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ASSESSING THE DYNAMIC SEDIMENTATION STABILITY OF STRUCTURED SUSPENSIONS MADE OF POLYDISPERSE MATERIAL WITH DIFFERENT DENSITY FRACTIONS

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Abstract. The current state of the coal industry was analyzed, and it is determined that one of the obstacles to implement mining and utilization of coal beneficiation waste is a high ash content, which reaches almost 90%. Today, different technologies for combusting coal with such ash content in the form of structured suspensions are developed, for example, combustion in fluidized bed boilers, while no technologies are available for transporting structured suspensions with high ash content. At the same time, the results of a number of studies indicate a significant dependence of the rheological characteristics of structured suspensions, especially dynamic sedimentation stability. Therefore, a pressing task is to study the dynamic sedimentation stability of structured suspensions made of high-ash coal of a polydisperse granulometric composition with the addition of mineral particles of different nature. This task is solved by comparing the gravity and repulsion forces, having an ion-electrostatic and Van der Waals nature, with the forces arising when the fluid flows around two particles of different density and size with taking into account the turbulent component and velocity deficits proportional to hydraulic sizes of interacting particles.

Based on the research results, it is for the first time, when the dependence was obtained between the average flow velocity, at which the aggregative stability of structured suspensions is disturbed, and parameters of the energy interaction between particles, size and density of the solid phase particles, geometric dimensions of the pipe, and rheological characteristics of the structured suspensions. It is established that the main factors determining the aggregative stability of structured suspensions transported through the main pipeline are the particle size and nature of solid material, its mineral inclusions, potential of their surfaces, as well as the rheological characteristics of suspensions. It is determined that an increase in the initial tangential stress decreases rate of velocity, as well an increase in the effective viscosity of the structured suspension. However, as the pipe radius increases, this velocity increases.

Keywords: structured suspensions, dynamic sedimentation stability, hydraulic particle size, density of the solid phase particles, aggregative stability.

Introduction. According to data of various studies [1–9], at least 500 million tons of coal beneficiation wastes with various ash content are concentrated in Ukraine. Mining and disposal of these coal sludge is inevitable and is only a matter of time, since, on the one hand, their processing will increase the production of thermal and electrical energy, and, on the other hand, it will improve the ecological situation in the region allowing the return to the agrarian fund of lands currently occupied by coal beneficiation waste storage facilities. One of the obstacles to the implementation of this is the high ash content of almost 90% of coal sludge. Different technologies for combusting coal with such ash content in the form of structured suspensions (SS) are developed, for example, combustion in fluidized bed boilers [2], while no technologies are available for transporting the SS from coals with such ash content. At the same time, the results of a number of studies indicate that the SS rheological characteristics, especially their dynamic sedimentation stability, depend significantly on this factor.

It is known that the specialists of the Italian company Snamprogetti, using the Reocarb technology, prepared and successfully transported SS from coals with an ash content on a dry weight basis of 15.32%, 12.68%, 10.06%, 7.43% and 4.79% [1, 3, 5, 10]. An analysis of the research results prove that the SS sedimentation stability increases with an increase in the ash content of the initial coal. In this case, there is a clear dependence of the SS rheological characteristics on the ash content: with a decrease in ash content in the studied range at a velocity gradient $\varepsilon = 11c^{-1}$, the viscosity decreases from 10.21 Pa·s to 5.40 Pa·s. Under the same conditions, the deviation rate of the SS behavior from the Newtonian fluid varies from 0.54 to 1.15. With ash content from 0% to 15%, the SS behaves like a dilatant fluid [11]. In this case, the SS dynamic sedimentation stability decreases with an increase in the ash content, and the time required for completing the degradation process almost doubles when the ash content decreases from 16% to 5% [1, 3, 5, 10]. The research results of domestic specialists are known [3, 5, 10–14], which confirm the possibility of preparing SS based on coal with a relatively high ash content. Thus, the specialists of CHEMEK LTD prepared SS based on anthracite sludge with an ash content of 34.5% with a mass concentration of 62.8% and an effective viscosity of 0.82 Pa·s. With these parameters, at a velocity gradient 9 c^{-1}, the SS remains in a stable state for 15 days. The same specialists prepared SS from gas coal sludge with an ash content of 42.86% with a mass concentration of 63.1% and an effective viscosity of 1.1 Pa·s, while sedimentation is stable at a velocity gradient of 9 c^{-1} for 10 days [10 – 14]. Studies of the influence of the coal mineral part individual components on the SS rheological characteristics are also known [13, 15]. In the work [15], the influence on the SS rheological properties of two natural relatively pure components of a mineral part, such as rocks of aluminosilicate clay and quartzite, which are always associated with coal and can get into the beneficiation waste, was studied. The experimental results show that the content of aluminosilicate clay in the mineral part of coal contributes to a decrease in viscosity, while quartzite increases it. At the same time, the influence of rocks, aluminosilicate clay and quartzite on the dynamic or static SS sedimentation stability was not studied.

