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INFLUENCE OF THE PROPERTIES OF SOLID PARTICLES ADDED TO A STRUCTURED SUSPENSION ON ITS DYNAMIC SEDIMENTATION STABILITY

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Abstract. The research paper analyzes previous studies of the influence of two natural relatively pure aluminum oxides on rheological properties of structured suspensions. The results of the research show that the content of these materials in the mineral part of coal contributes to a decrease in viscosity inversely proportional to the ash content of coal to a certain fractional degree. The analysis showed that the effect of additions of mineral particles, their size and concentration on the dynamic or static sedimentation stability of structured suspensions has never been studied.

The aim of the research paper is to study the effect of additions of mineral particles of polydisperse granulometric composition of different nature on the dynamic sedimentation stability of a structured suspension of high-ash coals.

The solution of the problem is carried out by comparison of the forces of attraction and repulsion, which are characterized by an ion-electrostatic and van der Waals nature, with the forces , which arise when a fluid flows around two particles of different density and size, with taking into account the turbulent component and speed deficits proportional to the hydraulic sizes of interacting particles.

As a result of the research, the authors developed and specified the hypothesis of the mechanism of aggregative stability of a structured suspension in dynamics. It takes into account the heterogeneity of the properties of particles of the solid phase, which made it possible to establish the value of the average flow velocity in a circular tube, at which the aggregative stability of a structured suspension is disturbed. It is found that the particle size, the nature of the solid material and its mineral inclusions, their surface potential, and rheological characteristics are the main factors, which determine the aggregative stability of structured suspensions.

The influence of rheological characteristics of the structured suspension and the radius of the pipeline on the flow velocity, at which its aggregative stability was disturbed, was studied for the case when the solid phase was represented by particles with different density and fineness. In addition, the minimum possible ratio of the Archimedes parameters of the interacting particles, at which the effect of pseudo-homogeneity occurred, was evaluated.

Keywords: pseudo-homogeneity, rheological characteristics, structured suspension, effective viscosity, ash content.

1. Introduction

According to the researches [1–9], at least 500 million tons of coal wastes with various ash content are located in Ukraine. Thus, the extraction and disposal of this coal sludge is inevitable and is only a matter of time. On one hand, their processing will increase the production of heat and electricity. On the other hand, it will improve the environmental situation in the region. This will enable us to return to the agrarian fund the lands currently occupied by coal waste storage facilities. One of the obstacles to implementation of this project is the high ash content, which is 90% of coal sludge. The technologies for burning coals with such ash content in the form of structured suspensions (SS) have already been created, in particular, combustion in fluidized bed boilers [2]. However, there are no technologies for transporting SS from coals with such ash content. At the same time, the results of numerous studies indicate a significant dependence of the SS rheological characteristics, especially the dynamic sedimentation stability, on this factor.

The Italian company SNAPROGETTI that was using the REOCARB technology prepared and successfully transported SS from coals with an ash content on a dry weight of 15.32%, 12.68%, 10.06%, 7.43% and 4.79% [1, 3, 5, 10]. The analysis of the results of these studies showed that the sedimentation stability of the SS increases with the increase in the ash content of the initial coal. At the same time, we have noticed a clear dependence of the rheological characteristics (RCh) of the SS on the ash content. With a decrease in the ash content in the studied interval at a velocity gradient ε = 11 s^{-1}, the viscosity decreases from 10.21 Pa·s to 5.40 Pa·s. Under the same conditions, the degree of deviation of the SS behavior from the Newtonian fluid varies from 0.54 to 1.15. At ash content from 0% to 15%, SS behaves like a dilatant liquid [11].

