UDC 532.584:532.32:550.385.37 DOI: https://doi.org/10.15407/geotm2023.165.084

DETERMINATION OF THE NON-DEFORMABLE CORE RADIUS OF FLOW IN STRUCTURED SUSPENSION PIPELINE USING THE THEORY OF STABILITY OF LYOPHOBIC COLLOIDS

[1]Semenenko Ye.V., [1]Tepla T.D, [2]Medianyk V.Yu., [3]Skosyrev V.H., [2]Babets D.V.

[1]M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, [2]Dnipro University of Technology, [3]Pryazovskyi State Technical University

Abstract. The objective of this research is to study the influence of ion-electrostatic and Van der Waals forces on the radius of the non-deformable core in the flow of structured suspensions with an inhomogeneous solid phase inside a pipeline. The study considers parameters such as the solid and liquid phase properties, the average flow velocity of the suspension, and its rheological properties. The article analyzes the results of dynamic sedimentation stability studies of structured suspensions, where the solid phase consists of particles of different sizes and densities, flowing in rod flow mode through the pipeline based on the stability theory of lyophobic colloids by Derjaguin – Landau – Verwey – Overbeek.

It is demonstrated that there is a boundary dividing the cross-section of the flow into two parts. In the central part of the flow, inside this boundary, pairwise coagulation bonds between adjacent particles remain intact, and the suspension structure remains undisturbed. This part is suggested to be considered as the non-deformable core of the flow in the rod regime of the suspension with pseudoplastic properties. Outside this boundary, the pairwise coagulation bonds between adjacent particles are disrupted, creating conditions for shear flow in this part of the cross-section of the pipeline. Unlike conventional methods for calculating the non-deformable core of structured suspensions, the proposed method does not take into account the acting pressure drop but considers the influence of the average flow velocity of the suspension, as well as the impact of not only the initial shear stress but also the effective viscosity of the suspension, the viscosity and density of its liquid phase, the concentration, density, and size of the solid phase, as well as the ion-electrostatic and Van der Waals forces.

It is established that the dimensionless radius of the non-deformable core of structured suspensions has a maximum possible value, which depends solely on the parameters of the ion-electrostatic and Van der Waals forces and the rheological characteristics of the structured suspensions, and is independent of the average flow velocity.

Keywords: non-deformable core of flow, rheological characteristics, structured suspension, lyophobic colloids, pipeline.

1. Introduction

In the mining industry of Ukraine, favorable conditions have emerged for the implementation of technologies based on the flow of structured suspensions (SS) through pipelines [1–7]. Mining and beneficiation plants are witnessing a global trend towards the disposal of enrichment waste in the form of paste or high-concentration hydro-mixtures exhibiting plastic properties [1–3]. Coal enrichment plants also envision developing waste repositories as technogenic deposits, followed by utilization in the form of coal-water fuel, which, according to numerous researchers, exhibits rheological properties similar to Bingham plastic [4–7]. These technologies involve the pressure transportation of SS through pipelines, and the costs associated with overcoming the hydraulic resistance of the mainline comprise the main portion of consumed energy. A peculiar feature of SS flow through pipelines is the existence of an non-deformable core in the central part, which moves as a solid body, while shear flow occurs in the near-wall part. The diameter of this non-deformable core significantly influences the hydrodynamic characteristics of the entire flow, as well as the flow in the near-wall layer, and to a large extent determines the hydraulic resistance of the mainline.

Initially, the radius of the SS flow core was determined proportional to the pipeline's radius, with the proportionality coefficient being the ratio of the product of the initial shear stress and the pipeline length in calibers to the acting pressure drop [8–10]. This calculation method was used for clayey and silty hydro mixtures, as well as for feed mixtures, cellulose, and paper masses with a concentration of more than 10%. Later studies on the hydrodynamics of wastewater sediment flows, which constitute an inhomogeneous dispersed system in composition and structure, with the liquid phase containing impurities of weak electrolytes, indicated a dependence of the core radius on the magnitude of the equivalent shear rate as well [11]. In the work [12], the relationship between the rheological and physicochemical properties of wastewater sediments was investigated, confirming the hypothesis that the non-Newtonian behavior of these suspensions is related to the surface charge of the flakes. It has been proven that surface radicals of solid phase particles and the presence of metal ions in the liquid phase have the most significant influence on the rheological properties of such suspensions. The research results [13] showed that the rheological properties of SS (wastewater sediments) and the dynamics of the flocculation process are significantly influenced by the pH of the liquid phase. Thus, the structure of secondary sludge flakes and their surface properties strongly depend on pH. The sludge particles form larger flakes at higher alkalinity compared to a more acidic sludge environment. Also, an increase in the pH of SS leads to an increase in its yield stress, as well as viscosity and initial shear stress. In the works [14–16], the influence of certain reagents added to the liquid phase, such as biopolymers with high molecular weight or non-ionic surfactants, on the rheological characteristics of SS was demonstrated. However, all these studies were focused on examining the impact of various factors on the rheological properties of SS, one of which is the initial shear stress, which may characterize the influence of these factors on the diameter of the non-deformable core of the flow. Hence, at present, there are only indirect pieces of evidence regarding the dependence of the non-deformable core diameter of the SS flow in the pipeline on the characteristics of forces of ion-electrostatic and Van der Waals nature, solid and liquid phase parameters, and the average flow velocity and rheological properties of the suspension. Partly, this situation can be explained by the fact that the non-deformable core diameter of the flow is used in calculating the hydraulic parameters of the SS flow process in the pipeline, while the forces of ion-electrostatic and Van der Waals nature are subjects of consideration in the theory of stability of lyophobic colloids known as the Derjaguin – Landau – Verwey – Overbeek theory (DLVO). However, the non-deformable core diameter of the flow significantly influences flow parameters and ultimately the energy consumption of the process. Therefore, justifying methods to control this parameter, being an alternative way to reduce hydraulic resistance in pipelines, is an important scientific and practical task.

