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STUDYING PATTERNS IN THE FLOCCULATION OF SLUDGES FROM WET GAS TREATMENT IN METALLURGICAL PRODUCTION

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Досліджено вплив концентрації твердої фази модельних шламів мокрої очистки газу і витрати флокулянта на зміну швидкості осідання твердої фази і міцність флокул. Це важливо, тому що коливання концентрації твердої фази в стічній воді є неконтрольованим процесом і істотно впливає на кінетику осідання твердої фази і приводить до збільшення витрати флокулянта.

Запропонована методика виявлення швидкості седиментації сфлокульованого шламу і міцності флокул після гідромеханічного впливу, що враховує концентрацію твердої фази і витрати флокулянта. Дослідження проводилися на модельній стічній воді, синтезованій шляхом змішення пилу сухої газоочищення реального виробництва з водою. Було встановлено, що концентрація твердої фази впливає на швидкість осадження флокул. Встановлено, що оптимальні умови агрегатоутворення даної модельної системи спостерігаються при концентрації твердої фази в інтервалі 8–12 г/л. Із зростанням концентрації твердої фази понад 16 г/л швидкість осадження флокул знижується непропорційно концентрації флокулянта. Зниження витрати флокулянтів і оптимізація його дозування можливі шляхом проведення процесу очищення з урахуванням вказаних закономірностей.

Встановлено, що гідромеханічний вплив на агрегати здійснює руйнуючу дію, ступінь якої залежить від концентрації твердої фази. Зокрема збільшення швидкості руху рідини призводить до більшого руйнування флокул, ніж збільшення часу менш інтенсивного впливу. Способом мінімізації руйнуючої дії на флокули може бути зниження швидкості транспортування суспензії в результаті зменшення продуктивності установки або збільшення перетину каналу (трубопроводу). Із зростанням концентрації твердої фази в модельній системі понад 16 г/л спостерігається істотне зниження міцності флокул. Тому при проектуванні установок очищення стічної води із застосуванням флокулянтів необхідно забезпечити оптимальні умови агрегатообразованія і мінімізувати гігдромехінічні впливи на флокули шляхом зниження швидкості руху рідини

Ключові слова: флокуляція, агрегатоутворення, міцність агрегатів, швидкість осадження, оптимізація, гідромеханічне руйнування флокул

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1. Introduction

Industrial activities related to processing natural raw materials at steel making enterprises are accompanied by the formation of significant quantities of anthropogenic waste, including sludge waste water, which is discharged into external sludge collectors. For example, according to [1], the smelting of steel produces the waste of up to 30 % of the steel output, 20 % of which are dust and gas treatment sludges. The solid part of these wastes consists mainly of fine particulate matter smaller than 1 mm, with about 80 % of them being less than 50 μm in size [2]. More than 70 million tons of finely-dispersed sludges have already been accumulated in Ukraine alone. The accumulation of waste increases the environmental risk of contamination of surrounding areas and groundwater. According to authors of [3], in the next 50 years water will become the scarcest resource. Therefore, dehydration of sludge water with the return of clarified water to an enterprise water circulation system, as well as recycling the sludge into useful products, is a relevant scientific task.

Existing water circulation systems at steel mills work with purging, which accounts for about 10 % of the consumption of water circulating in water systems. The main reason for purging and dumping the untreated wastewater into external sludge collectors is the low efficiency of water circulation treatment plants. One of their most problematic areas is the insufficient cleaning of sludges from suspended substances, which leads to significant contamination of the clarified water and the need for additional dilution of sludge (recharge) with clean tap water. This relates to that the flocculation of sludge at the inlet to a thickener does not occur with proper efficiency, despite the supply of a flocculant solution. Typically, at treatment plants a flocculant is dosed based on experience and at constant flow rate, without adjusting the dose of a flocculant when the concentration of sludge changes. Changing the properties of water contaminated in the production cycle, as well as a fluctuation in the solid phase concentration over a short time, reduce the efficiency of cleaning systems used in an enterprise circulation scheme.

The complexity and lack of detailed studies of the processes of flocculation, formation, as well as the destruction of formed aggregates in the transportation of fine-dispersed sludge, render relevance to the experimental and theoretical research into these processes.

2. Literature review and problem statement

A common scheme to clean sludges through an enterprise water circulation cycle is their clarification in radial thickeners or other sedimentation installations. Different methods for the intensification of a particle enlargement process are used in order to increase the deposition rate of suspended substances, for example by applying flocculants.