At the same time, the dynamic sedimentation stability of SS decreases with increasing ash content, and the time required to complete the degradation process practically doubles when ash content decreases from 16% to 5% [1, 3, 5, 10]. The results of studies 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, specialists from SPA HAIMEK prepared SS based on anthracite sludge, with an ash content of 34.5%, mass concentration of 62.8%, and an effective viscosity (EV) of 0.82 Pa·s. With these parameters, at a velocity gradient of 9s^{-1}, the SS remains in a stable state for 15 days. The same specialists prepared SS from gaseous coal sludge with ash content of 42.86% with mass concentration of 63.1% and EV of 1.1 Pa·s, sedimentation stable at a velocity gradient of 9 s^{-1} for 10 days [10–14]. We have taken into consideration the research of the influence of individual components of the mineral part of coal on the SS RCh [13, 15]. The source [15] studies the effect of two natural relatively pure aluminum oxides on the rheological properties of SS. The results of experiments show that content of these materials in the mineral part of coal contributes to a decrease in viscosity inversely proportional to the ash content of coal to a certain fractional degree.

The sources [1, 11] show the results of studies of the effect of ash content on SS RCh. It is stated that an increase in the ash content of the dispersed phase in all cases leads to an increase in the initial shear stress (ISS) and EV of suspensions, which is most pronounced at A^d > 45%. At the same time, numerical processing of the experimental data makes it possible to recommend an exponential function to describe this dependence.

The results of the experiments were obtained in the study of the RCh of coal SS with different particle sizes of the solid phase [9]. The numerical processing of these results indicates a linear dependence of the ISS on the volume concentration, the free term of which is determined by the size of the solid particles.

There are also the experiments done by the researchers of the Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine. These studies are conducted on the basis of industrial experiments at the processing plant of the Mining and Metallurgical Combine in Volnogorsk [16], the results of which indicate a power-law dependence of the relative EV of SS on the size and concentration of the solid phase.

V. Murko, relying on the studies carried out for coals, recommended a linear regression dependence of the ISS on the concentration and ash content of the solid phase of the suspension [10].

The scientists agree that SS RCh depend most strongly on the content of fine fractions in the mixture of particles. Different groups of researchers distinguish different upper limits of these fractions: 40 μm, 60 μm, 74 μm. Such particles form stable SS due to the structural or coagulation bonds that arise between them. A measure of the stability of such SSs is the rate of sedimentation of particles of the solid phase, which is extremely low in stable media.

There are numerous studies of foreign authors on the effect of various surfactants on the sedimentation stability of suspensions [17–22]. It is proven that this stabilization method significantly depends on the size of magnetite particles [18]. Positive results were obtained on ensuring stability of the suspensions by such suspending agents as methylcellulose, hydroxypropylmethylcellulose, sodium carboxymethylcellulose, and psyllium mucus Plantago ovata [19, 20]. There are also studies on the stability of suspensions that take into account its rheology, zeta potential, and particle size of the solid fraction, which are considered monodisperse [22]. However, none of the researchers studied the effect of additions of mineral particles, their size and concentration on the dynamic or static sedimentation stability of SS.

Thus, a necessary task is to investigate the effect of additions of mineral particles of polydisperse granulometric composition of different nature on the dynamic sedimentation stability of SS from high-ash coals.

2. Methods

The solution of the problem is carried out by comparison of the forces of attraction and repulsion, which have an ion-electrostatic and van der Waals nature, with the forces, which arise when a fluid flows around two particles of different density and size, with taking into account the turbulent component and speed deficits proportional to the hydraulic sizes of interacting particles.

The dynamic sedimentation stability of SS is understood as the ability to maintain the structure and uniform distribution of particles of the solid phase over the volume of the suspension during its flow through the pipeline [17–23]. This model is based on the results of the studies of the stationary sedimentation stability of SS from the standpoint of the theory of stability of lyophobic colloids of Deryagin - Landau - Fairwijk - Overbeck (DLVO theory). It was established when the interaction between particles of the solid phase of the SS was evaluated from the point of view of the stability of the extrema of the force interaction, with taking into account the forces of attraction and repulsion, having ion-electrostatic and van der Waals nature. The abscissas of the extrema of the sum of the considered forces determine the distances between the particles, at which the processes of irreversible and reversible coagulation begin [23]. In this case, the first of the extremums (the maximum lying closer to the origin of coordinates) determines the onset of coagulation, leading to a disturbance of the homogeneity of the SS. The second extremum (the minimum lying farther from the origin of coordinates) determines the onset of coagulation, which determines the manifestations of the thixotropic properties of the SS. That is why knowing of the coordinates of these extrema, as well as the values of the function in them, is important for ensuring the aggregative stability, as well as the dynamic and static sedimentation stability of the SS. Between the considered extrema, there is a point of intersection of the curve of the graph of the function with the abscissa axis, which corresponds to a stable structural state of the suspension. Another equilibrium point is located between the maximum of the function and the origin, but this point is not stable, small deviations from it lead to disturbance of the homogeneity of the SS [23].

