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BENEFICIATION PROPERTIES OF ASH-AND-SLAG DUMPS

Purpose. Development of a mathematical model for the indices of TPP ash-and-slag waste separation in closed flotation circuit when applying recleaning operations of enriched product.

Methodology. The methods for calculating separation indices using the separation characteristics of separation processes and calculating the indices of the release of valuable mineral using statistical relationships between the particle size of the inclusion, ash content and particle size distribution function were used.

Findings. Separation characteristics of rough and recleaning flotation operations were preliminarily determined experimentally, relations that allow calculating the indices of the release of coal particles in ash-and-slag dumps were defined, based on which the functions of particle distribution by their content of valuable mineral – fractional composition – were found. The separation characteristics of the connections of the separation blocks, including several operations of cleaning of the enriched – froth product, were determined. Calculations to determine the quantitative and qualitative separation indices were performed.

Originality. Analytical relationships to determine the indices of the release of coal inclusions in the process of material from ash-and-slag dumps grinding were obtained.

Practical value. The established dependencies make it possible to justify the required grinding coarseness to achieve the specified parameters of the enrichment process based on the values of the beneficiation properties of ash-and-slag dumps.

Keywords: *thermal power stations, fly ash, ash-and-slag dumps, coal inclusions release, separation characteristics, flotation*

Introduction. In the process of operation of thermal power plants, which burn coal, ash-and-slag waste (ASW) is formed. During the operation of the TPP more than 370 million tons of ash-and-slag waste has been accumulated in Ukraine, which occupies an area of 3170 hectares. In just a year of operation, for example, Chernihivska TPP produces more than 438 thousand tons of waste [1]. Utilization of this waste in Ukraine is still limited due to its toxicity. At the same time, dumps are a source of increased environmental hazard and have a negative impact on human health, ground and surface waters, the atmosphere, flora and fauna (in windy weather, they generate dust, mobile forms are washed out by precipitation and pollute water and soil) [2, 3]. To prevent the negative impact of waste on the environment, it is necessary to look for ways to reduce and recycle it.

Therefore, it is necessary to take a set of measures to transfer ash-and-slag waste from potential to real value – commercial product.

At thermal power plants (TPPs), coal is burned at a temperature of 1,300–1,600 °C. Solid fuel, supplied to the power plant, is characterized by various particle sizes (from fractions of a millimeter to 100–200 mm, and sometimes even larger). The main requirement for solid fuel before combustion is its particle size – it should be a powder (coal dust) with a particle size of less than 90 microns. After grinding in a ball mill, coal turns into polydisperse dust with particle sizes from the smallest (0.1 microns) to 300–500 microns. The fineness of grinding is determined by screening a sample of the milled material weighing 25–50 g for 20 minutes on a testing screen with a standard set of sieves. For screen analysis, sieves with standard mesh sizes of 1,000; 800; 400; 200; 120; 90; 75 and 60 μm are used [4, 5].

The part of the material that remains on the sieve after screening – residue or oversize product – is expressed as a percentage of the original mass of the sample. R indicates the amount of the residue on a sieve, while the size of the sieve is indicated in a subscript (for example, R_{200} means the residue of material on the sieve of 200 μm, and so on). The part of the material that has passed through the sieve is called the undersize product, or minus material. D indicates the amount of undersize product, the mesh size of the sieve is also indicated in a subscript.

In case of screening on a sieve, the following expression is valid

$$R_x + D_x = 100\ \%.$$

According to the screen analysis data, a curve, called the integral particle size characteristic, is plotted. The mesh size of the sieves x is laid off along the X-axis, and the yield of the residue on the sieves is laid off along the Y-axis.

Fossil fuel contains a combustible part of substances, waste rock minerals (non-combustible ash) and moisture. In turn, the combustible part consists of carbon, hydrogen, oxygen, nitrogen and sulfur. Carbon makes up the bulk of the combustible mass of the fuel. Depending on its content, the amount of heat released during fuel combustion changes.

The ash content of coals takes on different values, depending on the inherent ash content, the content of waste rock after beneficiation, and so on. When coal is burned, ash-and-slag waste is formed, consisting of an unburned part of fuel and mineral impurities that have undergone high-temperature firing.

Slag is a non-combustible mineral mass, which, under the action of high temperature, has been fused (sintered), and acquired significant strength.

Ash is a powdered, unburned mineral part of the fuel. In turn, it is subdivided into *fly ash* – dust-like part, which is carried out by flue gases from the furnace and settles in convective gas ducts, and *fall* – coarse fraction of ash, falling into the cold boiler funnel.

Depending on the conditions of solid fuel combustion, the material composition of slag and ash changes. The main factors include combustible loss, duration of particles exposure to high temperatures, gaseous medium in the boiler and interaction of various components of particles with each other. Ash contains various oxides, for example: Fe_2O_3, Al_2O_3, SiO_2, CaO, MgO, to a lesser extent sulfates $FeSO_4$, $CaSO_4$, $MgSO_4$. Also, there is a small content of phosphates, oxides of alkali metals K_2O, Na_2O, and others [6].

In the process of milled coal burning in the furnaces of the TPP, volatile compounds in the form of steam and smoke are formed, and the non-combustible part of the fuel forms focal residues, which make up the bulk of the ash. Ash particle size ranges from 3 to 150 microns. These particles are carried away by the flue gases into the ash collectors (wet scrubbers). The cleaning efficiency amounts 97 %. Particles, captured by spraying with water in scrubbers, settle, form a suspension and are removed in a sludge storage. Heavy ash particles settle on the grate of the furnace and are fused into lumpy slag with aggregate size from 0.15 to 100 mm. Further, it is crushed and removed by a hydraulic system.