Thus, the purpose of this article is to establish the influence of the characteristics of forces of ion-electrostatic and Van der Waals nature, solid and liquid phase parameters, the average flow velocity, and the rheological properties of the suspension on the radius of the non-deformable core of the flow during the SS flow in the pipeline.

2. Methods of research

The solution to the stated problem is based on comparing the attractive and repulsive forces with ion-electrostatic and Van der Waals nature to the forces arising when the liquid flow surrounds two particles of different density and size, taking into account the turbulent component and velocity deficits proportional to the hydraulic sizes of interacting particles.

3. The theoretical part

The DLVO theory considers the interaction between solid phase particles in SS from the perspective of stability of extremums of force interaction, considering the attractive and repulsive forces with ion-electrostatic and Van der Waals nature. Thus, this theory has not been used to determine the geometric dimensions of the non-deformable core of the flow during SS flow in the pipeline [7, 17–19]. Typically, the results of this theory are used to assess the stationary sedimentation stability of SS, i.e., when the liquid is at rest [7, 17–19]. The implementation of water-coal fuel technologies and paste thickening technologies required solving the problem of hydraulic calculation of pipeline systems transporting SS. Therefore, there was a need to evaluate the dynamic sedimentation stability of SS, which characterizes the suspension's ability to maintain its structure and uniform distribution of solid phase particles throughout the volume during flow in the pipeline [17, 20]. In this case, in addition to the attractive and repulsive forces with ion-electrostatic and Van der Waals nature, it is necessary to consider the fluid flow energy, which tends to increase or decrease the distance between the two particles under consideration [7, 17, 20]. Several researchers [17] have indicated that the magnitude of this energy is determined by the difference in the suspension's liquid phase velocities at the location of the particles and the difference in hydraulic sizes of the interacting particles under constrained conditions [4–7, 17, 20]. Studies on the dynamic sedimentation stability of SS are available both for cases when the particles are of the same size and density [17, 18] and when the interacting particles have different sizes and densities [19].

Although these studies were not directly aimed at evaluating the dimensions of the non-deformable core of the flow, the results obtained during their execution can be used to address the objective of this article. In works [17–19], based on the analysis of the balance between attractive and repulsive forces with ion-electrostatic and Van der Waals nature and forces caused by the SS flow in the pipeline, the following restriction was derived for the mean suspension velocity, adherence to which ensures the breakdown of paired coagulation bonds between adjacent particles with different sizes and densities:

$$U \geq \Theta e^{-8.52s} - 1, \tag{1}$$

$$U = \frac{k_\tau}{k_\eta}\frac{\eta V}{\tau_0 R}, \qquad \tau = 46\frac{k_\tau \tau_0}{A\chi^3}, \qquad E = \frac{A\chi}{24\pi\varepsilon_n \varphi_\delta^2}, \qquad s = \frac{r_T}{R},$$

$$\Theta = \frac{1 + ArC}{Ar - 1}\left(1 + \frac{\delta^3}{\nu}(1 - C)^n Ar\sqrt{Ar - 1}(1 - w)e^{4.26E}\right)^2 \frac{e^{-8.52E}}{\tau\ \delta^2 E^2},$$

$$\nu = 6.14\frac{\nu\ \delta}{gR^3}\sqrt{\frac{\varepsilon_n}{\rho_f}}, \qquad \delta = \frac{r}{R}, \qquad Ar = \frac{\rho_s - \rho_f}{\rho_f}, \qquad w = \frac{r\ Ar'}{r^2 Ar},$$