Current scientific literature describes techniques of using flocculants both as a separate reagent and in combination with inorganic polyelectrolytes [4]. Sometimes several flocculants are applied with different molecular weights [5] or a charge in the so-called «double flocculation process» [6]. However, there are still unresolved issues related to choosing the optimal quantity of a flocculant in the amount sufficient to clean a particular type of waste water.

The effectiveness of a particular flocculant is determined by the optimal flocculation concentration, which should be a minimum and isoelectric point determined from the medium pH [7]. However, it should be noted that the choice of the type and technique to use a flocculant is based only on an actual experiment regarding its flocculation effect.

The dispersal composition and the solid phase concentration are important factors influencing the size and strength of floccules. This relates to that the consumption of a flocculant depends on the total specific surface of particles. Studies [8, 9] have shown that there are optimal conditions for effective aggregation. For coal sludge, they are the following: the concentration of solid within 10–30 g/l and the largeness of particles above 40 μm is over 20 %. The presence of the optimal solid phase concentrations was also identified for clay solutions at the level of 4–6 g/l [10]. However, the cited studies do not provide clear recommendations on the effect of solid phase concentration for other types of sludge, such as wet gas treatment sludge.

The effect of mineralization and ionic conditions on coal sludge coagulation was investigated in [11]. Paper [12] used an example of a kaolin suspension to show that the effectiveness of flocculation is also influenced by the medium pH. However, the above results are not applicable to other dispersal systems and wastewater.

Article [13] proposes optimizing the processes of flocculation and selection of suitable process conditions, such as pH, the type of a polymer and concentration, by changing zeta-potential. However, a change in the zeta-potential is not possible in the operation at treatment plants and requires special equipment.

Paper [19] revealed the optimal dose of reagents for wastewater from brick production. The authors took into consideration the effect of the degree of acidity of the medium, the speed and time of agitation, on the efficiency of cleaning.

Thus, the process of cleaning highly-dispersed sludges, using flocculants to intensify the solid phase deposition processes, is multifactorial and not studied enough.

Therefore, the practice of wastewater treatment by a coagulation-flocculation technique employs experimental dependences. For example, articles [14, 15] describe a methodology for determining the flow rate of reagents at aggregation by using a statistical analysis of experimental data. The method implies building a 3D surface of the desired value response from two variables. The resulting equations of the response surface in the form of second- and third-order polynomials make it possible to calculate the consumption of reagents with high accuracy. A similar approach was reported in the publications by other authors [16–18] regarding the wastewater from specific industries. Typically, the dependent variable is the degree of wastewater purification, rather than the flocculant consumption. A variety of factors influencing the process of flocculation leads to an increase in the dosage of reagents, rather than optimizing the process of aggregation itself.

Waste water after wet gas treatment devices is characterized by the non-uniform composition and constant fluctuations in the solid phase concentration [20]. This in turn changes the effectiveness of cleaning. As a result, the treatment plants have either undue overruns of reagents or insufficient efficiency of the treatment equipment. At present, there are no clear data to predict the impact of various factors and wastewater impurities on the aggregation processes.

The difficulty of accounting for the change in many parameters on which the efficiency of aggregation depends, and, consequently, the floccule deposition rate, leads to a decrease in the efficiency of treatment plants operation. However, despite many publications in the field of aggregation, today there is no a unified methodology for conducting laboratory studies on the selection of the optimal dose of flocculants. Even less studied is the selection of technological tests for rapid adjustment of reagents supply without the use of specialized devices and expensive equipment. Such a set of tests should be simple enough to apply them without moving away from the cleaning equipment. At present, the only effective way to predict the work of flocculants under specific industrial conditions is an experiment with actual wastewater.

The common unresolved issue in the above publications is the lack of recommendations to minimize the consumption of a flocculant by creating optimal conditions for aggregation. In addition, the scientific literature pays little attention to the issue of the destruction of formed floccules and the ways to preserve their strength. The unresolved part of the problem is related, specifically, to the flocculation of waste water from wet gas treatment plants at metallurgical enterprises, containing the finely dispersed solid phase. This is especially important as metallurgical production is one of the most capacious and dangerous consumers of water, returning which to the production cycle after cleaning is a relevant scientific task.

