-coal fuel with an expedient level of ash content", Abstract of D. Sc. dissertation, Chemical technology of fuel and lubricants. Dnipropetrovsk, Ukraine.

12. Semenenko, Ye.V., Demchenko, T.D and Ryzhova S.A. (2016), "Investigation of dynamic sedimentation stability of structured suspensions under the action of turbulent pulsations", *Geo-Technical Mechanics*, no. 130. pp. 115–124.

13. Yahno, O.M. and Zhelyak, I.V. (1995), *Gidravlika nenyutonlvskih ridyn: navch. Posibnik* [Hydraulics of non-Newtonian rivers: Navch. Helper], Vischa shkola, Kyiv, Ukraine.

14. Yahno, O.M. and Dubovitskiy, V.F. (1976), *Osnovyi reologii polimerov* [Fundamentals of polymer rheology], Vischa shkola, Kyiv, Ukraine.

15. Semenenko, Ye.V., Tepla, T.D, Medianyk, V.Yu., Skosyrev, V.H. and Babets, D.V. (2023), "Determination of the non-deformable core radius of flow in structured suspension pipeline using the theory of stability of lyophobic colloids", *Geo-Technical Mechanics*, no. 165. pp. 84–96. https://doi.org/10.15407/geotm2023.165.084

16. Semenenko, Ye.V., Slobodiannykova, I.L., Medianyk, V.Yu., Kyrychko, S.M. and Tepla, T.D. (2022), "The technologies for the removal of coal technogenic deposits in the form of highly concentrated hydro mixtures", *Geo-Technical Mechanics*, no. 163. pp. 46–60, https://doi.org/10.15407/geotm2022.163.046

17. Semenenko, Ye.V., Medvedieva, O.O., Tatarko, L.G., Khamynych, O.V. and Yeluzakh M (2022), "Influence of the properties of solid particles added to a structured suspension on its dynamic sedimentation stability", *Geo-Technical Mechanics*, no. 163. pp. 96–107, https://doi.org/10.15407/geotm2022.163.096

18. Papayani, F.A. and Switly Y.G. (1995), "Utilization of Coal-Water Fuel in Heat Power Industry and by Public Utilities of Ukraine" *Coal Utilization & Fuel Systems: The Proceedings of the 20- Intern. Techn. Conf.*, March 1995. – Clearwater, Florida, USA, pp. 193–202.

19. Ohki, Akira (1995), "Adsorption Behavior of Polyanion Additives and Coal-Water Mixture Properties", *Coal Utilization & Fuel Systems: The Proceedings of the 20- tht Intern. Techn. Conf.*, March 1995. Clearwater – Florida, USA, pp. 75–85.

20. Randell, J.K., Henry C. D. and Butt B. (1995), "Recovery of Fine Coal and Reclamation of Coal Slurry Impoundments", *Coal Utilization & Fuel Systems: The Proceedings of the 20- th Intern. Techn. Conf.*, March 1995. – Clearwater, Florida, USA, pp. 583–594.

21. Sastrawinata, T. (1996), "Current Status of Coal Water Slurry Techno-logy in Indonesia and its Prospects", *Coal Utilization & Fuel Systems: The Proceedings of the 21-st Intern. Techn. Conf.,* March 1996. – Clearwater. Florida, USA, pp. 821–828.

22. Terenzi, A. (1996), "Rheological Properties and Setting Behaviour Influences in CWS Pipeline Flow", *Coal Utilization & Fuel Systems: The Proceedings of the 21-st Intern. Techn. Conf.*, Clearwater, Florida, USA, March 1996. pp. 645–656.

23. Kurganova, A.M. (ed.) (1986), *Gidravlicheskie raschetyi sistem vodosnabzheniya i vodootvedeniya: spravochnik* [Hydraulic calculations of water supply and drainage systems: reference book], Stroyizdat, Leningrad, Russia.

24. Gaved, A. (1995), Cashing in Coal's Liquid Assets, *World Coal*, February, pp. 19–28.

25. Collivignarelli, M.C., Carnevale Miino, M., Bellazzi, S., Caccamo, F.M., Durante, A. and Abbà A. (2022), "Review of rheological behaviour of sewage sludge and its importance in the management of wastewater treatment plants", *Water Practice & Technology*, Vol. 17, no. 1, pp. 483-491, https://doi.org/10.2166/wpt.2021.098

26. Hong, E., Yeneneh, A. M., Sen, T. K., Ang, H. M. and Kayaalp, A. (2018), "A comprehensive review on rheological studies of sludge from various sections of municipal wastewater treatment plants for enhancement of process performance", Advances in Colloid and Interface Science, no. 257, pp. 19-30. https://doi.org/10.1016/j.cis.2018.06.002

27. Vachoud, L., Ruiz, E., Delalonde, M. & Wisniewski, C. (2019), "How the nature of the compounds present in solid and liquid compartments of activated sludge impact its rheological characteristics", Environmental Technology (United Kingdom), vol. 40(1), pp. 60-71. https://doi.org/10.1080/09593330.2017.1378729

28. Nishiguchi, K. and Winkler, M. K. H. (2020), "Correlating sludge constituents with digester foaming risk using sludge foam potential and rheology", Water Science and Technology, vol. 81(5), pp. 949-960. https://doi.org/10.2166/wst.2020.180

29. Numkam, G. L. and Akbari, B. (2019), "Effect of surfactant chemistry on drilling mud performance", Journal of Petroleum Science and Engineering, vol. 174, pp.1309-1320. https://doi.org/10.1016/j.petrol.2018.11.075

30. Mislyuk, M.A. and Bogoslavets, V.V. (2017), *Gidroaeromehanika v burinni: Metodichni vkazivki* [Hydroaeromechanics in drilling: Guidelines], Ivano-Frankivsk National Technical University of Oil and Gas, Ivano-Frankivsk, Ukraine.

