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REGULARITIES OF CLEANING AND DEWATERING OF GAS CLEANING SLUDGE FROM COAL DUST AT THERMAL POWER PLANTS

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The object of this study is the technology of cleaning and dewatering of sludges from wet gas purification systems of dust preparation department emissions in Ecomash SHS521AS-113 settling centrifuges in order to solve the problem of increasing the efficiency of treatment facilities and secondary use of purified water.

Samples of gas purification sludges have been analyzed under industrial conditions, and it was found that sludges from thermal power plants contain finely dispersed dust particles less than 20 microns, which during the hydration process stick together into aggregates up to 250 microns in size.

It was found that the use of settling tanks without chemical reinforcement of the process is long-term; however, they are effectively precipitated using the anionic flocculant A-19. The optimal dose of flocculant for sludges with a concentration of 20–30 g/l was selected, which was 130–150 g/t. In this case, flocs are formed with a sedimentation rate of 8.2–8.6 mm/s, which is sufficient for effective settling. In order to quickly determine the concentration of the solid phase in the sludge, a relationship was established between the concentration of the dispersed phase, the temperature in the range of 20–45°C, and the density of the sludge.

The study of sludge purification in centrifuges without the use of reagents has made it possible to identify the relationship between the efficiency of solid phase retention, centrifuge productivity, and the value of the relative screw revolutions. It was found that the efficiency of solid phase retention in centrifuges increases with a decrease in work productivity, as well as a decrease in the value of the relative screw revolutions. The purification productivity of up to 15–20 m^3/h was achieved with an efficiency of over 97% and a residual concentration of suspended particles of less than 0.5 g/l. The use of a modular sludge purification and dewatering unit based on a thin-layer clarifier and centrifugal units with the introduction of a flocculant before the clarifier has been proposed. It was found that the degree of sludge dehydration in Ecomash SHS521AS-113 centrifuges of wet gas treatment sludge was 32–36%

Keywords: coal dust emissions, coal sludge, dehydration efficiency, gas treatment sludge purification, environmental safety

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1. Introduction

The operation of modern thermal power units, in particular thermal power plants (TPPs), is accompanied by intensive formation of coal dust and sludges that accumulate in dust and gas cleaning systems. These sludges are highly dispersed multicomponent mixtures containing carbon particles, ashes, metal oxides, and organic residues. Due to high humidity and unstable rheological properties, such wastes are difficult to dispose of or reuse. The accumulation of sludges is a serious environmental and technological issue, accompanied by secondary environmental pollution.

Scientific papers [1, 2] highlight a number of methods for sludge dewatering, most of which are adapted to classical sludges after flotation or enrichment, while sludges from dust and gas cleaning plants have a different morphological structure and chemical composition. Those studies offer innovative solutions, but they have not yet been tested on materials similar to coal sludge from thermal power plants, which creates a scientific gap in the field of adapting existing technologies to specific conditions. This causes limited effectiveness of standard approaches to their dewatering.

The task of effective processing and dewatering of technogenic coal sludge is of global importance. In countries with developed coal energy such as China, India, South Africa, and Poland millions of tons of sludge are generated every year, some of which cannot be reused precisely because of high humidity and heterogeneous composition.

World practice indicates an urgent need for new or adapted to the specificity of technogenic sludge dewatering technologies, capable of ensuring effective reduction of waste volumes and increasing the potential for their utilization. At the same time, most existing studies do not take into account the influence of particle morphology, chemical composition, and physicochemical interactions, which play a critical role in the processes of precipitation and dehydration.

Thus, studies of the patterns of coal dust capture and dehydration of gas cleaning sludge at TPPs are relevant not only on a national but also on a global scale. They are aimed at devising solutions that would contribute to reducing the environmental load and increasing resource efficiency in the energy sector.

2. Literature review and problem statement

Modern gas purification technologies at thermal power plants (TPPs) are accompanied by the formation of significant volumes of coal sludge, which pose a potential environmental threat due to the high concentration of fine carbon dust and heavy metals [3]. The problem of dealing with such formations is being actively studied but there are still a number of aspects that are insufficiently investigated. Among them are the morphological structure of particles, which affects the efficiency of precipitation and dehydration; complex and variable chemical composition with the content of heavy metals; unstable rheological properties that complicate transportation and processing; insufficiently studied ecotoxicity and impact of sludge on the environment. Also requiring further study are the adaptation of flocculation methods to the characteristics of coal sludge, the feasibility study of new dehydration schemes, the possibility of recycling and reuse of treated sludge, as well as the automation of cleaning processes and parameter control.

The authors of [4] consider flotation and gravity methods for the utilization of coal sludge in the preparation of coal-water suspensions. Although the authors achieved certain results in increasing the efficiency of processing low-quality coal, the work did not pay due attention to the features of dehydration of fine fractions formed after gas purification processes.

Study [5] considers the purification of water from residual sludge, in particular after electrofiltration. However, the work does not include an analysis of the mechanisms of dust particle aggregation, which is critical for the effective preparation of sludge for dehydration.

A detailed study on the processes of centrifugation of coal sludge is reported in work [6], in which attention is focused on improving the dehydration of brown coal using surfactants (surfactants). However, the specificity of sludges formed specifically in dry and wet dust collection systems were not taken into account, and therefore the results of the study cannot be directly extrapolated to the conditions of power plants.

Work [7] considers the chemical treatment of sludges to intensify their dehydration. The authors modeled the settling of particles of coal origin; however, the study lacks a connection with the real operating conditions of gas purification equipment and does not take into account the influence of particle morphology and their chemical composition on the efficiency of the process.

The authors in [8] performed a simulation of processes in a centrifuge taking into account operating parameters (humidity, rotation frequency, residence time), but the study does not cover the characteristics of sludges enriched with metal oxides and organic residues after gas cleaning.