where χ – inverse Debeye radius, m^{-1}; ε_n – absolute dielectric constant of water, F/m; r – radius of solid particles of the first type, m; r' – radius of solid particles of the second type, m; δ – dimensionless radius of solid particles of the first type; φ_δ – potential of the diffuse double electric layer on the surface of solid particles, V; A – Hamaker constant, J; w – parameter accounting for the difference in density and size of interacting particles; n – exponent [20]; r_T – current value of the radius, m; s – current value of the dimensionless radius; k_τ, k_η – approximation parameters of Buckingham's equation [1, 6]; V – mean cross-sectional velocity of SS, m/s; U – dimensionless mean cross-sectional velocity of SS; τ_0 – initial shear stress of SS, Pa; η – effective viscosity of SS, m^2/s; τ_* – dimensionless initial shear stress of SS; ν – kinematic viscosity coefficient of the liquid phase of SS, m^2/s; ν_* – dimensionless kinematic viscosity coefficient of the liquid phase of SS; Ar – Archimedes parameter of the first type of particles, assumed that $Ar > 1$; Ar' – Archimedes parameter of the second type of particles, assumed that $Ar' > 1$; g – acceleration due to gravity, m/s^2; ρ_f – density of the liquid phase of SS, kg/m^3; R – radius of the pipeline, m; π – constant, equal to 3.14; C – volumetric concentration of SS, dimensionless, fractions of units; E – DLVO parameter characterizing the influence of forces with ion-electrostatic and Van der Waals nature; Θ – interphase interaction parameter.

The condition (1), depending on the value of the dimensionless velocity and the interphase interaction parameter, may not hold true along the entire height of the pipeline section. The exponent in the first term of the right-hand side reaches its minimum value at the axis of the pipeline when $s = 0$, and its maximum value on the surface of its inner wall when $s = 1$. If at a certain height, inequality (1) becomes a valid equality, this point – let's call it the boundary point – divides the cross-section into two parts:

$$S = 0.117 ln\left(\frac{\Theta}{U + 1}\right), \tag{2}$$

where S – dimensionless radius of the boundary point.

In the part above the boundary point, which is determined by formula (2), i.e., at smaller current radii, $s < S$, the right-hand side of equation (1) is greater than the left-hand side, and thus, paired coagulation bonds between adjacent particles are maintained. In the part below the boundary point, i.e., at larger current radii, $S < s$, the right-hand side of equation (1) is smaller than the left-hand side, and in this part, paired coagulation bonds between adjacent particles will be disrupted. At the boundary point itself, the forces trying to break the paired coagulation bonds between adjacent particles and the forces trying to maintain them are equal to each other. Therefore, it is considered that in the $S \le s$ part the coagulation bonds between solid phase particles are broken.

From expression (2), it can be observed that with an increase in the dimensionless flow velocity, the value of the dimensionless radius of the boundary point decreases. At the same time, the maximum possible value of this quantity and its deviation due to the flow of SS can be calculated using the formulas:

$$S = S^{'} - \Delta s,$$

$$S^{'} = 0.117 ln\Theta, \qquad \Delta s = 0.117 ln(U + 1), \tag{3}$$

where S' – maximum possible dimensionless radius of the boundary point; Δs – deviation of the dimensionless radius of the boundary point from its maximum value for a given flow velocity.

Condition (1) makes sense if its left-hand side is greater than zero, which imposes the following constraint on the value of the interphase interaction parameter:

$$\Theta < e^{8.52},$$

and allows for calculating the value of this parameter using the following formulas:

$$\Theta = ke^{8.52}, \tag{4}$$

$$k = \frac{1 + ArS}{Ar - 1}\left(1 + \frac{\delta^3}{\nu}(1 - S)^n Ar\sqrt{Ar - 1}(1 - w)e^{4,26E}\right)^2 \frac{e^{-8.52(E+1)}}{\tau\ \delta^2 E^2},$$

where k – interphase interaction coefficient, $k \le 1$.

Considering the dependency (4), formulas (1) - (3) can be written in a more convenient form for calculations:

$$U \ge ke^{8.52(1-s)} - 1, \tag{5}$$

$$S = 1 + 0.117 ln\left(\frac{k}{U+1}\right), \quad (6)$$

$$S' = 1 + 0.117 lnk. \quad (7)$$

From formula (6), it follows that for each value of the flow velocity of SS, the maximum value of the dimensionless radius of the boundary point is achieved when the interphase interaction coefficient is equal to one, $k = 1$, and, taking into account formulas (3), it is determined by the expression:

$$S * 1 - \Delta s, \quad (8)$$

where $S*$ – maximum possible dimensionless radius of the boundary point for the given flow velocity.