When studying the dynamic sedimentation stability of SS from the standpoint of the theory of stability of DLVO lyophobic colloids, in addition to the forces of attraction and repulsion (which have an ion-electrostatic and van der Waals nature) it is necessary to take into account the energy of the fluid flow, which, according to some authors, is proportional to the square of the difference in the velocities of the considered particles relative to each other [9, 17–24]. According to the research results presented in [23], an assessment of the flow energy of the liquid phase SS, which tends to disrupt the structure and uniform distribution of solid phase particles throughout the volume of the suspension during its turbulent flow through the pipeline, was determined. We assume that this energy is the kinetic energy of the relative motion of particles and arises due to the difference in the velocities of the phases, which, in turn, is proportional to the hydraulic fineness of the particle in cramped conditions [1, 23–27]. Using this algorithm, in [23], a dependence was obtained for the average suspension velocity, which ensures the destruction of pairwise coagulation bonds between adjacent particles, which was subsequently generalized by the authors to the case when the interacting particles have different densities and sizes. An analysis of the obtained formulas shows that the difference in the properties of the interacting particles is taken into account by the difference between their hydraulic sizes:

$$\Delta w = \frac{2g}{9\nu}\left(r^2 Ar - r'^2 Ar'\right)(1-C)^n, \qquad (1)$$

$$n = lg\left(\frac{10^5 \nu^2}{8gr^3}\right), \quad Ar = \frac{\rho_s - \rho_f}{\rho_f}, \quad Ar' = \frac{\rho_s' - \rho_f}{\rho_f},$$

where Δw is difference between hydraulic sizes of interacting particles, m/s; n is exponent [1, 22, 24–26]; ν is coefficient of kinematic viscosity of the liquid phase SS; Ar is Archimedes parameter; g is acceleration of gravity, m^2/s; ρ_f is liquid phase density SS, kg/m^3; r' is radius of non-coal particle, m; Ar' is the Archimedes parameter of a non-coal particle.

In order to use the formulas proposed in [23], it is necessary to estimate the intervals of variation of the parameter Δw. The value of Δw will be zero if the two considered particles have the same densities and diameters. Otherwise, that is, when both interacting particles have different densities and different diameters, the value Δw will be proportional to the hydraulic fineness of coal particles:

$$\Delta w = Ww, \qquad (2)$$

$$W = 1 - \left(\frac{r'}{r}\right)^2 - \frac{1+Ar}{Ar}\left(\frac{Ar'}{Ar} - 1\right)\left(\frac{r'}{r}\right)^2, \qquad (3)$$

where W is integral parameter of inhomogeneity of particles of the solid phase.

If coal particles and impurities differ in both of these parameters, then the value of Δw is determined by formulas (2) and (3), and if particles of the same density are considered, then by the formula

$$\Delta w = W_r \cdot w, \quad (4)$$

$$W_r = 1 - \left(\frac{r'}{r}\right)^2, \quad (5)$$

in the case when only the particle density is different, then we use:

$$\Delta w = -W_\rho \cdot w, \quad (6)$$

$$W_\rho = \frac{1 + Ar}{Ar}\left(\frac{Ar'}{Ar} - 1\right), \quad (7)$$

where W_r is the parameter of inhomogeneity of particles of the solid phase in terms of size; W_ρ is the density inhomogeneity parameter of the phase particles in terms of density.