In work [4], an innovative technology is reported that demonstrates high efficiency in reducing the moisture content of sludges. However, the proposed methodology has not yet been tested on samples similar in composition and dispersion characteristics to coal sludges formed in dust gas cleaning processes at thermal power plants.

Similarly, in study [5], the use of lignite to improve the structure of coal sludge in order to simplify its dehydration was considered but the effectiveness of the approach was also not tested on the corresponding types of man-made formations.

Thus, our review of the literature [5, 7] shows that the problem of handling coal sludges, which are formed as a result of the operation of gas purification systems at thermal power plants, remains insufficiently studied in key aspects. Existing studies concern sludges after enrichment, while sludges from dust collection at thermal power plants differ significantly in composition and properties [4, 6].

Some works consider water purification from residual sludges [5] but do not analyze the features of aggregation and stability of fine coal dust particles, which critically affects the efficiency of subsequent dehydration. Also, the influence of particle morphology, the presence of heavy metals and organic inclusions on the efficiency of the processes of precipitation, thickening and mechanical dehydration remains insufficiently studied [7].

In study [9], the results of industrial tests of the coal sludge and gas treatment sludge dewatering module of metallurgical enterprises using flocculants are reported. The data are practically significant; however, the work does not detail the features of the interaction of particles of different dispersion under centrifugation conditions. The influence of the dispersed composition of granular and fine coal sludge on the efficiency of dehydration and solid phase retention is considered in [10]. It was established that a means of increasing the efficiency of centrifuges is to reduce the feed productivity, as well as increase the content of granular fractions larger than 250 μm. However, the dependence of the influence of flocculants on the operation of centrifuges has not been established, and the influence of screw revolutions has not been taken into account. The features of flocculation and coagulation processes when capturing coal particles in sludge are described in [11]; however, examples of the implementation of processes in modern centrifugal units and technological chains of devices are not described. Papers [12, 13] consider the processes of coal suspension filtration and the features of sediment dehydration.

Existing papers that consider the technical aspects of centrifugation are rarely adapted to the specificity of the treatment of sludge after gas treatment, which are formed in the form of highly dispersed hydrophilic systems with a complex colloidal structure. In addition, most available studies focus on individual stages, dehydration, or chemical preparation, without a comprehensive analysis of the relationship between the properties of the sludge, mechanical treatment modes and the final level of dehydration. The high dispersion, heterogeneous composition, and significant moisture of such waste significantly complicate their further disposal or reuse, causing an increase in the volume of technogenic accumulations and additional environmental burden. Existing methods of sediment dehydration are in most cases developed for other types of sludge and are ineffective for coal sludge from dust and gas purification systems.

The scientific gap relates to the insufficient adaptation of technologies to the morphological and physicochemical characteristics of these sludges. In this regard, further research into improving the efficiency of their dehydration and purification is important for achieving environmental safety and sustainable functioning of the energy industry.

Thus, the scientific gaps that remain open are:

– insufficient study of the physicochemical characteristics of coal sludge after gas cleaning at thermal power plants;

– lack of a systematic approach to studying the influence of sludge parameters and composition on centrifugation efficiency;

– lack of adapted solutions for dehydration specifically for fine-dispersed technogenic sludges formed as a result of the operation of modern gas cleaning systems.

In view of the above, there is a need to conduct a comprehensive study into the processes of dewatering coal sludges formed in dust and gas cleaning systems at thermal power plants, taking into account the characteristics of particles, phase composition, and properties of aggregated systems. This will make it possible to formulate practical recommendations for increasing the efficiency of mechanical dehydration, reducing sludge volumes, and increasing the environmental safety of thermal power plants through the secondary use of purified water in wet gas cleaning systems.

3. The study materials and methods

The purpose of our study is to determine the patterns of suspended particle capture and sludge dewatering at thermal power plants under industrial conditions using a modular installation that includes a settling tank, sedimentation centrifuges, a flocculant preparation station, and auxiliary equipment. This will make it possible to design and implement at the enterprise effective equipment for cleaning wet gas treatment sludge to the standards of their secondary use in wet gas treatment systems and return the dehydrated sludge to the coal preparation shop. Such solutions will reduce the negative impact on the environment, reduce sludge discharge, and return coal dust and water as secondary resources.

To achieve this goal, the following tasks had to be solved:

– to examine samples of gas treatment sludge and devise a system of tests for operational control over the concentration of the solid phase in them;

– to investigate the operation of the equipment of the wet gas treatment sludge cleaning and dehydration module under a reagent-free mode and with the use of flocculants.

4. Materials and methods of research

4. 1. Characteristics of the source of gas cleaning sludge formation at a thermal power plant

The object of our research is the technology of cleaning and dewatering sludge from wet gas cleaning systems of emissions of the dust preparation department at a thermal power plant in Ecomash SHS521AS-113 settling centrifuges (Ecomash 6800 Module, Ukraine). The hypothesis of the research was to verify the possibilities of effective cleaning of wet gas cleaning sludge to the standards of secondary water use by capturing and dewatering the solid phase on the Ecomash 6800 module. Research on the capture and dehydration of coal dust was carried out on real gas cleaning sludge of one of the thermal power plants (Ukraine) in the dust preparation shop, which operates as follows (Fig. 1).