4. Results and discussion

Calculations were performed based on formulas (1) – (8) for cases where the dimensionless flow velocity of SS varied in the range from 0 to 150, and the value of the interphase interaction coefficient ranged from 0 to 1. Dependencies of the dimensionless radius of the boundary point on the interphase interaction coefficient at different values of the dimensionless mean cross-sectional velocity of SS were plotted (Figure 1), the maximum possible dimensionless radius of the boundary point on the interphase interaction coefficient (Figure 2), the dependence of the deviation of the dimensionless radius of the boundary point from its maximum value for a given flow velocity on the value of the dimensionless mean cross-sectional velocity of SS (Figure 3), as well as the dependence of the maximum possible dimensionless radius of the boundary point for a given flow velocity on the value of the dimensionless mean cross-sectional velocity of SS (Figure 4).

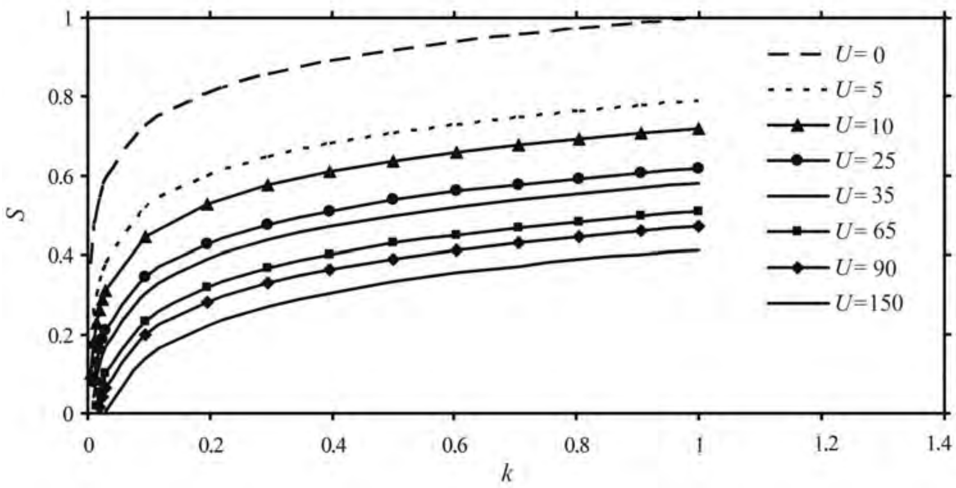

Figure 1 – The dependence of the dimensionless radius of the boundary point on the value of the interphase interaction coefficient at different values of the dimensionless mean cross-sectional velocity of SS.

From Figure 1, it can be observed that the dimensionless radius of the boundary point increases with an increase in the interphase interaction coefficient and decreases with an increase in the dimensionless flow velocity of SS. In the range of variation U from 5 to 150, the dependence on the dimensionless flow velocity of SS, for which the changes in the dimensionless radius of the boundary point do not exceed the precision of engineering calculations, i.e., 13%, is described by a power function with a fractional positive exponent (Figure 5):

$$k' = 0.2453U^{0.2167},$$

where k' – estimated value of the interphase interaction coefficient.

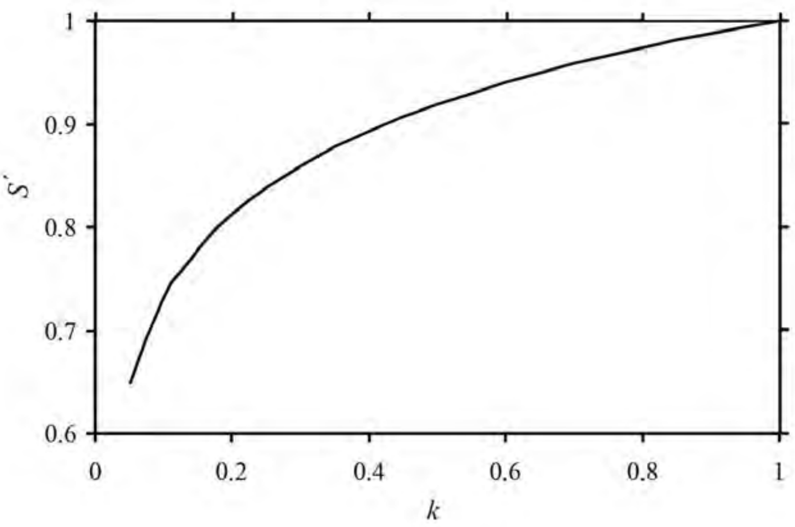

Figure 2 – The dependence of the maximum possible dimensionless radius of the boundary point on the value of the interphase interaction coefficient.