Analyzing the formulas (2)–(7) to determine the integral parameter of the inhomogeneity of the particles of the solid phase of the suspension, we can propose the following dependencies:

$$W = (1 + W_\rho)W_r - W_\rho, \quad (8)$$

It can be seen from formula (8) that the pseudo-homogeneity effect is possible, when $W = 0$ and when solid particles of different size and density do not affect the stability of the SS. This is realized at the following values of the parameters of the inhomogeneity of particles of the solid phase in size and density:

$$W_r' = \frac{W_A}{1 + W_A}, \quad (9)$$

where W_r' is the value of the parameter of inhomogeneity of particles of the solid phase in terms of size, at which the effect of pseudo-homogeneity happens; W_A is the effective parameter of the inhomogeneity of solid phase particles in terms of density.

Considering the formulas (4)–(9), we obtain expressions for calculating the parameters of particles of the solid phase, in which the effect of pseudo-homogeneity happens:

$$\left(\frac{Ar'}{Ar}\right)_0 = 1 + \frac{Ar}{1 + Ar}\left(\frac{r}{r'}\right)^2, \quad (10)$$

$$\left(\frac{r'}{r}\right)_0 = \frac{1}{\sqrt{1+\frac{1+Ar}{Ar}\left(\frac{Ar'}{Ar}-1\right)}}, \tag{11}$$

where $\left(\frac{Ar'}{Ar}\right)_0$, $\left(\frac{r'}{r}\right)_0$ are the values of the parameters of the particles of the solid phase, at which the effect of pseudo-homogeneity happens; W'_ρ is the value of the density inhomogeneity parameter of the solid phase particles, at which the effect of pseudo-homogeneity is realized.

Under the condition that the formula (11) should not be a complex number, a restriction on the ratios of the Archimedes parameters of the interacting particles follows:

$$\frac{Ar'}{Ar} > \left[\frac{Ar'}{Ar}\right], \tag{12}$$

$$\left[\frac{Ar'}{Ar}\right] = \frac{1}{1+Ar}, \tag{13}$$

where $\left[\frac{Ar'}{Ar}\right]$ is the minimum possible ratio of the Archimedes parameters of the interacting particles, at which the effect of pseudo-homogeneity is realized.

3. Results and discussion

According to the formulas (2)–(13), we calculate the corresponding dependencies for the characteristic intervals of variation of the quantities included in them and the parameters used (Fig. 1–8).

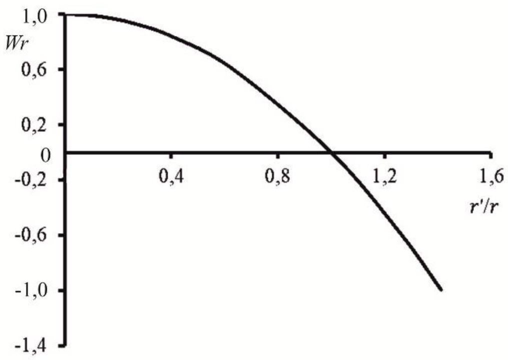

Figure 1 – Dependence of the parameter of inhomogeneity of particles of the solid phase by size W_r on $\frac{r'}{r}$ when the argument is less than 1.4

These figures show that the dependence of the value of W_r on the ratio of particle radii is described by a decreasing function, the value of which changes significantly when the argument is more than 1.4. In this case, this value remains more than zero, and then becomes negative until the value of the argument equal one (Fig. 1, 2). In contrast to the value of W_r, the dependences of W_ρ on the ratio of the Archimedes parameters of particles are described by increasing functions, the values of which are monotonous and not so significant , as in the case with W_r, throughout the entire interval of the change in the argument (Fig. 3, 4).