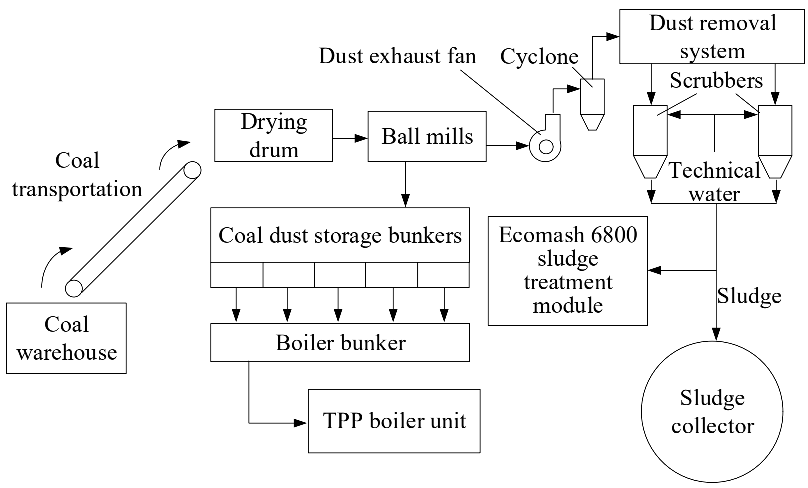


Fig. 1. Simplified technological scheme of the dust preparation workshop

Coal or a mixture of coal from an open coal warehouse is fed by bulldozers to a conveyor of one of the three sections of the dust preparation shop. During the study of the operation of the wet dust collection system, the power plant operated on gas coal of the "G" and "DG" brands. Coal was fed by a conveyor into a drying drum. Superheated steam with a temperature of +115°C was also fed there through pipes. Then the coal was crushed to the required size in a ball mill. The crushed coal was fed into storage bunkers, and then into the bunker of a two-section boiler for generating steam, which is fed to the TPP turbine. Dust from the mills is sucked off by an exhaust fan and through a cyclone is sent to scrubbers with water irrigation. Dust that has settled in the cyclone is sent to the bunker. 2 scrubbers are mounted in each section, which operate in parallel. Water for scrubber irrigation comes from the general collector of the TPP, which is fed from the surface water intake of the Siverskyi Donets River. Wastewater from the scrubbers was drained by gravity through a 300 mm diameter water pipe into a sludge collector. The wastewater flow rate during the research was ≈ 30 m^3/h.

Wastewater during the research was directed to the Ecomash 6800 modular unit. The purpose of the tests was to verify the efficiency of the wastewater treatment technology of wet dust collection and coal dust dehydration using the Ecomash 6800 module based on a thin-layer sedimentation tank and a settling centrifuge under operating production conditions. Before the tests, laboratory analysis of sludge samples for solid phase content was carried out, the kinetics of solid particle sedimentation were studied, and trial centrifugation and flocculation were performed using standard methodologies described in more detail in [14, 15].

4. 2. Description of the Ecomash 6800 module operation

The Ecomash 6800 module is used to purify wastewater from suspended particles by sedimentation in gravitational and centrifugal fields and dehydration of the separated solid phase to a transportable state. Intensification of sedimentation processes is achieved due to the possibility of using flocculants. The module is designed for quick installation (dismantling) of equipment at the work site and conducting pilot-industrial tests in manual control mode. The module included a receiving tank, a thin-layer sedimentation tank Ecomash 3400, an Ecomash SHS521AS-113 centrifuge, a flocculation station, and auxiliary equipment (Fig. 2).

The Ecomash 6800 module worked as follows. The wastewater sludge entered the receiving tank, which was equipped with a static mixer, and, if necessary, a flocculant was supplied there. In the receiving tank, the volume flow of sludge was recorded visually using a slot flowmeter and, additionally, a level gauge signal, a multiple of the sludge flow rate, was displayed on the operator's console. The operator measured the solids content in the pulp by determining its density and adjusted the flocculant flow rate.

Next, depending on the operating mode, the sludge can be fed either to the centrifuge pos. 2 or to the thin-layer sedimentation tank pos. 3 through the fugate collection tank pos. 4.

During tests under industrial conditions, the maximum sludge flow rate was $Q = 20$ m^3/hour. During the tests of the Ecomash 6800 module, the following measurements were performed:

– volumetric productivity of the module using a slot flowmeter in the receiving capacity;

– solids content in the feed sludge, in clarified water, in the mains by the express method, by weighing 1 dm^3 of sludge and additionally in the laboratory by drying to constant weight of the sample volume in a drying cabinet;

– humidity of the dehydrated sludge in the laboratory by drying to constant weight at $t = +105$°C according to the methodology MVV No. 081/12-0785-11;

– operating parameters of the module centrifuges according to the indications of the control cabinets;

– flocculant flow measurements were carried out by recalculating the flow rate of the flocculant working solution ($C_f = 0.05\%$), which was determined by measuring the level of the working solution in the tank over a period of time;

– the amount of wet sediment was measured by collecting sediment for a certain time (~ 5 minutes) into an empty prepared cart with subsequent weighing of the sediment.

Measurements of the solid phase content in the feed, clarified water, and moisture content of the dehydrated product were additionally carried out at the thermal power plant laboratory.