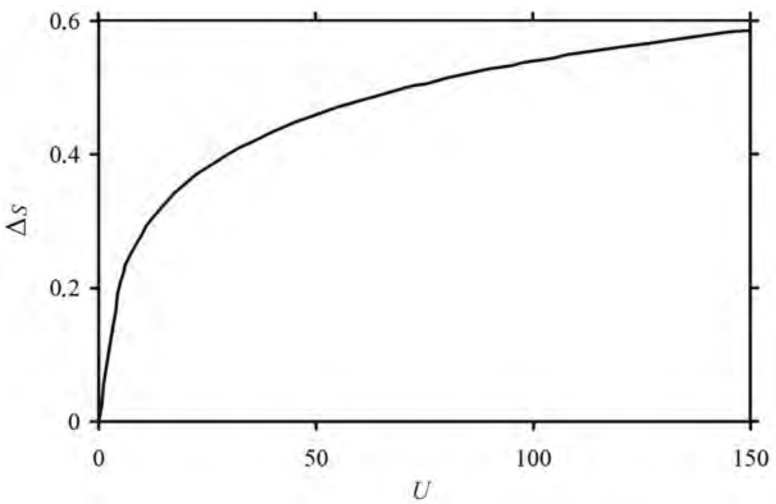

Figure 3 – The dependence of the deviation of the dimensionless radius of the boundary point from its maximum value for a given flow velocity on the value of the dimensionless mean cross-sectional velocity of SS.

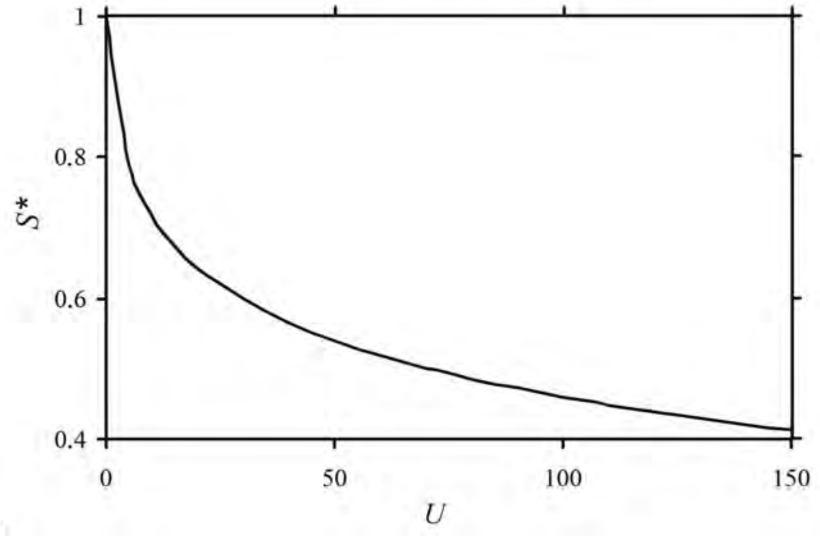

Figure 4 – The dependence of the maximum possible dimensionless radius of the boundary point for a given flow velocity on the value of the dimensionless mean cross-sectional velocity of SS.

Thus, from Figures 1 – 5, it can be inferred that the main changes in the dimensionless radius of the boundary point occur at values of the interphase interaction coefficient less than 0.4.

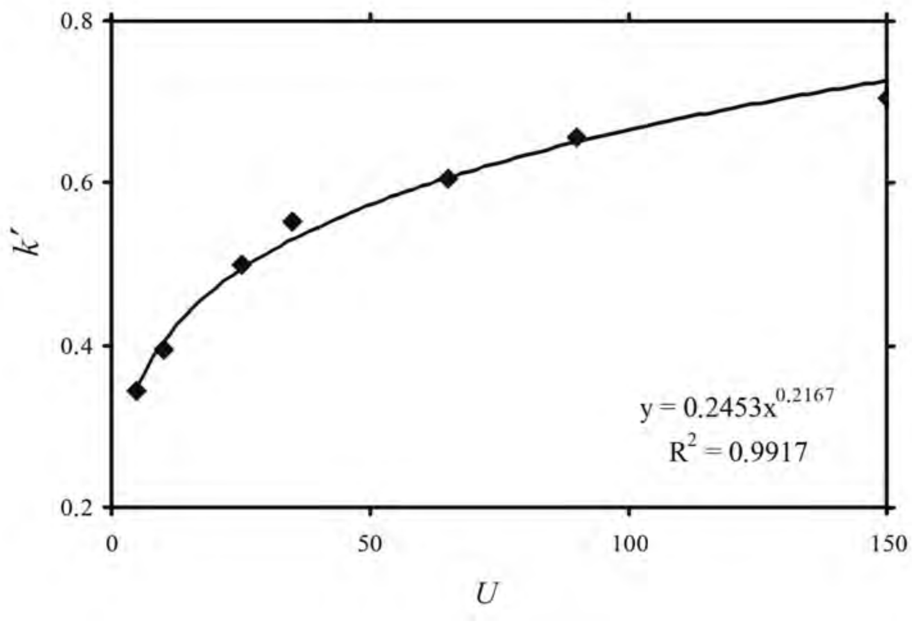

Figure 5 – The dependence of the estimated value of the interphase interaction coefficient on the value of the dimensionless mean cross-sectional velocity of SS.

