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INVESTIGATION OF EXTRACTION AND DEHYDRATION EFFICIENCY OF GRANULAR COAL SLUDGES

The object of research is the process of extracting the solid phase and dewatering carbon-containing products of a coal enrichment plant in the technological chain of devices "drum screen – centrifuge". One of the most problematic areas of coal enrichment technology is the sludge waters of coal enrichment plants, which require high-quality cleaning and are promising for obtaining a fine coal fraction. This allows to reduce the load on radial thickeners, prevent coal losses and environmental pollution.

During the study, an industrial experiment was used to determine the efficiency of the module, which consisted of an Ecomash DS 511A-113 drum screen and an Ecomash SHS 511A-113 centrifuge. It was established that classes larger than 1.5 mm are advisable to capture and dewater by filtering on the developed drum screen to a moisture content of 15–22 % by filtration methods. Polydisperse sludge after removal of classes larger than 1.5 mm is effectively dehydrated in a centrifuge to a residual moisture of 19.7–33 %. The degree of sludge dehydration in a centrifuge is affected by the fraction of the class content larger than 0.4 mm and the centrifuge feed capacity, which determine the formation time, compression and compactness of particle packing in the sludge. It has been established that when dewatering fine-dispersed sludge of fine classes with a particle size of less than 0.4 mm, the moisture content of the centrifuge sludge increases with increasing solid phase retention efficiency. An increase in the fraction of fine-dispersed classes in the sludge, represented mainly by wet clay, leads to an increase in moisture content to 33 % and an increase in ash content to 83–85 %. An increase in the content of granular classes 0.4–1.5 mm to 30 % and above contributes to a decrease in sludge moisture content, other things being equal, due to the squeezing of moisture from the surface of fine particles that are squeezed by larger particles. The technological chain of the module, tested in industrial conditions, consisting of a filter screen and a centrifuge, allows for the effective extraction of the granular fraction of the sludge, capturing up to 87.4 % of the solid phase, leaving only finely dispersed high-ash clay with a particle size of less than 40 microns in the centrate.

Keywords: *polydisperse sludge, solid phase retention efficiency, sludge dewatering, settling centrifuge, filtration, coal sludge purification.*

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1. Introduction

Coal sludges are usually coal-containing products with a size of less than 0.5–1 mm. A distinction is made between granular (>50–60 μm) and fine (<50–60 μm) sludges. Depending on the place of formation, sludges are divided into primary (arrived at the plant with run-of-mine coal) and secondary (formed during the enrichment process) [1]. At coal enrichment plants, sludge is in unenriched form (run-of-mine) and enriched (flotation concentrate, hydrocyclones, concentration tables, screw separators and filter centrifuges). According to experimental data, the content of 1–3 mm size classes in run-of-mine coal reaches 20 to 40 % [2]. An additional source of formation of fine coal fractions are coal transportation and enrichment operations. At the final stage of enrichment of run-of-mine coals, coal-containing products with a size of less than 3 mm are formed, characterized by high ash content, for example: concentrate of spiral separators with an ash content of 20 % to 50 % and waste from spiral separators with an ash content of more than 70–80 % [3].

These coal-containing products are united by a polydisperse composition of the solid phase, which determines the features of the processes of extraction and dehydration of such coal-containing products of operating coal preparation plants [4].

A similar situation is with coal-containing products in external sludge ponds and dumps of coal preparation plants. The accumulation of mining waste leads not only to operating costs for servicing sludge ponds, but also to secondary pollution of the environment [5]. Today, coal preparation plants in different countries have significant resources of sludge and waste from the enrichment of coke and power-generating coal [6]. An increase in the amount of these resources leads to a loss of resources and an environmental burden on natural ecosystems [7]. The solution to this problem is the processing and additional extraction of coal products from sludge collectors by filtering and centrifuging them. Therefore, in recent years, sludge waste from coal preparation plants has been of particular interest, as it can be subject to repeated enrichment in order to extract additional coal from it [8].

Thus, technologies for the effective extraction and dehydration of coal-containing products of granular sludge, which allows closing the process chain of devices and, thus, eliminating the discharge of liquid enrichment waste into external sludge collectors with the loss of the granular coal fraction, are relevant.