3. The aim and objectives of the study

The aim of this research was to define patterns in the aggregation, sedimentation, and destruction of floccules in the sludge from wet gas treatment at metallurgical enterprises. This would make it possible to improve the efficiency of cleaning finely-dispersed sludges and to minimize the consumption of reagents.

To accomplish the aim, the following tasks have been set:

– to devise the methodology and criteria for studying aggregation on model sludges with the assigned solid phase concentration;

– to identify the dependence of floccule sedimentation depending on the solid phase concentration and the flocculant consumption in waste water;

– to study the effect of hydromechanical influences on the flocculated aggregates.

4. Methodology for experimental study of patterns in the flocculation of wastewater from wet gas treatment

4. 1. Substantiating the choice of parameters for research

For wastewater treatment using flocculants, the subsequent ways for separating the solid and liquid phases are important. Typically, following the aggregation in the mixers of different design, or flocculators, the sludge is fed into sedimentation installations for clarification. The choice of the structure of sedimentation installations and the time waste water stays there depend on the deposition rate of the solid phase. Therefore, the first criterion to be investigated is the deposition rate of the formed aggregates after flocculation (V_1).

Next, the sludge condensed at sedimentation installations is fed for dehydration to, for example, centrifuges or filter presses. The effectiveness of the process of removing moisture and obtaining a clean filtrate or fugate depends on the strength of floccules after sedimentation. According to earlier studies [8], the residual strength of floccules can be estimated by the deposition rate of aggregates after mechanical impact (V_2). The value of this criterion for different equipment will have its optimum value (for example, according to [9], for dehydration in centrifuges it is at least 2 mm/s). The strength of floccules or the residual deposition rate depend on the intensity and time of the hydromechanical impact from the moment of aggregates formation to their transportation to dehydrating equipment. The intensity (the speed of fluid movement in pipes and apparatuses) and the time of sludge flow depend on performance of the installation and its design (the magnitude of cross-section of pipelines or apparatuses). Therefore, the optimal value for an aggregates strength criterion (V_2) should be established in the laboratory, by acting hydromechanically on the sludge with a certain intensity and over a specific time. Such an impact should be consistent with actual conditions and design of the treatment equipment. At the same time, staff at existing treatment plants usually know the speed and time of waste water flow in the devices, as well as the values for criteria V_1 and V_2, which must be maintained for the effective water clarification and sediment dehydration. The problem statement follows from the above: to forecast a change in the deposition rate of floccules due to a fluctuation in the solid phase concentration in waste water, that is, to find the following function

$$V=f(C, Q), \tag{1}$$

where C is the solid phase concentration in waste water, g/l; Q is the flocculant consumption per mass unit of the solid phase, g/t.

In addition, in practice, there is also a task on determining the flocculant consumption, necessary to achieve the required values for the specified criteria, taking into account a change in the solid phase concentration:

$$Q=f(C, V). \tag{2}$$

Knowing this dependence makes it possible to optimize the dosing of a flocculant in such a way that the required values for V_1 and V_2 criteria are reached, which exclude the flocculant over consumption.

Thus, in order to optimize the consumption of a flocculant and maintain the efficient operation of treatment equipment, it is required that the dependences in line with formulae (1) and (2) for the V_1 and V_2 criteria should be established under laboratory conditions.

4. 2. Preparation of model samples of waste water

Our experimental study involved model solutions of wastewater with an adjustable concentration in the range of 4 to 30 g/l; they were prepared by mixing a batch of the solid phase of the desired mass with water. To create a model waste water after a wet gas treatment at a metallurgical enterprise, we used the dust from dry gas treatment at a foundry of one of the metallurgical enterprises.

The dust was preliminary sifted through sieves the size of cells 100 µm, to exclude larger particles, which are well deposited even without the use of reagents. Then the batch of dust was weighed at the laboratory scale of TVE-0.21-0.001-a (Ukraine) with an accuracy of 0.005 g and was mixed with tap water until reaching the concentration necessary for experiments. The composed waste water is believed to be close in composition and concentration to actual sludge from wet gas treatment.

The USB-connected Digital Microscope (China) enabling a 1,600 magnification was used to study the process of aggregation and to acquire microphotographs.

4. 3. Procedure for studying the deposition rate of floccules

For the laboratory study, through a series of preliminary experiments, we selected the cation-type flocculant K-7 made by Ecoflok. For our experiments, a concentrated 0.5 % flocculant solution was prepared, which was diluted to a working concentration of 0.05 %.