The analysis of the calculation results indicates the existence of a lower limit for the values of the dimensionless radius of the boundary point, which is different from zero (Figure 6):

$$k \geq k_0 , \qquad k_0 = (U+1)e^{-8.52} ,$$

where k_0 – minimum possible value of the interphase interaction coefficient.

The results of numerical analysis within the range of variation U from 25 to 150 suggest that it is possible to approximate the dependence of the minimum possible value of the interphase interaction coefficient on the dimensionless flow velocity of SS with a linear function for calculations conducted with engineering precision (Figure 6).

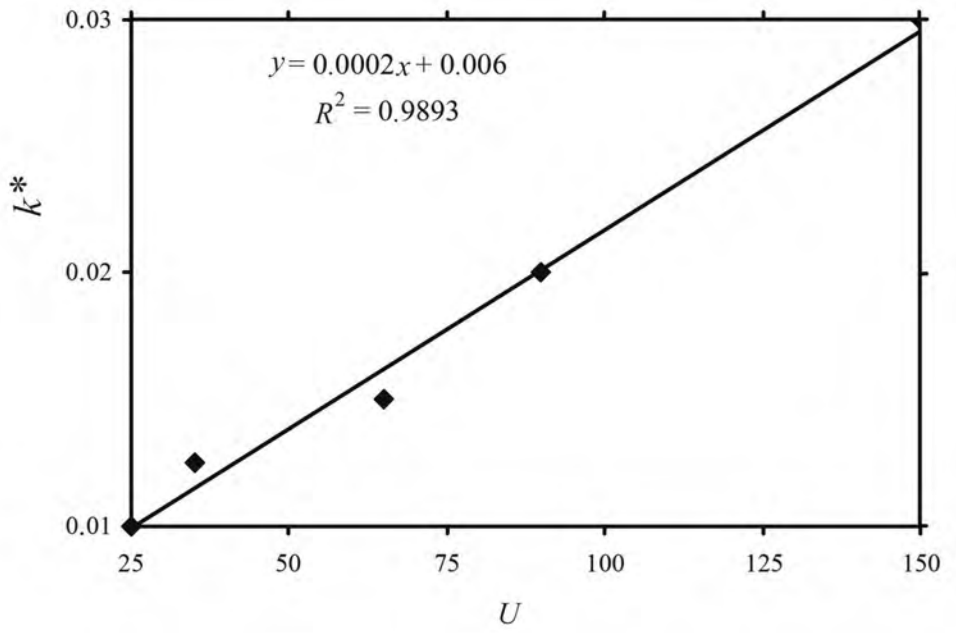

Figure 6 – The dependence of the minimum possible value of the interphase interaction coefficient on the value of the dimensionless mean cross-sectional velocity of SS.

The dependence of the maximum possible dimensionless radius of the boundary point on the value of the interphase interaction coefficient is described by an increasing convex function and significantly exceeds the values of the boundary point radius due to the presence of SS flow (Figure 2). This maximum possible value of the dimensionless radius of the boundary point is independent of the flow velocity of SS but takes into account a complex set of parameters such as the ion-electrostatic and Van der Waals forces' nature, concentration, density, and size of the solid phase of SS, viscosity, and density of the liquid phase of SS, as well as rheological characteristics of the suspension. The dependence of the maximum possible dimensionless radius of the boundary point on the value of the interfacial interaction coefficient actually sets the upper limit, above which the pairwise coagulation bonds between adjacent particles will always be broken or extremely unstable.

The dependence of the deviation of the dimensionless radius of the boundary point from its maximum value for a given flow velocity on the value of the dimensionless mean cross-sectional velocity of SS (Figure 3) indicates that the reduction in this value caused by the flow of SS exceeds 25% of its maximum value as shown in Figure 2. Comparing the values of the dimensionless radius of the boundary point (Figure 1) in the range of low growth intensity (Figure 5) with their corresponding maximum values (Figure 2), it is possible to approximate the dependence of the relative change in the considered value in the range of variation *U* from 5 to 150

$$z = \frac{S' - S}{S'},$$

from the dimensionless flow velocity of SS with the following function (Figure 7):

$$z = 0.147U^{0.3},$$

where z – relative change in the dimensionless radius of the boundary point from its maximum value.