The main issue when choosing a technology for extracting the coal fraction of sludge from coal enrichment of a granular product is the question of the advisability of dehydrating such sludge with one class, or preliminary classification by grain size. This is due to the fact that

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the fine fraction of suspended particles in the sludge of coal preparation plants with a size of less than 40 microns is mainly represented by the clay fraction, the ash content of which reaches 80 %, and particles larger than 40 microns contain coal particles [9]. In modern practice, it is considered that the finely dispersed fraction, which is of no interest for secondary use, should be discharged into radial thickeners, and the granular fraction should be tried to be extracted.

There are no clear data in the literature on the efficiency of dewatering the sludge of the specified range due to the fact that the fractional composition of the sludge is a multifactorial process that depends on both the nature and properties of the raw material and the coal enrichment technology at a particular enterprise. Therefore, the values of the performance indicators of the equipment that allows extracting solid phases of various sizes from the sludge require clarification during industrial testing on a specific product. A common method for cleaning coal enrichment sludge is settling centrifuges [10]. However, the presence of a class larger than 1.5 mm reduces the service life of the centrifuge due to mechanical damage, so it is recommended to remove them before the centrifuge using filter equipment. A promising method for cleaning sludge and extracting solid phases of various sizes from them are modular units, which are a chain of settling, filtering and dewatering devices [11]. For example, a combination of filtering devices with sedimentation centrifuges allows for the step-by-step extraction of granular products of different sizes during filtration and then centrifugation, leaving the finest clay fraction in the liquid phase. Due to the fact that the processes of dewatering the solid phase in filtering devices and sedimentation centrifuges differ significantly, these studies were conducted of a module for cleaning and dewatering granular sludge from coal enrichment using a drum sieve and a sedimentation centrifuge.

The aim of this research is to study the possibility of extracting the granular fraction using a modular unit consisting of a filtering device and a sedimentation centrifuge.

To achieve this aim, it is necessary:

– to study the composition and properties of real sludge flows from a coal enrichment plant during the operation of the technological chain of devices of the "drum sieve – sedimentation centrifuge" module;

– to investigate the efficiency of retention of solid phase of granular classes and the degree of dehydration of enrichment products on the module devices;

– to investigate the influence of factors on the efficiency of dehydration of granular sludge after classification of solid phase by size classes in the technological chain of devices.

2. Materials and Methods

The object of research is the process of solid phase extraction and dehydration of coal-containing products of a coal preparation plant in the technological chain of "drum sieve – centrifuge" devices.

To determine the qualitative and quantitative indicators of dehydration of granular coal-containing products under the conditions of one of the coal preparation plants (Pavlohrad, Ukraine), tests of the dehydration module of granular coal-containing products were carried out. According to the current scheme of operation of the coal preparation plant, after enrichment, granular coal-containing products are sent to pressure hydrocyclones, the thickened sludge of which is enriched in spiral separators. Spiral separator waste is a polydisperse sludge, promising for additional extraction of a coal fraction smaller than 3 mm. In this study, real sludge from spiral separator waste was used.

A module for dehydration of granular coal-containing products was assembled to dehydrate the classified sludge. It is a technological chain of devices: drum screens of the Ecomash DS type and a centrifugal unit Ecomash SHS 511A-113 (NTC Ecomash LLC, Kharkiv, Ukraine). The diagram of the chain of devices of the dewatering module for classified coal-containing granular sludge is shown in Fig. 1.

The operating principle of the module is illustrated in the circuit diagram of the apparatus (Fig. 1). When process waters containing a polydisperse solid phase are supplied, particles larger than the cells of the screening surface are separated in the rotor of the drum screen, forming an oversize product by filtration. The design of the drum screen is shown in Fig. 2, and the technical characteristics are in Table 1.

The main unit of the Ecomash DS drum sieve is a rotor 1 of cylindrical-conical shape, on the outer surface of which replaceable sieving surfaces are fixed (Fig. 2). Inside the rotor are spirals 3 of the auger. The rotor is driven by a gear motor 2, ensuring its constant rotation around the axis. During operation, the pulp is fed through a feed pipe 4 into the rotor. The retained solids of the pulp form an oversize product, which is transported by the rotor auger into the oversize product discharge shaft. If additional requirements for the moisture content of the oversize product are met, a drying drum is attached to the rotor discharge cone, the operation of which is ensured by blowing with hot air. The undersize product of the rotor enters the housing, where it can be averaged using a mixer 5. An emergency overflow is equipped in the housing of the drum sieve, which allows an electric valve to be installed at the outlet of the housing, regulating the flow of purified liquid into the process chain of the devices.