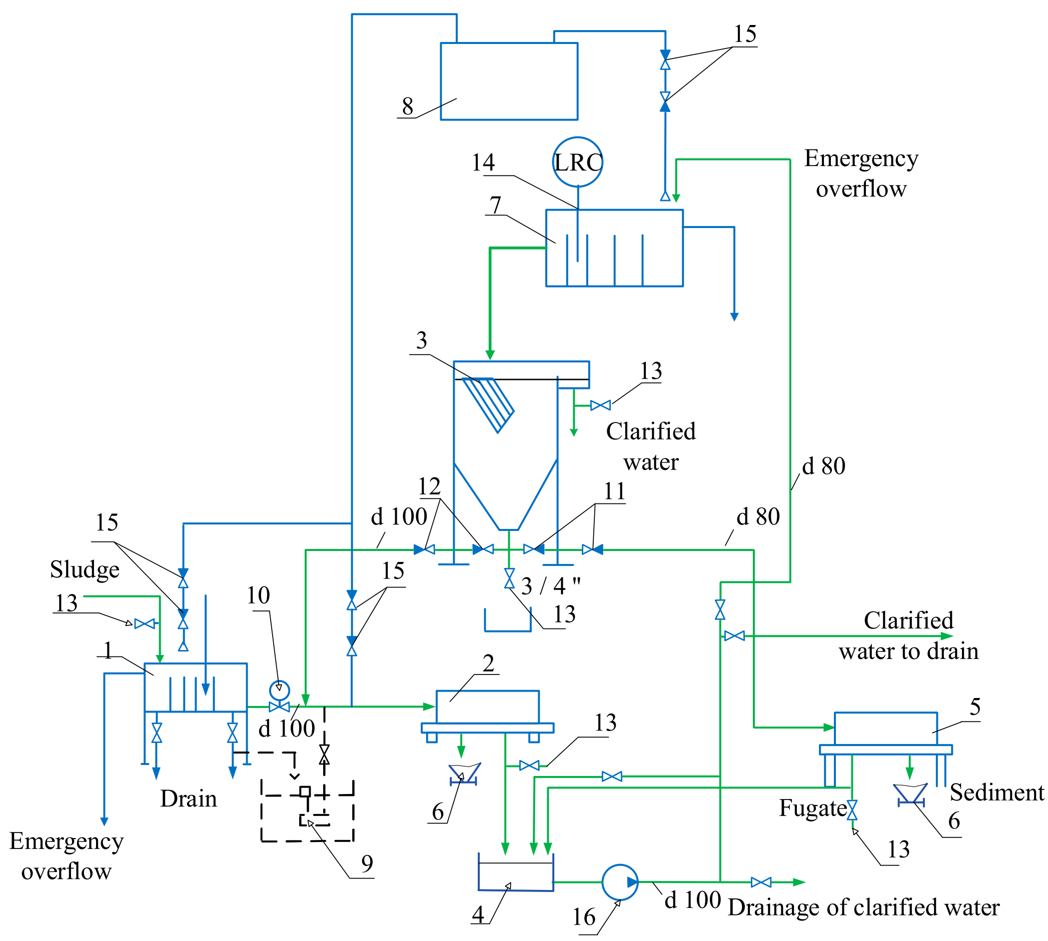


Fig. 2. Technological scheme of the Ecomash 6800 module apparatus chain for conducting tests on sludge cleaning and coal dust sediment dehydration: 1 — receiving tank with flow meter and mixer; 2 — Ecomash SHS 521AS-113 centrifuge; 3 — Ecomash 3400 thin-layer clarifier; 4 — centrifuge slurry collection tank; 5 — Ecomash SHS 311AS-213 backup centrifuge; 6 — sediment trolley; 7 — sludge mixing tank with flocculant with flocculation quality control; 8 — flocculation station; 9 — centrifugal thickener; 10 — electric crane for regulating the load in the Ecomash SHS 521AS-113 centrifuge; 11 — valves for discharging thickened sludge into the Ecomash SHS 311AS-213 centrifuge; 12 — valves for draining thickened sludge into the Ecomash SHS 521AS-113 centrifuge; 13 — sampler; 14 — level gauge; 15 — valves for regulating the flocculant flow rate; 16 — disk pump for pumping slurry

5. Results of investigating the efficiency of coal dust capture and dehydration of gas cleaning sludge from thermal power plants

5. 1. Results of laboratory studies of gas cleaning sludge samples and development of express methods for determining the concentration of the solid phase

During the studies, it was found that the temperature of the sludge during different periods of operation varies from 20 to 45°C. To design express tests for the rapid determination of the concentration of the solid phase, the dependence between the density of the sludge and the content of the solid phase at different temperatures was established. Before the installation of the module, sludge samples were taken at three temperatures (+20°C, +30°C, and +45°C) to determine the content of the solid phase and to construct density dependences (Fig. 3).

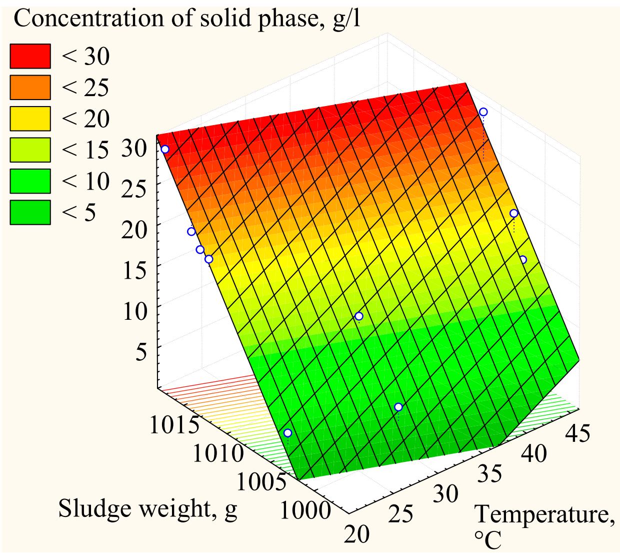


Fig. 3. Dependence of the mass of 1 liter of coal dust sludge on the concentration of the solid phase in it at different temperatures

Based on the results of this series of experiments, a plane equation was determined, which made it possible to quickly determine the concentration of the solid phase (C_{sp}, g/l) with an accuracy of up to 5% by measuring the weight of 1 liter of sludge and its temperature according to formula. Based on the results of this series of experiments, a plane equation was determined in natural (non-normalized) coordinates, which made it possible to quickly estimate the concentration of the solid phase (C_{sp}, g/l) in coal sludge with an accuracy of up to ±5% by measuring the temperature and mass of one liter of sludge

$$C_{sp} = -1924.7787 + 0.6603 \cdot m + 1.9081 \cdot t, \quad (1)$$

where m is the mass of 1 liter of sludge in the range from 995 to 1020 g;

t is the temperature of the sludge from 20 to 45°C.

This equation makes it possible to quickly estimate the concentration of the solid phase without the need for laboratory drying of samples, which is especially convenient for operational control under production conditions.

The study of the particle size of the solid phase in sludge by the sieve method showed that 99.31% of the particles have a size of less than 20 microns, which is already clear.

Additionally, the chemical parameters of the circulating water were determined in the laboratory using standard methodologies, given in Table 1.