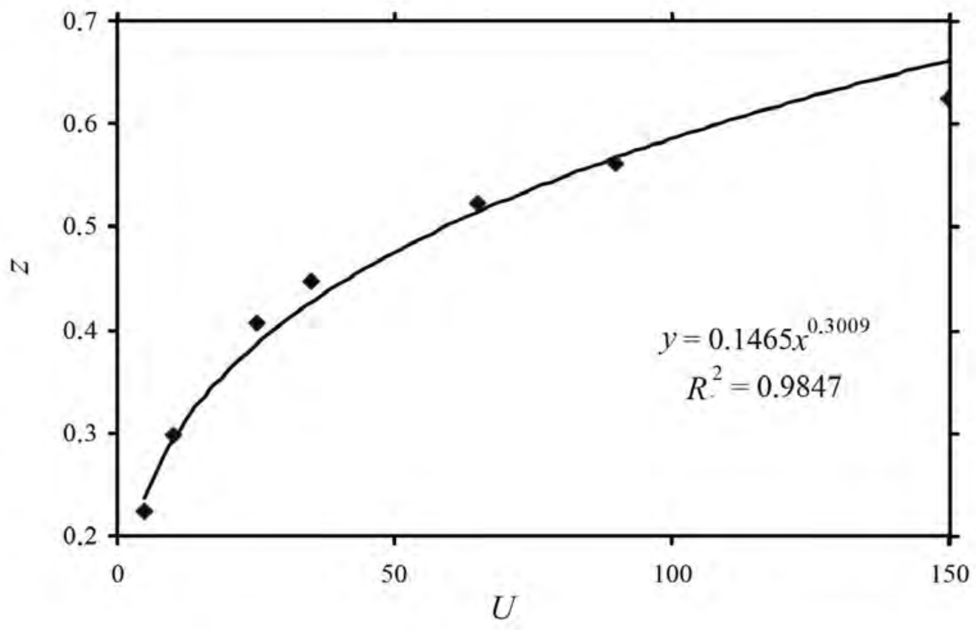

Figure 7 – The dependence of the relative change in the dimensionless radius of the boundary point on the value of the dimensionless cross-sectional average velocity SS

Since the curves shown in Figure 1 represent the area where the paired coagulation bonds between neighboring particles are preserved, they limit the central part of the flow where the suspension's structure will not be disturbed. This part can be considered as the non-deformable core of the flow in a rod regime of suspension flow with pseudoplastic properties. In the part above these curves (Figure 1), the paired coagulation bonds between neighboring particles will be disrupted, creating conditions for shear flow in this part of the cross-sectional area of the pipeline.

Thus, the radius of the boundary point serves as a characteristic of the geometric size of the non-deformable core during SS flow in a rod regime. Unlike known methods for its calculation, the proposed parameter does not consider the existing pressure drop and is determined considering the influence of ion-electrostatic and

Van der Waals forces. Moreover, it takes into account the influence of the average flow velocity of the suspension, not only the initial shear stress but also the effective viscosity of the suspension, as well as the density, concentration, and size of its solid phase.

The obtained results indicate the necessity of further research into the issues of dynamic sedimentation stability of SS during flow through a pipeline in a rod regime, aiming to improve the methods for their hydraulic calculations.

5. Conclusions

Thus, the article investigates and establishes the influence of the non-deformable core radius on the flow of colloidal suspensions (SS) in a pipeline, considering the characteristics of ion-electrostatic and Van der Waals forces, parameters of the solid and liquid phases, the average flow velocity of the suspension, and its rheological properties. This allowed proposing, for the first time, a method to estimate the non-deformable core radius of SS flow in a pipeline under pressure, which differs from existing calculation methods. The proposed method not only relies on the relationship between the initial shear stress and the effective pressure drop but also takes into account the characteristics of ion-electrostatic and Van der Waals forces, parameters of the solid and liquid phases, the average flow velocity of the suspension, and its rheological properties.

A dependence was obtained to estimate the non-deformable core radius of SS flow in a pipeline depending on the average flow velocity of the suspension, its rheological characteristics, and the parameters of ion-electrostatic and Van der Waals forces.

It was found that the non-deformable core radius increases with an increase in the interphase interaction coefficient, with the main changes occurring at interphase interaction coefficient values less than 0.4. Numerical analysis of the results allows stating that the dependence of the dimensionless flow velocity on the interphase interaction coefficient, starting from which the changes in the non-deformable core radius will not exceed 13%, can be described by a power function with a fractional positive exponent.

It is shown that there exists a maximum possible value for the dimensionless radius of the non-deformable core of SS flow, which depends only on the parameters of ion-electrostatic and Van der Waals forces and the rheological characteristics of SS, and does not depend on the average flow velocity. This value limits all possible values of the non-deformable core radius from above. However, as the flow velocity of SS increases, the non-deformable core radius decreases relative to this maximum value, and the higher the flow velocity, the greater the reduction.