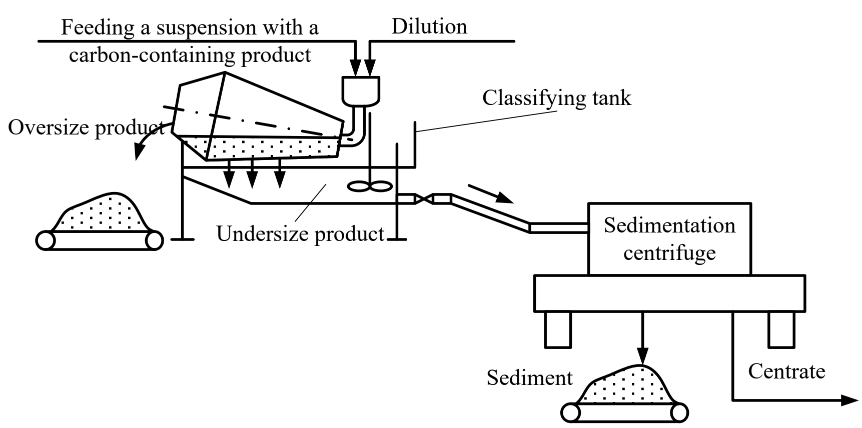


Fig. 1. Circuit diagram of the dewatering module apparatus with gravity product transport system

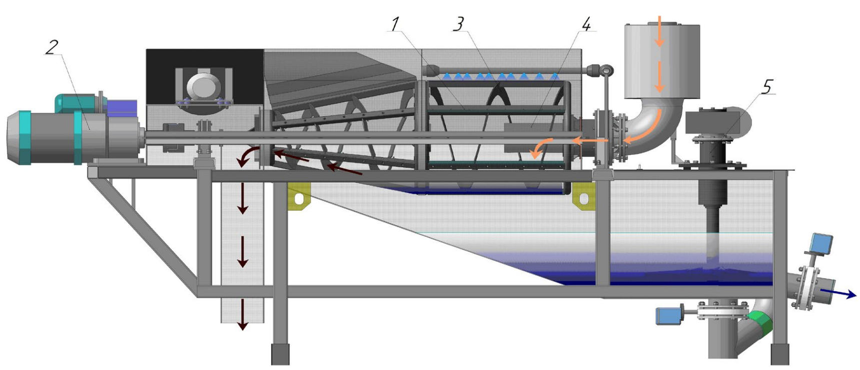


Fig. 2. Operation diagram of the Ecomash DS drum sieve: 1 – rotor; 2 – gear motor; 3 – spirals; 4 – feed pipe; 5 – mixer

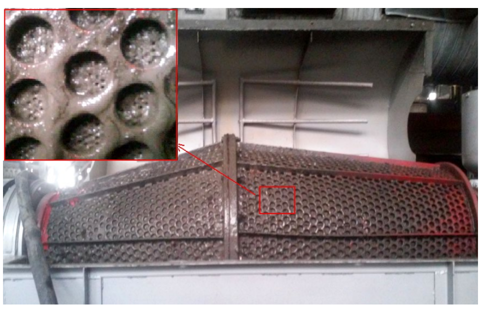
Table 1

Technical characteristics of the Ecomash DS drum screen

No.	Parameters	Indicators
1	Volumetric capacity for water with porosity of screening surface more than 23 %, Q_p, m^3/hour, not less than	100
2	Capacity for oversize product, t/hour, max	8
3	Rotation frequency of classifying rotor, rpm	30; 45
4	Diameter of opening or clearance of transverse bars of screening surface of rotor, mm	0.5–3.0
5	Maximum size of solid particles in feed, mm	13
6	Mass of classifying tank, not more than, kg	1800
7	Installed power, kW	9.7

The rotor is covered from the outside with a lifting lid, inside which devices for regeneration of the sieving surface are installed: with air and (or) water.