We measured the kinetics of floccules deposition after introducing the f flocculant under a free (unrestricted) deposition in the laboratory measuring cylinders with a volume of 500 ml and a diameter of 50 mm. By using a syringe, we added to a sample of wastewater of a certain concentration a dosed amount of the flocculant, required for the experiment. After introducing the flocculant, the sample was stirred by a tenfold overturning of the measuring cylinder (about 10 s). Following the flocculation, the stopwatch measured the time it took for the phase boundary to travel a path that equals

3/4 of the cylinder height. This path was taken based on the free deposition condition for model wastewater with a solid phase concentration of less than 30 g/l (we visually observed the cramped deposition and a drop in the deposition rate in the lower quarter of the cylinder). According to the experimental data obtained, the deposition rate of aggregates (V, mm/s) was calculated as the ratio of the path traveled by the phase boundary to the time of free settling from (1):

$$V=\frac{0.5H}{t_i}, \qquad (3)$$

where H is the height of the cylinder, mm; t_i is the time of free settling of aggregates and the clarification of $0.5\cdot H$ cylinder, s.

For each sample of waste water, depending on the solid phase concentration, the dosage of a flocculant (in ml per 0.5 l) was recalculated for its mass consumption per unit of a solid phase mass (in g/t). Thus, the amount of the introduced solution of reagents corresponded to a certain concentration of the solid phase in the volume of waste water.

The temperature of all wastewater samples was kept constant at 20±1 °C.

We studied the effect of hydromechanical impact on the flocculated sludge using the laboratory magnetic stirrer with an adjustable number of revolutions and a digital display MM-85-2 (China) in the following way. Following the introduction of the flocculant and the formation of floccules, the waste water was poured into a 0.5-litre measuring glass and placed on the magnetic stirrer with the assigned number of revolutions. The study was conducted under two modes at 400 and 800 rpm, which corresponded to the average fluid speed of approximately 0.5–1 m/s and 1.5–2 m/s. Every 20 seconds of stirring, the sample was gently poured into a measuring cylinder to measure the rate of deposition.

4. 4. Procedure for processing experimental results and defining mathematical dependences

The data obtained were processed by establishing the dependence of response on independent variables, by representing them graphically and building the related regression models for the specified parameters. Mathematical treatment of experimental results was carried out using the Statistica software package, designed to statistically process data from experimental studies.

In the regression analysis, the task was set to find a functional dependence of the mathematical expectation of response $M(Y)$ on values for the specified factors X: $M(Y)=f(X1, X2, ..., Xn)$. The criteria described above, the rate of floccule deposition upon aggregation (V_1) and the same speed after hydromechanical impact (V_2), were considered as a response function in the experiments.

The dependence of the amount of a flocculant required to achieve the specified criteria on the solid phase concentration was also established. The solid phase concentration and the time of the hydromechanical impact on floccules leading to their destruction were chosen as independent variables that affect the response function.

The initial results from experiments were mapped by graphs along the following coordinates: the time of floccule settling – the solid phase concentration in sludge. Each point on these graphs was an average value of the results from three to five experiments. The relative deviation of experimental data from the average value ranged between 0.05 and 0.2 mm/s, but did not exceed 5 % of the average.

5. Results of studying the kinetics of deposition of the flocculated solid phase of sludge from wet gas treatment

Our study has found that the rate of floccule deposition depends on the solid phase concentration (Fig. 1). The range of model sludge concentration of 4–30 g/l demonstrates an extremum in the region of concentration of 8–12 g/l.

An increase in the flocculant concentration significantly increases the rate of floccule deposition to a certain limit (10–11 mm/s), after which the increase in the concentration of the polymer (over 250 g/t) does not lead to a significant acceleration of the sedimentation process.