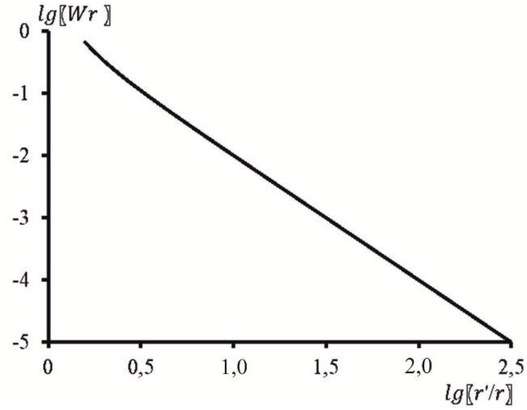

Figure 2 – Dependence $-lg W_r$ on $lg\frac{r'}{r}$ when the $\frac{r'}{r}$ is more than 1.4

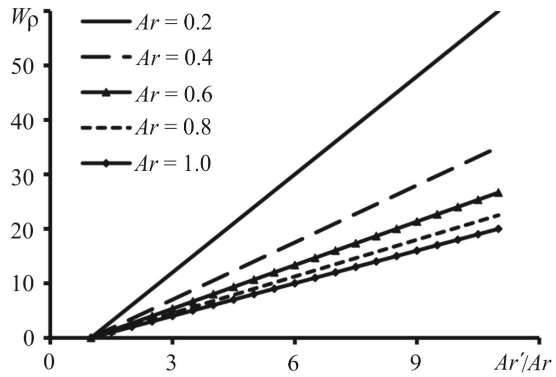

Figure 3 – Dependence W_ρ on the value $\frac{Ar'}{Ar}$ for values of Ar not more than 1.0

The dependence of the estimate of the Archimedes parameters on the estimate of their radii, in which the pseudo-homogeneity effect is realized, about the occurrence of a decreasing estimate, and the most significant changes when the argument is less than the estimate (Fig. 5, 6). In this case, the values are entered into the values of the argument of smaller and smaller values of the larger values of the Archimedes parameter, the smaller values of the functions (Fig. 5, 6).

The dependence of the ratio of the radii of solid particles on the ratio of the Archimedes parameters, at which the pseudo-homogeneity effect is realized, is described by a decreasing function and is characterized by a monotonic change over the entire range. In this case, large values of the Archimedes parameter correspond to large values of the function (Fig. 7).

The minimum possible ratio of the Archimedes parameters of interacting particles, in which the pseudo-homogeneity effect is realized in the entire range of values of the Archimedes parameters is less than unity (Fig. 8), which provides unambiguously real values of the quantity determined by formula (12).

The dependence of the ratio of the Archimedes parameters on the ratio of their radii, at which the pseudo-homogeneity effect is realized, is described by a decreasing function, and is characterized by the most significant changes when the argument is less than one (Fig. 5).

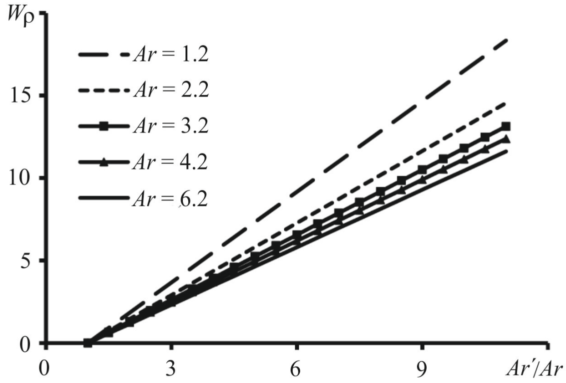

Figure 4 – Dependence W_A on the value $\frac{Ar'}{Ar}$ for values of Ar more than 1.0

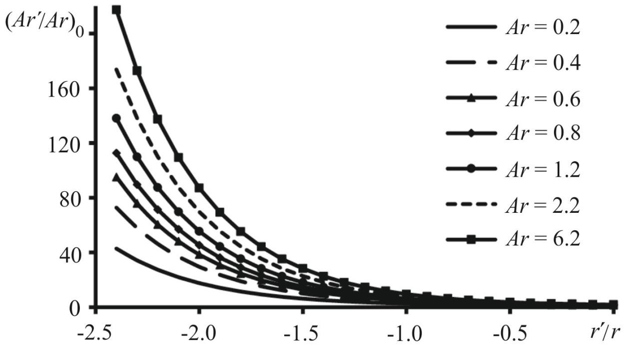

Figure 5 – Dependence $\left(\frac{Ar'}{Ar}\right)_0$ on $\frac{r'}{r}$, if the argument is less than 1.0 with different values of Ar