Thus, it is a pressing task to study the dynamic sedimentation stability of SS of high-ash coals with polydisperse granulometric composition and with mineral particle additives of different nature.

Research methods. The task set is solved by comparing the gravity and repulsion forces, having ion-electrostatic and Van der Waals nature, with the forces arising when the fluid flows around two particles of different density and size with taking into account the turbulent component and velocity deficits proportional to hydraulic sizes of interacting particles.

Theoretical part. The SS dynamic sedimentation stability is the ability to maintain the structure and uniform distribution of the solid phase particles over the suspension volume when it flows through the pipeline [16 – 22]. This model is based on the use of the research results of the stationary SS sedimentation stability from the standpoint of the stability theory of the Derjaguin – Landau, Verwey – Overbeek (DLVO theory) lyophobic colloids. According to this theory, the interaction between the solid phase particles of the SS is assessed from the point of view of the force interaction extrema stability with taking into account the gravity and repulsion forces having ion-electrostatic and Van der Waals nature. The sum extrema abscissas of the considered forces determine the distances between the particles at which irreversible and reversible coagulation processes begin [22]. In this case, the first of the extrema, the maximum, lying closer to the origin of coordinates, determines the beginning of coagulation leading to a disturbance of the SS homogeneity. The second extremum, the minimum, lying farther from the origin of coordinates, determines the beginning of coagulation, which specifies the manifestations of the SS thixotropic properties. The function graph curve intersection point with the abscissa axis, which corresponds to a stable structural suspension state, is located between the studied extrema. Another equilibrium point is located between the function maximum and the origin of coordinates, but this point is not stable, since small deviations from it lead to a disturbance of the SS homogeneity [22].

When studying the SS dynamic sedimentation stability from the standpoint of the DLVO stability theory of lyophobic colloids, in addition to the gravity and repulsion forces having ion-electrostatic and Van der Waals nature, it is necessary to take into account the fluid flow energy, which tends to increase or reduce the distance between the two considered particles [9, 16 – 18, 22, 23]. According to the research results presented in [22], the value of this energy is determined by the velocity difference of the suspension liquid phase at the distance of particles and the difference in the hydraulic sizes of the considered particles in cramped conditions [1, 22, 24 – 26]. However, since the case of particles of the same size and density was studied in [22], the influence of the second component on the SS dynamic sedimentation stability was not taken into account. Thus, the results of this work are only applicable for the SS solid phase, which is represented by a material that is homogeneous in size and mineral composition. The fractions, the particles of which determine the suspension solid phase ash content, differ from the coal fractions primarily in particle density and size, and the influence of these factors in most practical cases cannot be neglected. Thus, in order to construct a mathematical model for assessing the dynamic and static SS sedimentation stability, it is necessary to perform the same transformations as in [22], but for the case when the particle size and density of the interacting particles are different.