Table 1

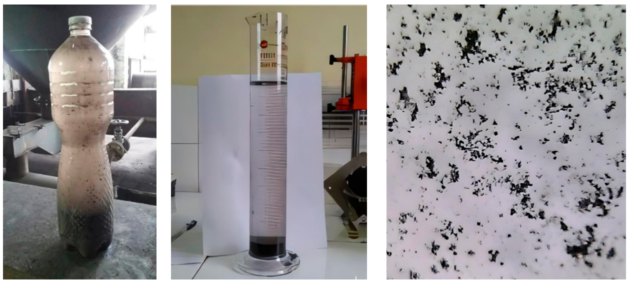
Chemical composition of recycled water

No.	Indicator	Concentration, mg/l	Methodology of determination
1	pH	7,8	DSTU 4077-2001
2	Content of ions Na^{+}	76	DSTU ISO 9964-2:2019
3	Content of ions Ca^{2+}	49	DSTU ISO 6059:2003
4	Content of ions Fe^{2+}	0,02	DSTU ISO 6332:2003
5	Content of ions Fe^{3+}	0,01	DSTU ISO 6332:2003
6	Content of ions Al^{3+}	0,06	DSTU ISO 10566:2017
7	Sulphates	311	DSTU ISO 10304-1:2003
8	Content of ions Cl^{-}	142	DSTU ISO 9297:2007
9	Content of ions HCO^{3-}	207	DSTU ISO 9963-1:2007

The study of sedimentation kinetics of sludge samples was carried out by settling the sample taken at the enterprise for 30 minutes at the sampling point in Fig. 4, *a* (sample height – 320 mm, thickened sludge separation limit – 75 mm). The separation limit of the clarified liquid and thickened sludge in the sample was found after 150 s of settling. The average rate of change in the height of the separation limit of the clarified liquid and thickened sludge zones was 0.136 mm/sec for 30 minutes.

Further study of the sedimentation kinetics was carried out in a measuring cylinder with a diameter of 50 mm and a volume of 0.5 l (Fig. 4, *b*). During the experiment, gradual precipitation of the solid phase in the sample, compaction of the sediment, and clarification of the liquid occurred. The temperature of the samples was +20°C, the concentration of the solid phase $C = 19.3$ g/l. The sedimentation of solid particles in the sludge samples at the initial moment (without the formation of a clear boundary between the clarified and thickened product) shows that the solid dust particles are close in size and less than 20 μm, which is confirmed by sieve analysis. The sedimentation process from the 18th to the 30th minute is characterized by sedimentation rates close to 0.18 mm/s, which indicates the formation of secondary structures with an approximate size of 100–125 μm (Fig. 4, *c*). Further sedimentation from the 20th to the 30th minute is characterized by limited sedimentation due to an increase in the concentration of the solid phase by more than 5 times and, as a result, a decrease in the sedimentation rate. After 30 minutes, a boundary between the clarified and thickened sediment is observed, while the concentration of the solid phase in the thickened product is approximately 100 g/l (humidity 94.4%). After 1260 minutes of sludge settling (Fig. 4, *b*), the concentration of the solid phase in the thickened product reached 240 g/l (humidity 86.7%).

The above-described sedimentation process indicates the aggregative and sedimentation instability of coal dust. Additionally, in the final part of the sedimentation, samples of secondary structures were removed from the sludge and photographed. Their size according to microscopic analysis was from 150 to 250 μm (Fig. 4, *c*) with a dry dust particle size of less than 20 μm. Thus, the sedimentation kinetics indicate the possibility of dust particles sticking together in the sludge with the formation of polydisperse aggregates. However, the time of complete settling to a transparent liquid indicates the inexpediency of sludge purification by settling in a gravitational field without the use of flocculants.



a b c

Fig. 4. Photographs of sludge samples: *a* — settled sludge sample; *b* — study of sludge kinetics in graduated cylinders; *c* — microscopic analysis of the hydrated solid phase (magnification x250, USB Digital Microscope)

When pulping in a laboratory centrifuge TsLN-2 (Kazakhstan) in a variable centrifugal field with a separation factor Fr = 632–1045, 87.5–90.63% of clarified liquid and 9.37–12.5% of sediment with a solid phase content of 187–303 g/l were obtained. Centrifugation provides transparent (without visible suspended particles) water and compacted sediment; therefore, industrial centrifuges are recommended for reagent-free dehydration of wet gas treatment sludge.

In the process of selecting flocculants to intensify the aggregation of sludge particles, it was found that the anionic flocculant ECOFLOC A-19 (China) is highly effective for coal sawdust. At the next stage of research, the optimal dose of flocculant was selected, which would ensure effective flocculation at a level of 6 mm/s and above. For flocculation, a sample of sludge from a wet dust collection system with a solids content of 29.3 g/l, a volume of 250 ml, was taken. A 0.05% solution of anionic flocculant A-19 (manufacturer) was added to the sample in two portions with a total dosage of 110 g/t, the sample was mixed by turning the cylinder ten times. The sedimentation rate of the solid phase after flocculation V_1 at a height of 60% of the total sample height was 8.2–8.6 mm/s. In this case, the clarified liquid was transparent, with a small content of fine suspension, which settled within 3 minutes. To assess the strength of the flocs, the thickened sediment was mixed with a turbine mixer for 40 seconds according to the methodology described in [15]. After stirring the thickened sediment, the sample volume was restored by adding clarified water, and the sedimentation rate of the solid phase after stirring V_2 was measured at a height of 60% of the total sample height (Table 2).

Table 2

Floccule settling rates during flocculation and mixing of thickened sludge

Limit of clarified water from above, *N*, mm	Condensed product limit from below, *N*, mm	Speed of movement of the phase interface boundary, mm/s	
		V_1	V_2
0	123	0	0
62	61	8.56	3.29
74	49	8.2	1.89

According to the results of analysis of Table 2, it was found that the sludge sample of the wet dust collection system is satisfactorily flocculated with a high-molecular polymer of the anionic type (ECOFLOC A-19) in the range of solid content of 20–30 g/l with a flocculant dosage of 130–150 g/t. The established solid phase deposition rates V_1 are implemented in an industrial thin-layer clarifier. The strength of the flocs (V_2 speed more than 2 mm/s according to previous studies [13, 14]) make it possible to transport the thickened product of the clarifier by screw or disk pumps to a centrifuge without the threat of complete destruction of the flocs.