During the tests, the pulp with polydisperse solids entering the drum sieve is filtered through the perforated surface of the rotor (Fig. 3, *a*) with a pore size of 1.5 mm. The pulp filtration process occurs under constantly changing conditions of transport, sediment turnover with an increase in the concentration of solids and sediment thickness along the length of the rotor as the oversize product is transported. In this case, the structure of the resulting sediment is destroyed and the residual moisture is additionally reduced. The oversize product is unloaded by the blades of the screw spirals of the rotating rotor (Fig. 3, *b*).



a

b

Fig. 3. Classifying tank: *a* – filter surface of the rotor drum 1.5 mm; *b* – unloading of filtered sediment by the blades of the screw spirals

The undersize product is fed to the centrifugal unit through an adjustable electric drive crane. The electric drive crane is controlled by the module automation, and the devices are controlled by personnel from a single control panel. Before feeding the load into the drum screen and then into the centrifugal unit, as well as after dewatering, samples of the sludge were collected. The sieve analysis of the solid phase of the pulp was studied, the ash content of the solid phase was determined, and the range of change in the content of solid classes in the pulp during operation of the coal preparation plant was assessed. The sieve analysis and determination of ash content before and after dewatering were carried out by the central laboratory of the plant using standard methods [12, 13].

The efficiency of trapping the solid phase in the sediment was estimated by the formula [4]:

$$\eta = \frac{C_{in} - C_{pr}}{C_{in}} \cdot 100\%, \quad (1)$$

where C_{in} – content of the solid phase in the initial suspension, kg/m^3; C_{pr} – content of the solid phase in the liquid separation product (centrifuge centrate or filtrate of the classifying tank), kg/m^3.

3. Results and Discussion

3.1. Results of studies on cleaning and dewatering of classified sludge

Tests of sludge dewatering in a centrifuge after classification in the technological chain of the module were carried out on waste from spiral separators and are presented using the example of 4 experiments in Table 2.

Table 2

Results of dewatering of waste from spiral separators

Performance indicators of the dewatering module	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Dewatering module feed capacity, m^3/hour	6	25	27	36
Solid phase concentration in the module feed, g/l	1144	132	156	166
Solid phase ash content in the feed, %	85	58.3	60	76.5
Solid phase load, t/hour	6.864	3.3	4.2	6.0
Sludge moisture content, %	22	27	26.3	14.9
Sludge ash content, %	83	22.2	25.2	76.1
Solid phase retention efficiency, %	38.8	27.3	6.4	61.4
Centrifuge feed after the classifying tank, m^3/hour	4	23	25	34
Solid phase concentration in the centrifuge feed, g/l	700	96	146	64
Solid phase ash content in the centrifuge feed, %	83	53	54.5	66.4
Sludge moisture content, %	19.7	28.7	30	33
Sludge ash content, %	85.8	42.2	42.1	64
Solid phase ash content in the centrifuge centrate, %	83	83.4	82	75
Solid phase concentration in the centrifuge centrate, g/l	142	22	38	22
Solid phase retention efficiency in the centrifuge, %	79.7	77.1	74	65.6
Total module efficiency for solid phase extraction, %	87.4	77	75.5	66

During the tests, stable operation of the oversize product discharge was noted, which was low-ash washed coal (Fig. 4) larger than 1.5 mm in size.

Fig. 4. Unloading of large coal fraction after filtration

The change in the sieve composition presented in Table 3 shows the effective retention of granular coal enrichment products with a size of more than 1.5 mm in the drum sieve, as well as part of the 0.4–1.5 mm class due to filtration of sludge through a layer of granular sediment and retention of small grains in the pores of the sediment.

Table 3

Comparative characteristics of the change in sludge parameters before and after the drum sieve

Experiment No.	Experiment 1		Experiment 2		Experiment 3		Experiment 4	
	Feed	Product	Feed	Product	Feed	Product	Feed	Product
Class size, μm	Class content, %							
+3000	15.40	0.00	23.8	0.53	13	0.2	0.00	0.00
+1000	0.65	0.25	14.11	17.22	10	12.5	80.35	1.49
+400	29.80	28.28	12.17	19.07	21	19.8	5.96	7.46
–400	54.14	71.47	49.9	63.18	56	67.5	13.69	91.04

The sieve composition of the centrifuge effluent was mainly (more than 97 %) represented by the class less than 0.4 mm, which characterizes the almost complete extraction of the granular fraction of coal from the sludge and discharge of the clay fraction with an ash content of 75–83 % as liquid waste (Table 2). The efficiency of retaining the solid phase of the drum sieve and the moisture content of the discharged sediment are determined mainly by the dispersed composition of the granular products. With an increase in the share of the class less than 0.4 mm, the moisture content of the sediment increases due to the discharge of the finely dispersed class together with the class larger than 1.5 mm (pore size of the filter surface). Thus, the minimum moisture content of 14.9 % and the maximum efficiency of 61.4 % are observed during dewatering of waste mainly of the coarse phase with a share of the class less than 0.4 mm of only 13.69 % (experiment 4, Table 2). This confirms the statement that sediments consisting of monodisperse large particles have a low moisture content due to a smaller surface with adsorbed and capillary moisture.