Thus, having considered the ratio of the gravity and repulsion forces, having ion-electrostatic and Van der Waals nature, with the forces of gravity and repulsion caused by the SS flow through the pipeline, after conversion, taking into account the assumptions introduced in [22] and dimensionless variables, the following condition for the SS destruction during its flow through the pipeline can be obtained:

$$y\,ln\left(1+e^{-y}\right) < E_0\left(y-E_1\right)^2 y + E\,, \qquad (1)$$

$$E_0 = \left(k_\tau + k_\eta u\right)\Theta_0 \frac{Ar-1}{1+ArS}\delta^2, \quad E_1 = \Theta_1(1-w)\delta^2\sqrt{\frac{1+ArS}{k_\tau + k_\eta u}}Ar(1-S)^n,$$

$$E = \frac{A\chi}{24\pi\varepsilon_n\varphi_\delta^2}, \; \Theta_0 = \frac{\tau_0 e^{8,56s}}{17,54\varepsilon_n\varphi_\delta^2\chi^2}, \; \Theta_1 = \frac{0,54}{e^{4,26s}}\frac{g\chi R^3}{\nu}\sqrt{\frac{\rho_f}{\tau_0}},$$

$$y = \chi h, \quad u = \frac{\eta V}{\tau_0 R}, \; s = \frac{r_T}{R}, \quad w = \frac{r'^2 Ar'}{r^2 Ar}, \quad \delta = \frac{r}{R}, \quad Ar = \frac{\rho_s - \rho_f}{\rho_f},$$

where y – dimensionless distance between particles, m; χ – inverse Debye radius, m^{-1}; ε_n – absolute dielectric water permeability, F/m; r – radius of the first type solid particles, m; r' – radius of the second type solid particles, m; φ_δ – potential of the diffuse of the double electric layer (DEL) particles on the surface of solid particles, V; h – distance between particles; A – the Hamaker constant, J; w – parameter that takes into account the difference in density and size of interacting particles; n – exponent [1, 22, 24–26]; r_T – current radius value; k_τ, k_η – approximation parameters for the solution of the Buckingham equation [5, 22]; V – the average SS velocity for section; u – the dimensionless average SS velocity for section; ν – kinematic viscosity coefficient of the SS liquid phase; τ_0 – initial tangential SS stress; η – effective SS viscosity; Ar – the Archimedes parameter of the first type of particles; it is assumed that $Ar > 1$; Ar' – the Archimedes parameter of the second type of particles; g – acceleration of gravity; ρ_f – the SS liquid phase density; R – pipeline radius; π – a constant equal to 3.14; S – the SS volume concentration.

Considering inequality (1) at the maximum of the resultant force and performing actions similar to those described in [22], after all the transformations, the following dependence is obtained for the average suspension velocity, which ensures the destruction of paired coagulation bonds between adjacent particles of different size and density:

$$V > U\frac{k_\eta}{k_\tau}\frac{\tau_0 R}{\eta}, \tag{2}$$

$$U = \left(\frac{\omega}{\Theta}\right)^2 - 1, \tag{3}$$

$$\Theta = \Theta''\sqrt{\frac{Ar-1}{1+ArS}}\delta, \quad \omega = 1 + \Theta'(1-S)^n Ar\sqrt{Ar-1}(1-w),$$

$$\Theta'' = \frac{0{,}09\,\mathrm{e}^{4{,}26(s+E)}}{\varepsilon_n\varphi_\delta^2}\sqrt{\frac{Ak_\tau\tau_0}{\rho_f\chi}}, \quad \Theta' = 0{,}163\,\mathrm{e}^{4{,}22E}\sqrt{\frac{\rho_f}{\varepsilon_n}\frac{gr^3}{\nu\varphi_\delta}},$$

where U – the dimensionless average suspension velocity, which ensures the destruction of paired coagulation bonds between adjacent particles of different size and density; ω – parameter that takes into account the heterogeneity influence of the properties of interacting particles; Θ – rheological parameter.

For the case of homogeneous particles in formula (3) it is necessary to take that $\omega = 1$, which leads to the following expression

$$U' = \frac{1-\Theta^2}{\Theta^2}, \quad (4)$$

where U' – the dimensionless average suspension velocity, which ensures the destruction of paired coagulation bonds between adjacent particles of the same size and density.