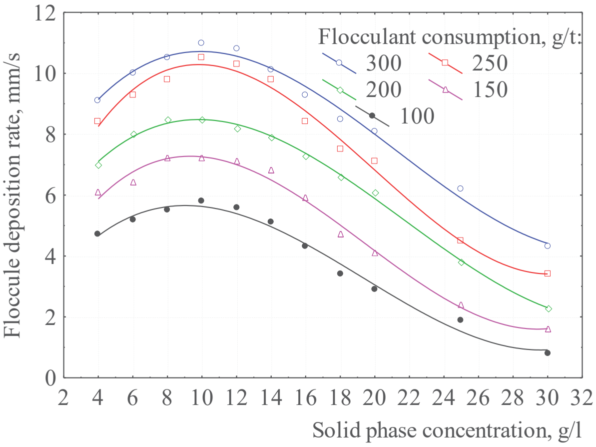


Fig. 1. Dependence of floccule deposition rate on the solid phase concentration and the flocculant consumption

The result of processing and smoothing the data from Fig. 2 is the derived regression equation, which makes it possible to calculate the rate of floccule deposition depending on the flocculant consumption and phase concentration:

$$V_1=0.7096+0.2408\cdot C+0.0385\cdot Q-0.0126\cdot C^2-$$
$$-0.0002\cdot C\cdot Q-2.8\cdot 10^{-5}\cdot Q^2, \qquad (4)$$

as well as the equation of the dependence of flocculant consumption on the solid phase concentration:

$$Q=-35.5991-13.4053\cdot C+40.4711\cdot V+0.5874\cdot C^2+$$
$$+0.4553\cdot C\cdot V-0.735\cdot V^2. \qquad (5)$$

Equation (5) makes it possible to calculate the flow rate of a flocculant in order to achieve the required deposition rate for different concentrations of the solid phase. The calculation results from formula (5) are shown in Fig. 2.

The formation of floccules at intensive agitation is followed by their destruction (Fig. 3). The introduction of a flocculant leads to the formation of aggregates by clumping the formed solid phase particles and their enlargement (Fig. 3, *a*). At the same time, the liquid around the floccules becomes almost transparent. The hydromechanical impact on floccules disrupts their structure, breaking them into small floccules (Fig. 3, *b*, *c*). Under an intense or prolonged exposure, the floccules are completely destroyed, and the particulate matter returns to its ground state, forming mud (Fig. 3, *d*).

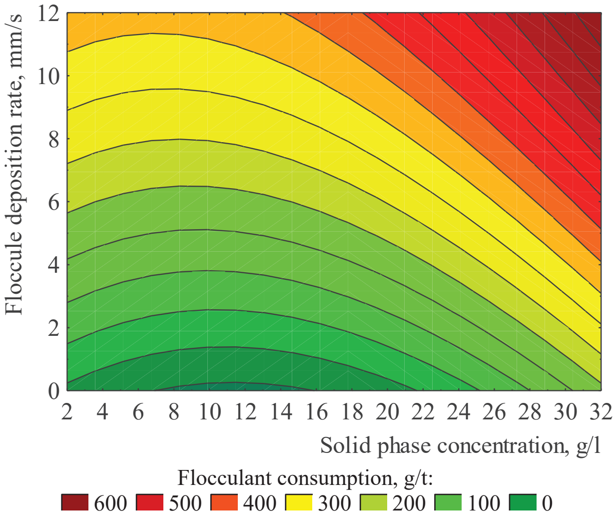
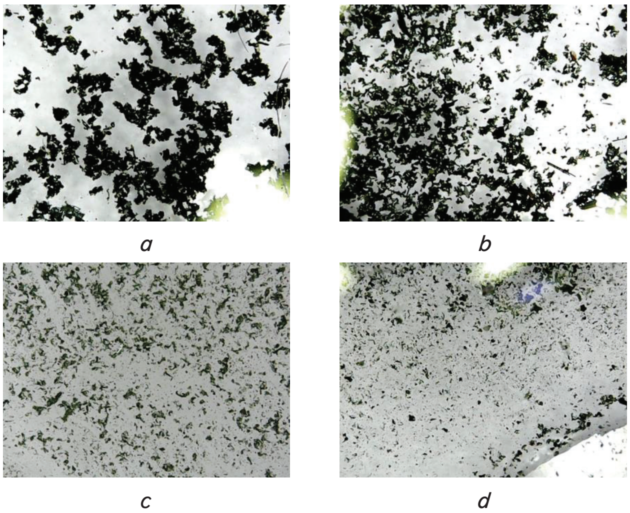


Fig. 2. Isolines of flocculant consumption depending on the required rate of floccule deposition and solid phase concentration


a *b*

c *d*

Fig. 3. Photographs of floccules at water purification: *a* – floccule formation; *b, c* – partial destruction of aggregates under hydromechanical impact; *d* – almost complete destruction of aggregates under intense or prolonged hydromechanical impact