Thus, the above-listed results of technological tests allow us to recommend industrial testing of sludge purification in centrifuges under a reagent-free mode, as well as when using the flocculant A-19 at a flow rate of 130–150 g/t.

5. 2. Research on the efficiency of cleaning sludges of wet dust collection and coal dust dehydration

5. 2. 1. Research on the efficiency of cleaning sludges of wet dust collection and coal dust dehydration without the use of flocculants

During the industrial test, various techniques of conducting the process under different modes were tested. At the first stage, the sludges of wet dust collection were fed according to the scheme in Fig. 2 into the receiving tank, pos. 1, then by gravity they entered the settling centrifuge, pos. 2, the fugate of which (clarified water) was drained. The tests were carried out at different sludge flows and centrifuge rotor speeds. The results are given in Table 3 and in the form of dependence plots of the efficiency of solid phase extraction on changes in feed flows (Fig. 5).

Table 3

Results of industrial research on the treatment of gas purification sludge in a centrifuge under a reagent-free mode

Centrifuge rotor speed, rpm	Relative screw speed, rpm	Centrifuge power, m^3/hour	Solid phase concentration, g/l		Solid phase capture efficiency $\eta = (C_{fd} - C_{fg}) / C_{fd}$, %
			In feed (C_{fd})	In fugate (C_{fg})	
2100	13	5	15	3.9	74.0
2100	13	6.5	5.5	2.75	50.0
2100	13	12	18.5	11	40.5
2100	13	5.1	14	4.75	66.07
2100	13	16.5	12.5	8	36.00
2100	13	2	10.5	0.25	97.62
2380	16	8.4	10.5	7.75	26.19
2380	16	13.8	14.25	11	22.81
2380	16	2	10.25	0.5	95.12
2380	11	7.6	11.5	1	71.30
2380	11	16.5	13.5	7.5	44.44
2380	11	3.3	14	0.75	94.64
2380	11	9	12	5.5	54.17
2380	8	8.6	14	4.75	66.10
2380	8	14.8	14	5.2	63
2380	8	5.4	12	3	81.00

The best stable result of the module operation was obtained at a centrifuge rotor speed of 2380 rpm, a relative screw speed of 8 rpm in the flow range up to 17 m^3/h (Fig. 5). Moreover, with a decrease in the sludge flow rate in the feed, the efficiency increased, which is explained by an increase in the sludge residence time in the centrifuge and is consistent with the results described in [9]. The sludge moisture content was 33–36%.

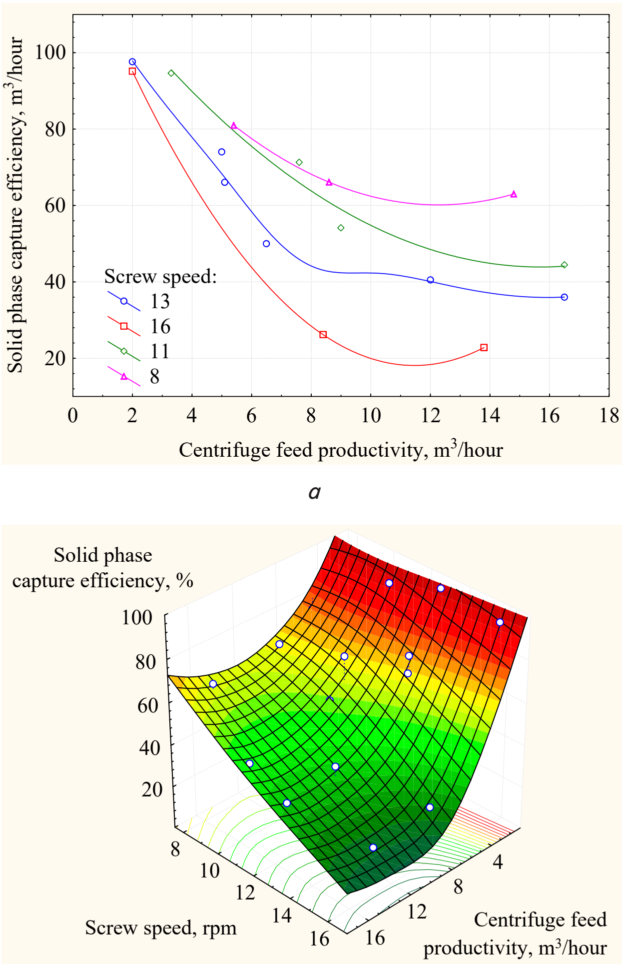


Fig. 5. Dependence of sludge cleaning efficiency on the productivity and relative speed of the centrifuge screw: *a* — experimental data; *b* — 3D visualization of the dependence

A relationship between the efficiency of solid phase capture and the relative screw revolutions was also established – with increasing revolutions, the efficiency decreases, which is explained by the sediment agglomeration and the destruction of sludge aggregates. This, in turn, leads to the removal of part of the solid phase from the centrifuge with the fugate.

At the second stage of the research, the sludge from the receiving tank pos. 1 was fed into the fugate collection tank pos. 4, mixed with the fugate of the centrifuge pos. 2, then fed by a disk pump into the thin-layer sedimentation tank pos. 3 through the mixing tank pos. 7, then the clarified water after the thin-layer sedimentation tank was directed to the drain. The thickened product of the thin-layer sedimentation tank was fed for dehydration into the sedimentation centrifuge pos. 2, the sediment was unloaded onto the cart pos. 6, the fugate was fed into the fugate tank pos. 4. The efficiency of the module during tests under the reagent-free mode at a feed flow rate of 16.8 m^3/h was 38%. The results of tests under this mode compared to a similar mode using a flocculant are given in Table 4.