Using formulas (3) and (4), it is possible to assess the relative change in the value U due to the difference in the density and size of interacting particles according to the following expression:

$$W = \frac{\omega^2 - 1}{1-\Theta^2}, \quad (5)$$

where W – relative change in value U due to the difference in the density and size of interacting particles.

Results and discussion. It is seen from formula (3) that the following restrictions are valid for the parameters ω and Θ:

$$\Theta < \omega, \quad \Theta < 1,$$

which imposes the following condition on the value w:

$$w < \langle w \rangle,$$

$$\langle w \rangle = 1 + \frac{1-\Theta}{\Theta'(1-S)^n Ar\sqrt{Ar-1}}, \quad (6)$$

where $\langle w \rangle$ – the maximum possible value of the parameter that takes into account the difference in the density and size of interacting particles.

It is easy to show that the heterogeneity influence of the properties of interacting particles can be neglected if $\omega \approx 1$, that is, when the following inequality is valid:

$$[w] \le w,$$

$$[w] = 1 - \frac{0{,}1}{\Theta'(1-S)^n Ar\sqrt{Ar-1}}, \quad (7)$$

where $[w]$ – the minimum significant value of the difference between the hydraulic sizes of interacting particles.

Based on formulas (6) and (7), it is possible to determine the range of parameter change that takes into account the difference in density and size of interacting particles, as well as the width of this range:

$$1-\frac{0{,}1}{\Theta'(1-S)^n Ar\sqrt{Ar-1}} \le w \le 1+\frac{1-\Theta}{\Theta'(1-S)^n Ar\sqrt{Ar-1}},$$

$$\Delta w=\frac{1{,}1-\Theta}{\Theta'(1-S)^n Ar\sqrt{Ar-1}},$$

where Δw – the width of value w range of changes.

According to formulas (2) – (5), taking into account restrictions (6) and (7), calculations were performed, the results of which are presented in Figs. 1 and 2. A dependence of a wide range of changes in the absolute value (Fig. 1) of the dimensionless average suspension velocity, which ensures the destruction of paired coagulation bonds between adjacent particles of different size and density, and its relative change (Fig. 2) on the rheological parameter at various values of the parameter, which takes into account the heterogeneity influence of the properties of interacting particles, is indicated.