Results from studying the dependence of intensity and agitation time on the solid phase concentration are shown in Fig. 4. Analysis of results shown by graphs in Fig. 4, *a*, *b*) reveals that the destructive effect on floccules is mostly due to the intensity of agitation than time. For example, at a solid phase concentration of 10 g/l, after stirring for 120 s, the rate of floccule deposition is 2.8 mm/s at 400 rpm (Fig. 4, *a*). And a 2-time increase in the speed and a reduction in the mixing time to 60 s leads to that the residual deposition rate decreased to 2.2 mm/s (Fig. 4, *b*). At intense agitation longer than 40 s there is a significant decrease in residual speed.

The data in Fig. 4 also show that an increase in the solid phase concentration leads to that the destruction of floccules occurs more intensively than that at low concentrations.

The result of experimental data processing is the derived regression equation that takes into consideration the dependence of floccule deposition residual rate on the time of their destruction (t, s) and the solid phase concentration at 400 and 800 rpm:

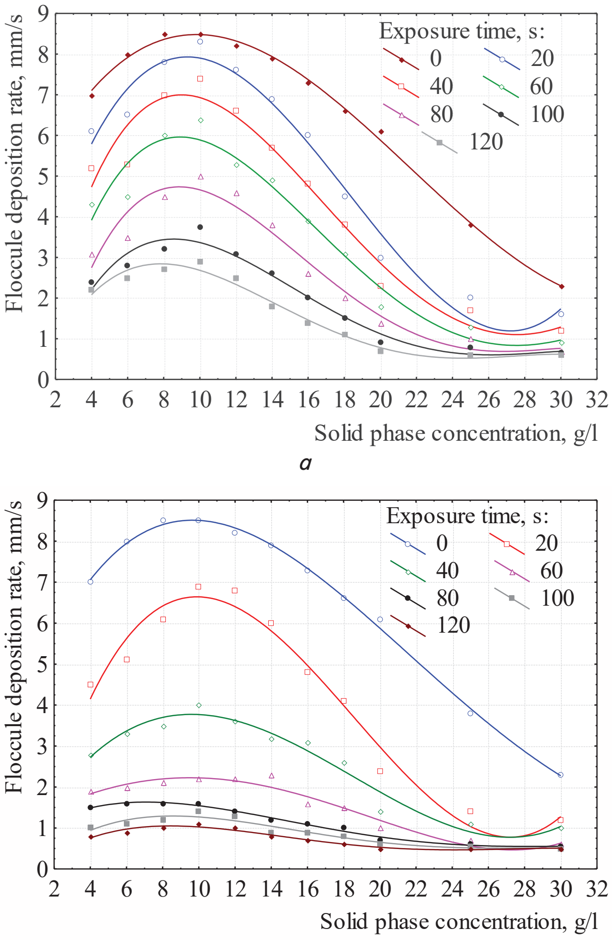
$$V_{2(400)}=9.1304-0.0334\cdot C-0.0771\cdot t-0.0068\cdot C^2+$$

$$+0.0013\cdot C\cdot t+0.0001\cdot t^2, \qquad (6)$$

$$V_{2(800)}=8.6631-0.0423\cdot C-0.144\cdot t-0.0049\cdot C^2+$$

$$+0.0018\cdot C\cdot t+0.0006\cdot t^2. \qquad (7)$$

These equations can be used to calculate the expected strength of floccules depending on the specified factors.



a

b

Fig. 4. Dependence of floccule deposition rate on the solid phase concentration and the time of hydromechanical impact (at a constant consumption of the flocculant of 200 g/t) under the modes of sirrer operation: *a* – 400 rpm; *b* – 800 rpm

For practical purposes, of interest is the dependence of floccule strength on the flocculant consumption at a known flow rate and motion time of the flocculated sludge (Fig. 5). It follows from Fig. 5 that the strength of floccules in concentrated wastewater (over 16–18 g/l) is significantly lower than the strength of less concentrated waste. For example, at the solid phase concentration of 10 g/l and a flocculant consumption of 200 g/t the strength of floccules is higher than that at the concentration of 18 g/l and the flocculant consumption of 300 g/t.