The efficiency of solid phase retention by the centrifuge unit after the drum screen was up to 79.7 %, the moisture content of dewatered waste was 19.7–33 %. The overall efficiency of solid retention by the dewatering module was 66–87.4 %.

3.2. Discussion of the results of extraction and study of dewatering of coal-containing products

The efficiency of solid retention in the centrifuge after sludge classification into classes up to 1.5 mm (after classification in the drum screen) depends to a greater extent on the sludge productivity and particle dispersion. The dependence of the efficiency of solid phase retention and moisture on productivity is shown in Fig. 5. With increasing productivity, the time of presence of the solid phase in the centrifuge and the time of sediment compaction decrease. This leads to a decrease in the efficiency of solid phase retention and sediment dewatering. By changing the productivity and, accordingly, the time of sludge presence in the centrifuge, it is possible to control the compressibility of the sediment, and, consequently, the humidity and the degree of solid phase retention.

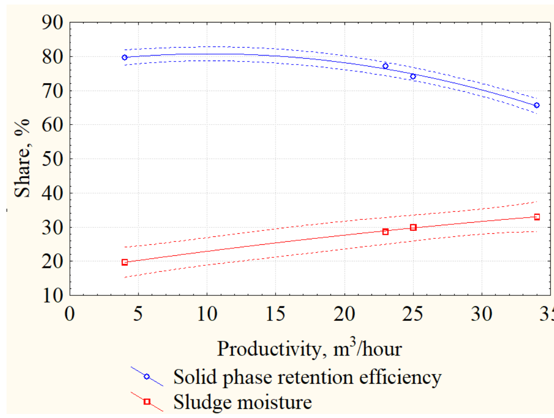


Fig. 5. Dependence of the efficiency of retention of the solid phase of the sludge of class less than 1.5 mm and the moisture content of the sediment on the centrifuge productivity

At the same time, the moisture content of the sediment of 19.7 % (experiment 1, Table 5) was obtained with the content of the class of 0.4–1.5 mm in the centrifuge feed of almost 30 % (experiment 1, Table 2), and the moisture content of 33 % (experiment 4, Table 2) with the content of the class less than 0.4 mm was 91 %. These data also confirm the possibility of the structure formation of the sediment with a minimum number of pores due to the squeezing out of liquid during its compaction in the presence of the fraction of 0.4–1.5 mm. With an increase in the share of this size class to 30 % in the sludge, a decrease in the residual moisture content of the sediment is observed. Thus, the presence of large classes above 0.5 mm in the sludge contributes to the effective removal of moisture in the centrifuge due to the formation of a compact, compacted sediment structure.

Studies have shown that removing classes larger than 1.5 mm does not reduce the possibility of effective sludge dewatering. Probably, to obtain the lowest humidity in centrifuges, the bulk of the sludge should consist of at least 30 % of the 0.4–1.5 mm class and no more than 45 % of the 0.4 mm class. Filling the gaps between the grains of this class with smaller grains will allow the sludge to compact in the centrifugal field and squeeze water out of the finely dispersed phase sandwiched between large particles. This indicates the possibility of creating favorable conditions for dewatering in centrifuges by preliminary preparation of sludge by dispersed composition. As a result of data analysis (points in Fig. 5), an equation was obtained for the dependence of the solid phase retention efficiency η (%) and sludge humidity W (%) on the centrifuge productivity Q (m^3/hour):

$$\eta = 77.966 + 0.5478 \cdot Q - 0.0269 \cdot Q^2, \quad (2)$$

$$W = 17.4 + 0.5883 \cdot Q - 0.0038 \cdot Q^2. \quad (3)$$

These equations adequately describe the obtained dependencies and allow calculations to be made with sufficient accuracy for industrial purposes. The standard deviation of the calculations is 2.7 % for equation (2) and 1.8 % for equation (3), respectively. The difference in the processes of dehydration of the solid phase in a filter centrifuge and a sedimentation centrifuge is interpreted in the following diagrams (Fig. 6). During the filter process (Fig. 6, *a*), if there are few fine particles, they are carried away together with moisture through the pore channels – the phenomenon of suffusion. If there are many fine particles, then colmatation of the pore channels is observed and dehydration worsens. In a sedimentation centrifuge (Fig. 6, *b*), centrifugal forces press large particles (grains) to the rotor wall and only if there is a sufficient number of medium and fine particles compressed by the grains, moisture is squeezed out in the direction opposite to the centrifugal forces. The obtained results are consistent with theoretical concepts of the filtration process [14, 15]. With a small number of finely dispersed particles, moisture is retained in the pore channels of the grains under the action of centrifugal forces.