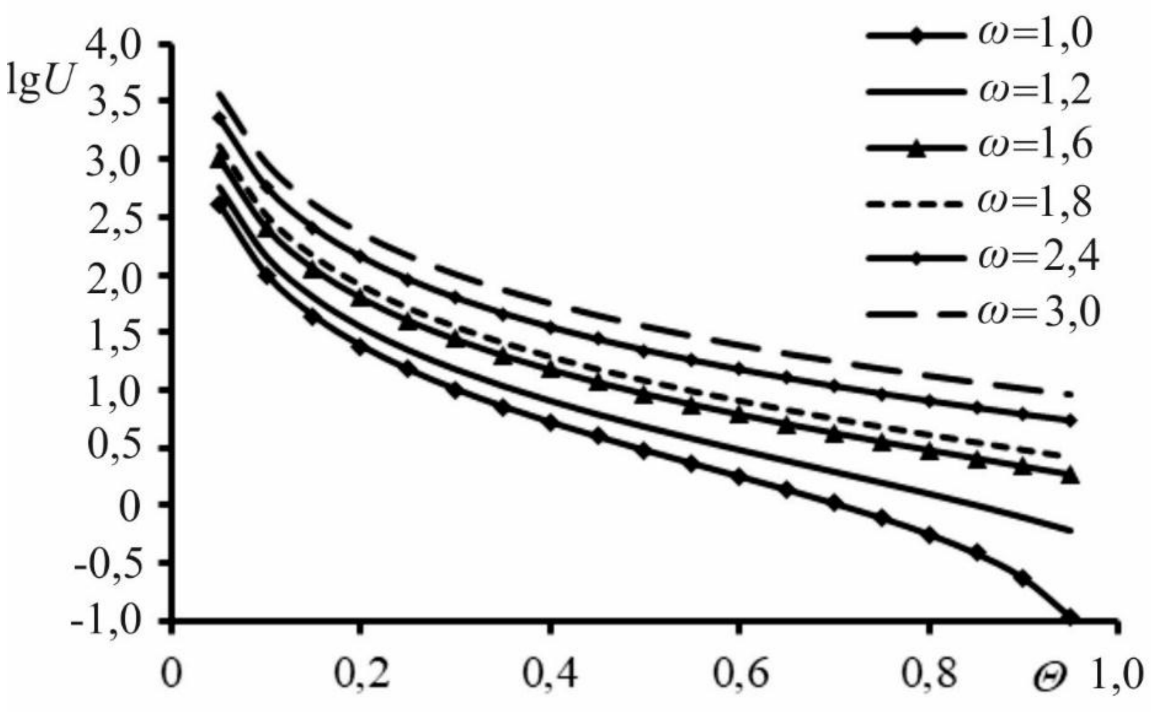

Figure 1 – Dependence of the dimensionless average suspension velocity, which ensures the destruction of paired coagulation bonds between adjacent particles of different size and density, on the rheological parameter at various values of the parameter, which takes into account the heterogeneity influence of the properties of interacting particles

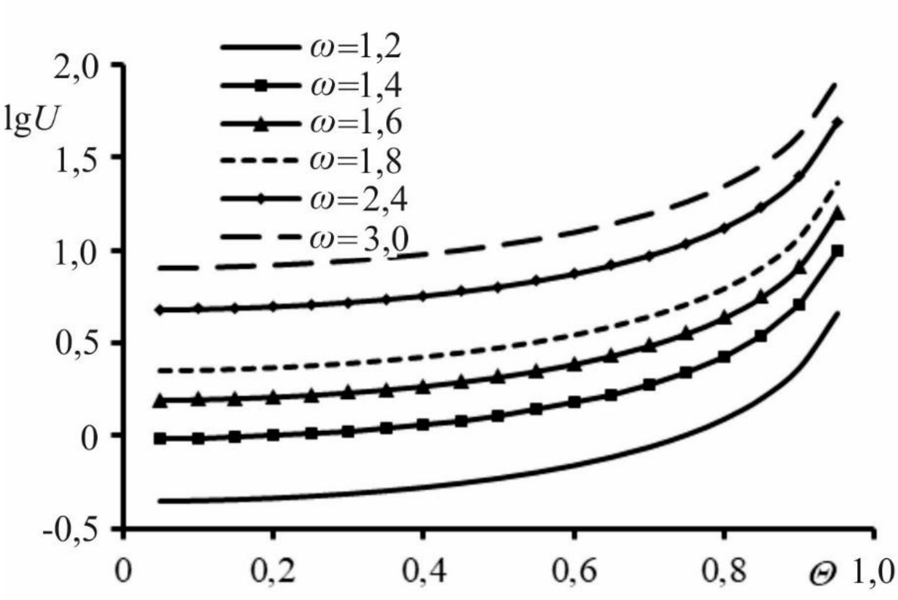

Figure 2 – Dependence of the relative change in value U due to the difference in the density and size of the interacting particles on the rheological parameter at different values of the parameter, which takes into account the heterogeneity influence of the properties of interacting particles

The calculation results necessitate a detailed research of influence of differences in the size and density of interacting particles on the SS dynamic sedimentation stability.

Conclusions. Thus, the hypothesis of the mechanism of the SS aggregative stability in dynamics is developed and specified with taking into account the heterogeneity of the properties of the solid phase particles. This made it possible, based on a comparison of the binding energy of the solid material heterogeneous particles in their coagulation structure and the external energy of the fluid flow directed at breaking this bond, to determine the value of the average flow velocity in a circular tube, at which the SS aggregative stability is disturbed.