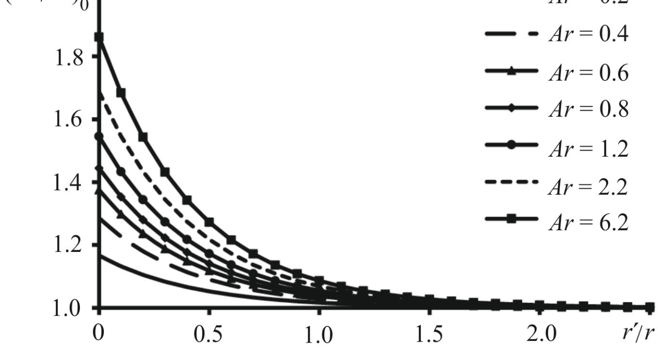

Figure 6 – Dependence $\left(\frac{Ar'}{Ar}\right)_0$ on $\frac{r'}{r}$, if the argument is more than 1.0 with different values of Ar

When the ratio of particle radii is greater than one, the ratio of the Archimedes parameters changes insignificantly, from 0.7 to 1.0 (Fig. 6). In this case, an asymptotic approximation of the values of the function to the minimum possible ratios of the Archimedes parameters of the interacting particles is observed, at which the pseudo-homogeneity effect is realized, which are determined by formulas (12) and (13) (Fig. 8). At the same time, in the region of argument values less than one, large values of the Archimedes parameter correspond to large values of the function, and vice versa when argument values greater than one, (Fig. 5, 6).

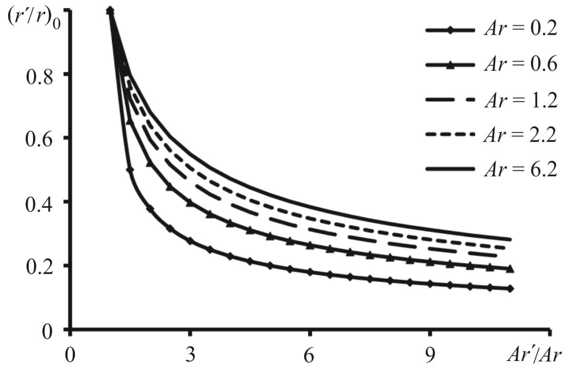

Figure 7 – Dependence $\left(\frac{r'}{r}\right)_0$ on $\frac{Ar'}{Ar}$ with different values of *Ar*

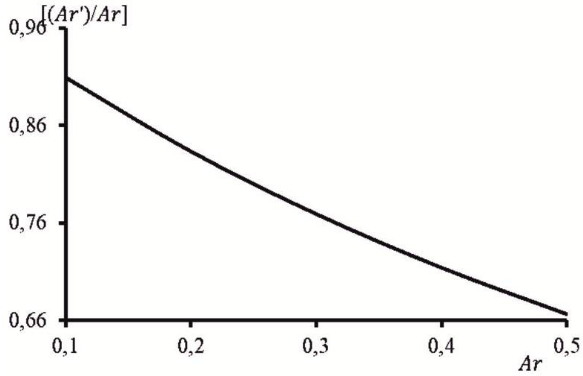

Figure 8 – Dependence $\left[\frac{Ar'}{Ar}\right]$ on the value *Ar*

Archimedes parameters, at which the pseudo-homogeneity effect is realized, is described by a decreasing function and is characterized by a monotonic change from 1 to 0.2 (Fig. 7). We observe an asymptotic approximation of the values of the function to values that increase with an increase in the Archimedes parameter of coal particles. In this case, large values of the Archimedes parameter correspond to large values of the function (Fig. 7).