5. 2. 2. Studying the efficiency of cleaning sludges of wet dust collection and coal dust dehydration using flocculants

The sludge after flocculation was fed by gravity to the settling tank, where after repeated treatment with a flocculant it was separated into clarified water and thickened sediment. Then the clarified water of the thin-layer settling tank was directed to the drain. The thickened product of the thin-layer settling tank was fed for dehydration to the centrifuge pos. 2, the sediment was unloaded into the cart pos. 6, the fugate was fed into the fugate tank pos. 4.

The stable results of the module operation, given in Table 4, indicate that the overall efficiency of the module in retaining the solid phase was 97.4%. At the same time, the concentration of the solid phase in the clarified liquid of the settling tank was 0.5 g/l, the moisture content of the sediment was 32%. Anionic flocculant was used in an amount of 150 g/t, calculated by introducing it into 2 flocculation points – 40% in the first (in the receiving tank) and 60% in the second (mixing tank).

At the final stage of our study, the wet dust collection sludge was fed into the receiving tank pos. 1, treated with a flocculant, and by gravity flow it was fed into the centrifuge pos. 2, where it was treated with a flocculant in the centrifuge. Anionic flocculant was used in an amount of 132 g/t based on 2 flocculation points. The efficiency of the centrifuge at a centrifuge feed rate of 5.4 m^3/hour with a solid phase concentration in the fugate of 15 g/l was 78.3%, with an increase in the flow rate, a decrease in the centrifuge efficiency was observed, which makes this mode and mode impractical for use.

Table 4

Results of studies on continuous stable operation of the module after adjusting technological parameters under a reagent-free mode and with the use of flocculants

Technological indicator	Value	
Amount of flocculant per 1 ton of solid phase in sludge, g/t	150	0 (flocculant-free)
Supply feed of the receiving tank, m^3/hour	16.8	16.8
Concentration of the solid phase in the gas cleaning sludge in the supply of the receiving tank, g/l	19	10
Sedimentation tank feed, m^3/hour	19.6	19.5
Concentration of the solid phase in the sump feed, g/l	28	11.1
Volume of condensed sludge of the sedimentation tank, which was sent to the centrifuge, m^3/hour	2.8	2.7
Concentration of the solid phase in the condensed sludge of the sedimentation tank (in the centrifuge feed), g/l	128	62.6
Volume of clarified water from the sedimentation tank, m^3/hour	16.6	16.8
Concentration of the solid phase in clarified water from the sedimentation tank, g/l	0.5	6.2
Centrifuge operating mode: rotor speed/relative screw speed	2380/8	2380/8
Volume of centrifuge fugate returned to the receiving container, m^3/hour	2.8	2.7
Concentration of the solid phase in the fugate, g/l	47	6
Sediment moisture, %	32	32.7
Total efficiency of the solid phase capture module, %	97.4	38

6. Discussion of results based on coal dust capture and dehydration of gas cleaning sludge from thermal power plants

Fig. 3 shows the dependence of the mass of 1 liter of coal sludge on the concentration of solid phase at different temperatures. The plot demonstrates a clear linear trend: with an increase in the concentration of the solid phase, the mass of a liter of sludge increases. This is explained by the fact that a higher content of solid particles leads to an overall increase in the density of the suspension. At the same time, with the same concentration of the solid phase, the mass of 1 liter of sludge decreases with increasing temperature. This dependence is due to the thermal expansion of the liquid phase, which causes a decrease in the density of the mixture. Therefore, temperature is an additional factor affecting the mass of a unit volume of sludge at a fixed content of solid residue. Therefore, it must be taken into account for operational concentration control using equation (1). TPP gas purification sludge is characterized by a high content of fine particles of coal dust. Sieving the sample through a set of sieves showed that 99.31% of the particles were smaller than 20 μm; however, the sedimentation kinetics during settling indicated sedimentation rates characteristic of larger particles. This observation and the results shown in Fig. 4*c* can be explained as follows.

When dry dust enters the scrubber, hydration of dust particles is observed, which leads to the formation of solvate layers that form on the surface of the particles due to the adsorption of the solvent – water (H^+ or OH^- ions). This contributes to a certain stabilization of the entire suspension. However, during sedimentation, particles can develop a speed sufficient to overcome repulsive forces and form secondary structures, which is observed in laboratory studies after 15–30 minutes of sedimentation (Fig. 4, *a*). Secondary coagulation structures that arise as a result of the interaction of individual particles usually arise as a result of a decrease in the aggregative stability of dispersed systems, which is what happens in coal dust samples. In addition, coal grinding in mills leads to the destruction of the crystal lattice and the formation of charged surfaces of different strengths in the fracture areas, which adsorb ions of the opposite charge. This also leads to uneven surface charge of coal dust of different signs and can be a factor in particle adhesion and coagulation. The size and shape of the initial dust particles have a great influence on the rate of structure formation. Coagulation of particles is probably also caused by the presence of polyelectrolyte ions in water, as evidenced by Table 1. The Al^{3+} and Fe^{3+} cations present in small quantities, as well as the pH of water, contribute to their hydrolysis and the formation of a developed surface of hydroxides. They act as coagulation foci, adhering to coal dust. Further, the particles grow, colliding with small particles as they fall in a gravitational field. Adsorption of cations by suspension particles leads to a decrease in their stability, as a result of which mutual adhesion of particles becomes possible. However, the forces promoting the adhesion are apparently not large enough compared to the mass of the particles and other factors that ensure their stability, but sufficient to obtain large heavy flakes. This explanation is consistent with the theoretical understanding of the process and literature data [11].