It is revealed that the main factors determining the aggregative stability of structured suspensions transported through the main pipeline are the particle size and nature of solid material, its mineral inclusions, potential of their surfaces, as well as the SS rheological characteristics.

It is for the first time, when the dependence of the average flow velocity, at which the SS aggregative stability is disturbed, on the parameters of the energy interaction between particles, the size and density of the solid phase particles, the geometric dimensions of the pipe, and the SS rheological characteristics, was obtained. It is determined that an increase in the initial tangential stress decreases the velocity value, as well an increase in the SS effective viscosity. However, as the pipe radius increases, this velocity increases.

The obtained formulas made it possible to study the influence of the SS rheological characteristics and the pipeline radius on the flow velocity, at which its aggregative stability is disturbed for the case when the solid phase is represented by particles of different density and size. It is established that, compared with the case of the solid phase homogeneous particles, the flow velocity at which its aggregative stability is disturbed increases in proportion to the square of the difference between the hydraulic sizes of heterogeneous particles.

For the case of the SS pressure flow from heterogeneous materials in pipelines, the minimum difference value between the hydraulic particle sizes of the solid phase was assessed, according to which the influence of the heterogeneity of the properties of solid particles on the velocity of the suspension aggregative stability loss can be neglected. It is determined that such a difference value between the hydraulic sizes of the solid phase particles is directly proportional to the potential of the diffuse of the double electric layer particles on the surface of these solid particles and the square root of the absolute dielectric permeability of the SS liquid phase, and also inversely proportional to the particle size and the square root of their density.

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ОЦІНКА ДИНАМІЧНОЇ СЕДИМЕНТАЦІЙНОЇ СТІЙКОСТІ СТРУКТУРОВАНИХ СУСПЕНЗІЙ З ПОЛІДІСПЕРСНОГО МАТЕРІАЛУ З ФРАКЦІЯМИ РІЗНОЇ ЩІЛЬНОСТІ

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Аннотация. Проаналізовано сучасний стан вугільної промисловості та встановлено, що однією з перепон на шляху реалізації видобутку та утилізації відходів вугільного збагачення є висока зольність, яка досягає майже 90%. Якщо технології спалювання вугілля з такою зольністю у вигляді структурованих суспензій вже розроблені, наприклад, спалювання в котлах киплячого шару, то технології транспортування структурованих суспензій з високим вмістом зольності на сьогоднішній день відсутні. При цьому результати ряду досліджень свідчать про суттєву залежність реологічних характеристик структурованих суспензій особливо динамічної седиментаційної стабільності. Тому актуальним завданням є дослідження динамічної седиментаційної стабільності структурованих суспензій з високо зольного вугілля полідисперсного гранулометричного складу з додаванням мінеральних частинок різної природи. Досягнення поставленого завдання здійснюється на підставі порівняння сил тяжіння та відштовхування, які мають іонно-електростатичну та Ван-дер-Ваальсовскую природу, з силами, що виникають при обтіканні потоком рідини двох частинок різної щільності та крупності, з урахуванням турбулентної складової та дефіцитів швидкостей, пропорціональних гідравлічним крупностям частинок, які взаємодіють.

За результатами досліджень вперше отримано залежність середньої швидкості потоку, при якій порушується агрегативна стійкість структурованих суспензій, від параметрів енергетичної взаємодії між частинками, крупністю та щільністю частинок твердої фази, геометричних розмірів труби та реологічних характеристик структурованих суспензій. Показано, що основними факторами, які обумовлюють агрегативну стійкість структурованих суспензій, що транспортуються магістральним трубопроводом, є крупністю частинок та природа твердого матеріалу, його мінеральні включення, потенціал їх поверхонь, а також реологічні характеристики суспензій. Встановлено, що підвищення початкової дотичної напруги знижує величину швидкості, так само як підвищення ефективної в’язкості структурованої суспензії. Однак зі збільшенням радіусу труби ця швидкість збільшується.

Ключові слова: структуровані суспензії, динамічна та седиментаційна стабільність, гідравлічна крупність, щільність частинок твердої фази, агрегативна стійкість.

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