4. Conclusions

Thus, in the article, the hypothesis of the mechanism of aggregative stability of SS in dynamics is developed and defined more precisely with taking into account the heterogeneity of the properties of particles of the solid phase. This made it possible to specify the value of the average flow velocity in a circular tube, at which the aggregative stability of the SS is disturbed, by comparing the bond energy of dissimilar particles of a solid material in their coagulation structure and the external energy of the fluid flow aimed at breaking this bond.

It is shown that the main factors determining the aggregative stability of SS transported through main pipelines are the size of particles and the nature of the solid material and its mineral inclusions, their surface potential, as well as the rheological characteristics of SS.

The obtained formulas made it possible to analyze the influence of the rheological characteristics of the SS and the radius of the pipeline on the flow velocity, at which its aggregative stability is disturbed. It is established that an increase in the initial shear stress, as well as an increase in the effective viscosity of the SS, reduces the value of this velocity. However, as the pipe radius increases, this velocity increases as well.

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

We established the correlation between the parameters of heterogeneity of solid phase particles in terms of size and density, which ensured the implementation of the effect of pseudo-homogeneity, which made it possible to obtain the dependences of the ratio of the diameters of solid particles on the ratio of their Archimedes parameters corresponding to these conditions.

We obtained the value of minimum possible ratio of the Archimedes parameters of interacting particles, at which the effect of pseudo-homogeneity happens. We established that this value is inversely proportional to the Archimedes parameter of particles of coal fractions of the solid phase.

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ВПЛИВ ВЛАСТИВОСТЕЙ ТВЕРДИХ ЧАСТИНОК, ЩО ДОДАЮТЬСЯ У СТРУКТУРОВАНУ СУСПЕНЗІЮ НА ЇЇ ДИНАМІЧНУ СЕДИМЕНТАЦІЙНУ СТІЙКІСТЬ

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Аннотація. У роботі проаналізовано проведені раніше дослідження впливу на реологічні властивості структурованих суспензій двох природних порівняно чистих оксидів алюмінію. Результати експериментів показують, що вміст у мінеральній частині вугілля цих матеріалів сприяє зниженню в'язкості, яке обернено пропорційно зольності вугілля в деякій дробовій мірі. Аналіз досліджень показав, що вплив добавок мінеральних частинок, їхньої крупності та концентрації на динамічну або статичну седиментаційну стабільність структурованих суспензій не вивчався.

Актуальним завданням роботи є дослідження впливу добавок мінеральних частинок полідисперсного гранулометричного складу різної природи на динамічну седиментаційну стабільність структурованої суспензії з високозольного вугілля.

Розв'язання поставленої задачі здійснюється на основі порівняння сил тяжіння та відштовхування, що мають іонно-електростатичну та Ван-дер-Ваальсівську природу, з силами, що виникають при обтіканні потоком рідини двох частинок різної густини та крупності, з урахуванням турбулентної складової та дефіцитів швидкостей, пропорційних гід крупностям взаємодіючих частинок.

За результатами проведених досліджень у роботі авторами розвинуто та уточнено гіпотезу механізму агрегативної стійкості структурованої суспензії в динаміці з урахуванням неоднорідності властивостей частинок твердої фази, що дозволило встановити величину середньої швидкості потоку в трубі круглого перерізу, при якій порушується агрегативна стійкість структурованої суспензії. Встановлено, що крупність частинок, природа твердого матеріалу та його мінеральних включень, потенціал їхньої поверхні, а також реологічні характеристики є основними факторами, що зумовлюють агрегативну стійкість структурованих суспензій.

Досліджено вплив реологічних характеристик структурованої суспензії та радіусу трубопроводу на швидкість потоку, при якій порушується її агрегативна стійкість для випадку, коли тверда фаза представлена частинками з різною щільністю і крупністю, а також отримана оцінка мінімально можливого співвідношення параметрів Архімеда взаємодіючих частинок, при якому реалізується ефект псевдооднорідності .

Ключові слова: псевдооднорідність, реологічні характеристики, структурована суспензія, ефективна в'язкість, зольність