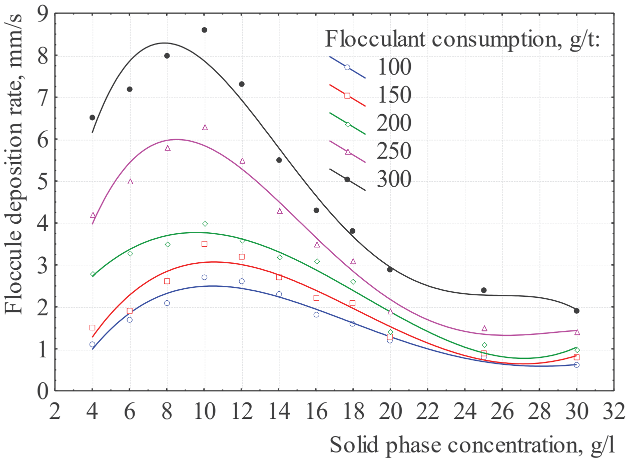


Fig. 5. Dependence of floccule deposition rate after hydromechanical impact for 40 s at the sludge motion speed up to 2 m/s on the solid phase concentration and flocculant consumption

The result of processing and smoothing the data from Fig. 6 is the derived regression equation that makes it possible to calculate the residual rate of floccule deposition (strength), depending on the flocculant consumption and solid phase concentration:

$$V_2=-0.0694+0.2399\cdot C+0.0036\cdot Q-0.0047\cdot C^2-$$

$$-0.0011\cdot C\cdot Q+7.6\cdot 10^{-5}\cdot Q^2, \qquad (8)$$

as well as the equation for the dependence of flocculant consumption on the solid phase concentration:

$$Q=83.626-14.3744\cdot C+54.246\cdot V+0.5034\cdot C^2+$$

$$+2.0691\cdot C\cdot V-4.4106\cdot V^2. \qquad (9)$$

Equation (9) makes it possible to calculate the flocculant consumption in order to achieve the required deposition rate for different solid phase concentrations (Fig. 6).

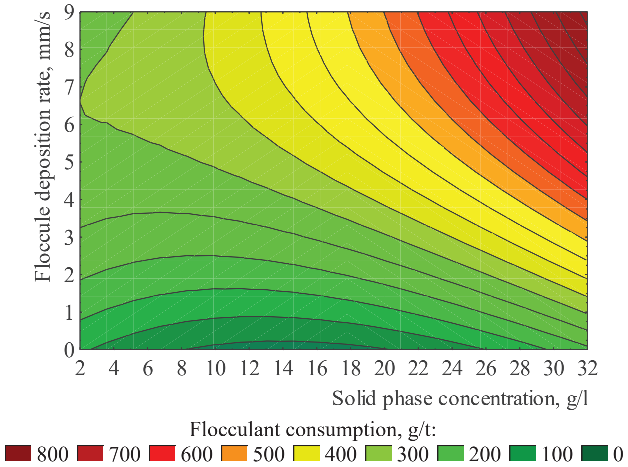


Fig. 6. Isolines of flocculant consumption depending on the required rate of floccule deposition and the solid phase concentration after hydromechanical impact for 40 s at the speed of sludge motion up to 2 m/s

The resulting graph (Fig. 6) and equation (9) can be used to calculate the required amount of a flocculant in order to achieve a certain strength of floccules for a given type of model waste water.

6. Discussion of results of studying the flocculation of sludge from wet gas treatment

Analysis of Fig. 1, 2 shows the presence of optimal conditions for aggregation depending on the solid phase concentration. For a given type of wastewater, the concentration of 8–12 g/l corresponds to the best distribution of the solid phase and macromolecules of the polymer (the ratio of the number of macromolecules per each solid phase particle) in the volume of the liquid. Such a distribution corresponds to the unimpeded diffusion and absorption of the polymer at the surface of particulate matter and the effective formation of large floccules due to the optimal distance between the particles. The existence of such a maximum in a certain region of concentrations is confirmed by earlier studies into the flocculation of coal sludge [8, 9] and drilling wastewater [10]. Changes in the solid phase concentration and in the flocculant concentration exert an impact on the effective volume (size) of the formed floccules and on their quantity. At low concentrations of the solid phase or insufficient amount of a flocculant, small floccules are formed. The decrease in the flocculation effect with an increase in the mass concentration of the solid phase in suspension is associated in the literature with a decrease in the distance between the particles and a change in the total surface energy at the phase boundary between particles of the dispersed phase and the dispersion environment.