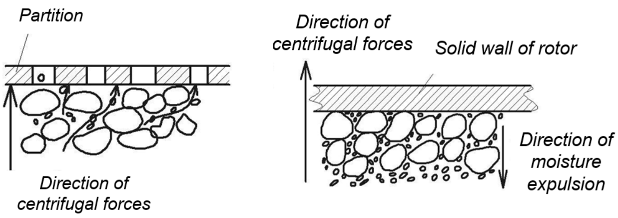


Fig. 6. Scheme of dewatering processes during filtration and centrifugation: *a* – carryover of moisture and fine particles in granular products under the action of centrifugal forces in the filter centrifuge; *b* – directions of moisture squeezing out during centrifugation

Thus, preliminary classification of sludge in a drum sieve by size class up to 1.5 mm allows to obtain a dewatered product with low moisture content, protect the centrifuge from mechanical damage and control the dewatering process. It is possible to control the moisture content of the sediment by adjusting the dispersed composition by classification or mixing of sludge with different content of classes, as well as by changing the operating modes of the centrifuges (for example, the feed capacity of the centrifuge), affecting the degree of retention of the solid phase. This opens up prospects for further research into the combined use of filtering and dewatering equipment.

Practical value. The studies have shown high efficiency of the proposed module and the developed equipment for extracting the granular class of coal from sludge. This allows to recommend the use of a drum sieve with a centrifuge for cleaning coal beneficiation sludge. The scope of application of the module can also be the extraction of small fractions of coal during the processing of sludge and sludge from industrial sludge collectors.

Limitation of the study. For more efficient industrial use, it is necessary to take into account the processed mode parameters and volumes of sludge - their volume and size of waste fractions. To increase the volume and increase productivity, it is possible to increase the number of centrifuges connected in series and change the holes of the drum sieve if additional classification by the size of solid phase grains is necessary.

Currently, *martial law conditions* limit the widespread implementation of technological solutions for the processing and disposal of coal from sludge and sludge collectors of coal preparation plants, especially in the combat zone and occupied territories. However, the use of the technology and equipment described in the article is promising for reducing coal losses during the post-war restoration of the coal and coal enrichment industry in Ukraine.

4. Conclusions

Studies of the composition and properties of real coal preparation plant sludge flows showed instability of the sludge composition and concentration. Thus, during the tests, the solid phase concentration in the sludge varied from 132 g/l to 1144 g/l depending on the coal preparation plant load. The size ratio of the solid phase larger than 1 mm varied from 0.65 % to 80 %, and smaller than 0.4 mm from 13.69 % to 54.14 %. Such fluctuations in the concentration and dispersion of sludge significantly affect the operating conditions of the dewatering equipment. It was found that the efficiency of retaining the solid phase of granular classes of coal preparation sludge during module tests was from 66 to 87.4 %, which makes it possible to reduce the load on radial thickeners for solid product and reduce raw material losses with sludge. The use of a cleaning and dewatering module at coal preparation plants makes it possible to additionally extract a part of the coal fraction. It was found that the efficiency of classified sludge dewatering in the centrifugal force field depends on the sludge particle size distribution and the centrifuge feed capacity. Depending on the sludge particle size distribution, it is possible to obtain an oversize product with a moisture content of up to 14.9 % for classes larger than 1.5 mm in a drum sieve, and a sediment with a moisture content of 19.7 % for classes less than 1.5 mm in a centrifuge. It was shown that during dewatering of fine sludge of classes less than 0.4 mm, the sediment moisture content increases with increasing centrifuge capacity as a result of decreasing the residence time and degree of sediment compaction. An increase in the proportion of finely dispersed classes leads to an increase in the moisture content to 33 %. An increase in the content of 0.4–1.5 mm classes to 30 % helps to reduce the sediment moisture content, all other things being equal, due to the squeezing out of the surface moisture of the fine classes by large particles during sediment compression in the centrifugal force field.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship or other, which could affect the study and its results presented in this article.

Financing

The study was performed without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in the creation of the presented work.

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