The study only explicitly examines the influence of the average flow velocity on the non-deformable core size. The impact of other factors, such as the parameters of ion-electrostatic and Van der Waals forces, concentrations, densities, and particle size of the solid phase of SS, as well as the viscosity and density of the liquid phase of SS, and the rheological characteristics of the suspension are considered comprehensively. This approach allows refining the parameters of SS flow in transitional flow regimes where the boundaries of the non-deformable core of the flow are unstable, and hence existing calculation methods are not applicable. Based on the results obtained in this study, further research is needed to investigate the influence of each of these factors individually. This will help to develop methods to achieve the desired value of the non-deformable core of SS flow at different flow velocities.

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About the authors

Semenenko Yevhen Volodymyrovych, Doctor of Technical Sciences (D.Sc.), Senior Researcher, Head of Department of Mine Energy Complexes, M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Science of Ukraine (IGTM of the NAS of Ukraine), Dnipro, Ukraine, evs_igtm@i.ua.

Tepla Tetyana Dmytrivna, Doctoral Student, Senior Engineer in Department of Mine Energy Complexes, M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Science of Ukraine (IGTM of the NAS of Ukraine), Dnipro, Ukraine, tanialitan9@gmail.com.

Medianyk Volodymyr Yuriiovych, Candidate of Technical Sciences (Ph.D.), Associate Professor, Associate Professor in Department of Mining Engineering and Education, Dnipro University of Technology (NTU "DP"), Dnipro, Ukraine, Medianyk.v.yu@nmu.one.

Skosyrev Viktor Heorhiiovych, Candidate of Technical Sciences (Ph.D.), Associate Professor in Department of Electrification of Industrial Enterprises, Priazovsky State Technical University under the Ministry of Education and Science of Ukraine, Dnipro, Ukraine, evs_post@meta.ua.

Babets Dmytro Volodymyrovych, Doctor of Technical Sciences (D.Sc.), Associate Professor, Professor in Department of Applied Mathematics, Dnipro University of Technology (NTU "DP"), Dnipro, Ukraine, babets.d.v@nmu.one.

ВИЗНАЧЕННЯ РАДІУСУ НЕДЕФОРМОВАНОГО ЯДРА ПОТОКУ ПРИ ТЕЧІЇ СТРУКТУРОВАНОЇ СУСПЕНЗІЇ ПО ТРУБОПРОВОДУ ЗА ТЕОРІЄЮ СТІЙКОСТІ ЛІОФОБНИХ КОЛОЇДІВ

Семененко Є.В., Тепла Т.Д., Медяник В.Ю., Скосирев В.Г., Бабець Д.В.

Анотація. Завданням дослідження є вивчення впливу на радіус недеформованого ядра потоку при перебігу структурованих суспензій з неоднорідною твердою фазою в трубопроводі сил іонно-електростатичної та Ван-дер-Ваальсівської природи, параметрів твердої та рідкої фаз, значення середньої швидкості перебігу суспензії та її реологічно. У статті проаналізовано результати досліджень динамічної седиментаційної стабільності структурованих суспензій, тверда фаза яких представлена твердими частинками різної крупності та щільності, при їх перебігу в стрижневому режимі трубопроводом на основі теорії стійкості ліофобних колоїдів Дерягіна – Ландау – Фейрвей.

Доведено існування меж, що поділяє поперечний переріз потоку на дві області. У центральній частині потоку, усередині цього кордону парні коагуляційні зв'язки між суміжними частинками зберігаються, і в ній структура суспензії не буде порушена. Цю частину пропонується розглядати як ядро потоку, що не деформується, при стрижневому режимі перебігу суспензії з псевдопластичними властивостями. В області зовні цього кордону парні коагуляційні зв'язки між суміжними частинками будуть порушені, що створює умови для зсуву в цій частині поперечного перерізу трубопроводу. На відміну від відомих методів розрахунку недеформованого ядра потоку структурованої суспензії запропонований метод не враховує діючий перепад тиску, проте враховує вплив середньої швидкості перебігу суспензії, вплив не тільки початкового дотичного напруги, але і ефективної в'язкості суспензії, в'язкість і щільність її рідкої фази, і крупність твердої фази, а також сили іонно-електростатичної та Ван-дер-Ваальсівської природи.

Встановлено, що для величини безрозмірного радіусу недеформованого ядра потоку структурованих суспензій існує максимально можливе значення, що залежить тільки від параметрів сил іонно-електростатичної та Ван-дер-Ваальсівської природи та реологічних характеристик структурованих суспензій, і не залежить від середньої швидкості течії.

Ключові слова: ядро потоку, що не деформується, реологічні характеристики, структурована суспензія, ліофобні колоїди, трубопровід.