Analysis of Fig. 4, 5 reveals that with an increase in the solid phase concentration over 16–18 g/l the strength of floccules for a given model waste water significantly decreases in comparison with the strength of the floccules formed during flocculation of sludge of lower concentrations. This leads to the conclusion that the optimization of flocculant consumption at wastewater treatment implies the search for conditions for the best aggregation (the ratio of solid phase concentration to flocculant concentration). Adjusting the solid phase concentration in the waste water supplied for cleaning, by diluting or condensing the suspension to optimal concentration, could result in significant savings of a flocculant. It is also quite clearly seen in Fig. 2, 6 and is consistent with earlier studies involving actual sludge from wet gas treatment [20, 21].

In addition, the data from Fig. 4 allow us to recommends the transportation of flocculated suspensions at lower intensity (speed), for example, by reducing an installation performance or increasing the pipeline cross-section. The ratio of parameters for the described laboratory test of hydromechanical agitation in a stirrer to the actual flow at treatment plants can be established, for example, from the Reynolds criterion, modified for a given case:

$$\mathrm{Re}=\frac{n\cdot d^2}{\upsilon}=\frac{v\cdot D}{\upsilon}=\frac{Q\cdot D}{\upsilon\cdot F}, \qquad (10)$$

where n is the frequency of stirrer rotation, s^{-1}; d is the diameter of a stirrer, m; v is the characteristic flow rate, m/s; D is the hydraulic (equivalent) diameter, m; υ is the kinematic viscosity of a medium, m^2/s; Q is the volumetric flow rate of a flux, m^3/s; F is the cross-sectional area of a channel, for example, a pipe, m^2.

Taking into consideration the similarity of fluid flow processes in a laboratory stirrer and at treatment plants, expression (10) can be transformed into a more convenient form:

$$n\cdot d^2 = v\cdot D = \frac{Q\cdot D}{F}. \qquad (11)$$

The procedure for flocculation estimation, proposed in this work, as well as the examples of investigating patterns in aggregation by using it, is simple, understandable, and does not require expensive equipment. Therefore, a given procedure can be recommended for application directly at treatment plants to determine optimal doses of reagents under conditions of constant change in the solid phase concentration in sludges.

The disadvantage of the current study relates to that the series of laboratory tests were performed on a model suspension, which undoubtedly differs from the actual wastewater at metallurgical enterprises. Our study does not take into consideration the possibility of change in the chemical composition (growth of mineralization) of the dispersed phase due to water circulation at production. At the same time, the results obtained are applicable in order to determine the consumption of reagents at the design phase of a cleaning system, with a possibility of further adjustment of flocculant consumption at an actual industrial facility.

Promising areas of the further research are to study the impact exerted by other factors on the strength of aggregates, for example the conditions of introduction and mixing of flocculants. In addition, a promising task for the further research is to search for ways to dispose of the solid phase in wastewater sediments, in particular, the sediments in sludge from gas treatment at metallurgical industries.

7. Conclusions

1. We have proposed a procedure for determining the speed of sedimentation of flocculated sludge (criterion V_1) and the strength of floccules exposed to hydromechanical influences (criterion V_2), taking into consideration the solid phase concentration and flocculant consumption. The methodology implies finding a response function in the form of V_1 and V_2 criteria under controlled conditions of change in the factors that affect the process of aggregation. The resulting dependences could be used to optimize a flocculant consumption and to select the technological process parameters (the installation performance in terms of sludge and the time of movement from the moment of flocculation to the moment of sediment dehydration).

2. As a result of the study, it was found that in the interval of solid phase concentration of 4–30 g/l, the optimal concentration of a given waste water is 8–12 g/l. Increasing flocculant consumption above 250 g/t even in an optimum zone of the solid phase concentration does not lead to a significant increase in the rate of floccule deposition. With an increase in the solid phase concentration above 16 g/l, the rate of floccule deposition decreases and, accordingly, the flocculant consumption increases to achieve a certain deposition rate.

3. It has been established that hydromechanical influences destroy floccules depending on the solid phase concentration, intensity, and the time of exposure. With an increase in the solid phase concentration in the sludge of the examined model system over 16 g/l, there is a significant decrease in the strength of floccules. The speed of fluid movement has a stronger effect on the destruction of floccules than the increase in the time of a less intense exposure. Established patterns make it possible to recommend the transportation of flocculated suspensions at a lower speed in order to minimize destructive effects on floccules.

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