31. Dudlia, M.A. (2011), Promivalnl rldini v burlnnl. Pldruchnik: 3-e vid. dop. [Drilling fluids in drilling. Textbook: 3rd ed.], State Higher Educational Institution "National Mining University", Dnepropetrovsk, Ukraine.

32. Petunin, O.I. and Zelenskyi, A.A. (2010), "High-quality drilling fluids are the key to successful construction of oil and gas wells", *Burinnya*, Vol. X, pp. 9–15.

33. Biletskyi, V.S., Krut, O.A. and Vlasov, Yu.F. (2006), "Rheological characteristics of water-coal suspensions depending on the quality of the initial coal", *Vistnik Krivorizkogo tehnlchnogo universitetu.* no. 11. pp. 49–55.

34. Maystrenko, A., Dunaevska, N, and Fridman, M. (1988), "Results of experiments on dust combustion of Ukrainian anthracites", *Vozmozhnosti modernizatsii ukrainskih ugolnyih elektrostantsiy, delovyie vozmozhnosti i potrebnost v investitsiyah: ukrainsko-amerikanskaya ob'edinyonnaya konferentsiya* [Opportunities for modernization of Ukrainian coal-fired power plants, business opportunities and investment potential: Ukrainian-American conference], Kyiv, Ukraine, pp. 121–125.

35. Ukraine Ministry of Coal Industry (1997), Resolution № 280 dated 28.03.97: *Prohrama rozrobky ta vprovadzhennia tekhnolohiy promyslovoho vykorystannia shlamiv vuhilnykh shakht, polipshennia ekolohichnoyi sytuatsiyi u vuhledobuvnykh rehionakh ta zapobihannya mozhlyvym nadzvychaynym sytuatsiyam, pov'yazanym z proryvamy damb khvostoskhovyshch* [Resolution №

280 dated 28.03.97: "Program for the development and implementation of technologies for the industrial use of sludge, improving the environmental situation in coal-mining regions and averting possible emergency situations associated with tailings dam breaches], Ukraine Ministry of Coal Industry, Kyiv, Ukraine.

36. Baranov, Yu.D., Blyuss, B.A., Semenenko, Ye.V. and Shuryhin, V.D. (2006), *Obosnovaniye parametrov i rezhimov raboty sistem gidrotransporta gornykh predpriyatiy* [Substantiation of parameters and operating modes of hydrotransport systems of mining enterprises], Novaya ideologiya, Dnepropetrovsk, Ukraine.

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ВИЗНАЧЕННЯ ПАРАМЕТРІВ НАПІРНОЇ ТЕЧІЇ СТРУКТУРОВАНОЇ СУСПЕНЗІЇ

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Анотація. Предметом дослідження є методи розрахунку параметрів та режимів течії структурованих суспензій, що мають значну перспективу використання для суттєвого зменшення енергоємності та питомого водоспоживання всіх технологій гідромеханізації, що застосовуються на гірничих підприємствах. Основною темою дослідження є питання стійкості структури суспензії та рівномірного розподілу частинок її твердої фази по об'єму при напірній течії по трубопроводу. Мета роботи полягає у встановлені залежності відносного радіусу, що окреслює область течії, де структура суспензії не буде зруйнована, не тільки від реологічних характеристик суспензії та гідравлічних параметрів течії, а й від сил тяжіння та відштовхування між частинками твердої фази суспензії, що мають іонно-електростатичну та Ван-дер-Ваальсовську природу. Встановлено залежність відносного радіусу, при перевищенні якого течія структурованої суспензії відбувається з руйнуванням її структури, а сама суспензія за реологічними характеристиками буде відповідати звичайній в'язкій рідині. На відміну від відомих формул, залежність, що отримана, складається з двох доданків: перший доданок це відомий в теорії гідродинаміці неньютонівської рідини відносний радіус недеформованого ядра потоку, що враховує співвідношення початкового дотичного напруження та дотичного напруження гідравлічного тертя на внутрішній поверхні труби, а другий доданок – враховує вплив електростатичних сил тяжіння та відштовхування між частинками твердої фази структурованої суспензії. Доведено, що сили, які мають іонно-електростатичну та Ван-дер-Ваальсовську природу, призводять до зменшення максимального значення відносного радіуса, при якому ще зберігається структура суспензії при її течії в трубопроводі, оскільки доданок, який враховує їх вплив завжди додатний, та віднімається від доданка, що враховує співвідношення початкового дотичного напруження та дотичного напруження гідравлічного тертя на внутрішній поверхні труби. Досліджено область існування доданку, що враховує вплив сил, які мають іонно-електростатичну та Ван-дер-Ваальсовську природу та інтервал змінення його значень при різних величинах параметру енергетичної взаємодії частинок твердої фази структурованої суспензії. Встановлено, що залежність цього доданку від відстані між частинками твердої фази суспензії має максимум. Величина та координати максимуму залежать від параметру енергетичної взаємодії частинок твердої фази. Встановлено, що із зростанням значення параметру енергетичної взаємодії частинок твердої фази суспензії значення максимальне значення доданку знижується, а координата цього максимуму – зростає.

Ключові слова: структурована суспензія, радіус недеформованого ядра потоку, іонно-електростатичні сили, напірна течія, трубопровід.