Our studies have shown the possibility of effective sludge purification under a reagent-free mode in the field of centrifugal forces. It was found that the efficiency of centrifugation improves with an increase in the residence time of particles in the centrifuge, which is achieved by reducing the centrifuge feed productivity and reducing the relative rotor speed (Fig. 5). However, increasing the productivity in terms of the volume of purified water requires the use of sedimentation tanks with pre-treatment of sludge with anionic flocculant of type A-19 in an amount determined experimentally. According to the studies reported in [9, 14, 15], the efficiency of flocculation, the rate of sedimentation, and the strength of flocs to destruction depend on the concentration of solid phase in the sludge and the ratio of the amount of flocculant to the area of the solid phase. That is why the consumption of flocculant must be checked by laboratory tests with real sludge at the enterprise and the concentration of the solid phase must be constantly monitored. For operational control over the concentration of solid phase in the research process, the dependence (Fig. 3) and the calculation formula (1) were established, which simplify the determination of the concentration of the solid phase by controlling the density of the sludge. However, the use of dependences shown in Fig. 3 when carrying out measurements by the express method requires the presence of scales with a minimum measurement error, as well as certified 1 l volumetric flasks for accurate volume measurement. When carrying out calculations, it is necessary to specify the actual values of the density of the solid phase, which affect the volume fraction of solid and water for specific pulp temperatures.

During module testing, the sludge flow rate was stable, and the solid phase concentration in the feed varied within 12–21.5 g/l for 30 minutes. When installing a receiving tank with a volume of ~ 10 m^3 in the module head, the solid phase concentration in the feed will be averaged. In this regard, for the automatic control system, it is sufficient to control the sludge flow rate with the flocculant dosage adjustment based on the average concentration. The absence of large foreign objects and particles in the feed ensured the continuity of the tests and the non-clogging of the mains and devices.

Based on the results of studies of various modes of sludge feeding and mixing with flocculant, the optimal sequence of technological operations and operating modes of the equipment have been established, namely:

– sludge feeding is carried out through a receiving tank into a thin-layer sedimentation tank with two-stage flocculation with anionic flocculant of type ECOFLOC A-19 with a total flocculant dosage of 130–150 g/t;

– visually transparent liquid discharge from the thin-layer sedimentation tank contains less than 0.5 g/l of suspended particles and can be directed to the water supply system of the thermal power plant for secondary use in dust collection systems with wet scrubbers;

– the thickened product of the thin-layer clarifier is fed into the Ecomash SHS521AS-113 sedimentation centrifuge (operating mode: rotor speed 2350–2450 rpm, relative screw speed 8–10 rpm), which dehydrates the coal dust to a humidity of 32%, and the centrifuge effluent is returned for further treatment, mixed with the initial sludge, and directed back into the thin-layer clarifier.

The limitations of our study are that the results and formulas are applicable only in the temperature range of 20–40°C and the solid phase concentration of 12–21.5 g/l. They relate to sludge from a specific TPP with a specific composition and characteristics; therefore, additional verification is required for other objects. For accurate control, high-precision measuring equipment is required, and the efficiency of flocculation depends on the type of flocculant, which requires individual selection of the dose. The system is sensitive to the presence of foreign impurities, and scaling the process to larger volumes requires additional research.

Due to the fineness of the particles, the suspension may be unstable under changed conditions, which affects the quality of dehydration.

The disadvantages of conducting the described studies are a certain inaccuracy and error in measurements of technological indicators of the module (flocculant consumption, sludge consumption) and the error in technological tests for determining the concentration, which does not take into account the possibility of changing the composition of the sludge during the testing process. However, under production conditions for the needs of operational control, such a methodology as described in this paper is acceptable and does not significantly affect the described patterns.

The described procedures and testing methodologies, as well as settings of sedimentation and centrifugation equipment, can be adapted for the treatment of wastewater and sludge in other industries. This is possible provided that changes in the properties and composition of sludge are taken into account, which is confirmed by previous studies with sludge from metallurgical industries and coal enrichment plants [14–16].

The prospect of further research is to devise the technology for setting up a chain of sedimentation and centrifugation equipment in other industries for the treatment of sludge of various nature, composition, and origin. This will make it possible to identify and clarify the patterns that affect the efficiency of water treatment processes and sludge dewatering.

7. Conclusions

1. As a result of our studies of sludge samples from the gas purification of emissions from the dust preparation shop at a thermal power plant, it was established that it consists of finely dispersed dust particles smaller than 20 microns, which, during hydration, stick together into aggregates up to 250 microns in size. The study of the sludge settling process indicates the inefficiency of using settling tanks without chemical enhancement of the process. It was established that the sludge from the wet dust collection system is flocculated with a high-molecular polymer of the anionic type ECOFLOC A-19 in the range of solid phase content of 20–30 g/l. When dosing the flocculant in an amount of 130–150 g/t, floc sedimentation rates of 8.2–8.6 mm/s were established. For effective control over the solid phase concentration in the sludge and dosing the appropriate amount of flocculants, a relationship was established between the concentration of the dispersed phase, the temperature of the dispersed medium in the range of 20–45°C, and the density of the sludge.

2. As a result of the study on sludge purification in centrifuges without the use of reagents, a relationship was established between the efficiency of solid phase retention, centrifuge productivity, and the value of relative screw revolutions. It was found that the purification efficiency increases with a decrease in work productivity. The best indicators of solid phase retention efficiency from 97% to 81% were achieved with a centrifuge feed productivity of 2 to 5.4 m^3/hour. It was found that it is possible to increase productivity to 15–20 m^3/hour and obtain purified water, which can be returned to production during the sedimentation of flocculated sludge in a settling tank with subsequent dehydration of thickened sludge.

As a result of industrial tests, the design indicators of the proposed technology for sludge purification and coal dust dehydration based on a thin-layer settling tank and an Ecomash SHS521AS-113 settling centrifuge using a flocculant were confirmed. The modular unit operated at production loads of up to 16.8 m^3/h with the following efficiency indicators: solids content in clarified water less than 0.5 g/l; humidity of dehydrated dust 32%; purification efficiency 97.4%.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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