Particles of unburned fuel are constantly present in ash-and-slag waste. Their amount ranges from 10 to 25 %.

Literature review. Jameson Cell was first introduced in the late 1980s as a device free from the design and operational disadvantages inherent in column and traditional flotation machines. Since the first commercial flotation of polymetallic ores at the Mount Isa mine in 1989, followed by the first application at the Newlands Coal Preparation Plant in 1990, this flotation machine has continually improved to increase productivity and become easier to operate. More than 320 machines of this type are currently in operation in various industries and for various applications. About 45 % of them are used in the coal industry. While most Jameson Cells are currently used for coking coal, they are increasingly being used to process ultra-fine thermal coal with high ash content [7, 8].

The purpose is to develop a mathematical model for calculating the indicators of flotational separation of ash-and-slag waste from TPPs using closed circuit of the enriched product recleaning.

Results. Grinding the ash that is removed from the furnace results in some release of the carbon-containing particles. A preliminary study [9] showed that it is possible to obtain a sufficient amount of low ash combustible mass on an industrial scale using flotational separation of ash.

Depending on the reactivity of carbon fuel, its mineral composition, parameters of the combustion process, the content of components in the resulting ash varies within wide limits. For instance, the carbon content in TPP ash ranges from 12 to 45 % within a few hours.

The average ash content in TPP ash reaches $A = 0.7$ %. Coarseness of grinding amounts $P(d \le 50\ \mu m) = 0.9$. The size of the unburnt organic matter is equal to 50 μm. Determine the average coarseness of grinding.

The grinding parameters indicate that in case of such a fine grinding, the particle size distribution can be characterized by the Poisson distribution (differential function)

$$f(d) = \frac{1}{\overline{d}} \cdot \exp\left(-\frac{d}{\overline{d}}\right), \qquad (1)$$

where $\overline{d}$ is average coarseness of grinding (distribution parameter).

Since the integral value of the grinding coarseness is given, the integral expression of the law will be as follows

$$0.9 = 1 - \exp\left(-\frac{d}{\overline{d}}\right).$$

Solving it with respect to the average grinding coarseness, we get

$$\overline{d} = \frac{-0.9}{\ln 0.1} = 39.1,$$

i. e. average grinding coarseness is equal to 39.1 μm.

In this case, the differential function is

$$f(d) = \frac{1}{39.1} \cdot \exp\left(-\frac{d}{39.1}\right).$$

To calculate the expected beneficiation indices, it is necessary to determine the release indices during grinding and separation characteristics during processing. Release of the valuable mineral (carbon) is the basis to determine attachment-distribution function $F(\alpha)$.

The paper (Mladetsky I. K., & Mostyka Yu. S., 1999) formulates theoretical assumptions and fulfills mathematical relationships for calculating the release parameters, namely: P_{cg}, P_{asg} – probability of released carbon and aluminosilicate grains recovery; P_{r_att}, P_{p_att} – probability of rich and pure attachments* recovery (*attachments of carbon to silicate). In our case, the valuable component is also impregnated. It can be characterized by an average impregnation size $\overline{d}_{im}$. With regard to rich and poor attachments, the following can be said.

Since the washability function is represented by four components, the curve takes the form of a broken line (Fig. 1).

The number of released carbon grains (P_{cg}) and rich attachments (P_{r_att}) is determined from the expression

$$P_{cg} = \alpha_{av} \cdot \int_0^{d_{im}} \left(1 - \frac{d}{d_{im}}\right) \cdot f(d)\partial d; \qquad (2)$$

$$P_{r\_att} = \alpha_{av} \cdot \left(\int_0^{d_{im}} \left(\frac{d}{d_{im}}\right) \cdot f(d)\partial d + \int_{d_{im}}^{\infty} f(d)\partial d \right). \qquad (3)$$

These integral dependencies are tabular and after taking the integrals, we obtain

$$P_{r\_att} = \alpha_{av} \cdot \left\{ \frac{\overline{d}}{d_{im}} \cdot \left(1 - \exp\left(-\frac{d_{im}}{\overline{d}}\right) \cdot \left(1 + \frac{d_{im}}{\overline{d}}\right)\right) + \exp\left(-\frac{d_{im}}{\overline{d}}\right) \right\}; \qquad (4)$$

$$P_{cg} = \alpha_{av} \cdot \frac{\overline{d}}{d_{im}} \cdot \left(1 - \left(1 + \frac{d_{im}}{\overline{d}}\right) \cdot \exp\left(-\frac{d_{im}}{\overline{d}}\right)\right). \qquad (5)$$

To obtain the distribution function of attachments, its initial coordinate P_{acg} is required, which can be defined in accordance with the following expression

$$P_{acg} = \left(1 - \alpha_{av}\right) \cdot \int_0^{r_{im}} \left(1 - \frac{d}{r_{im}}\right) \cdot f\left(d\right)\partial d, \qquad (6)$$

where r_{im} is an average distance between grains of an impregnation; $r_{im} = d_{im} \cdot \left(\sqrt[3]{\frac{0.65}{\alpha_{av}}} - 1\right)$; α_{av} is average carbon content.

After integration, equation (6) is transformed to the form

$$P_{acg} = \frac{\left(1 - \alpha_{av}\right) \cdot \overline{d}}{r_{im}} \cdot \left(1 - \left(1 + \frac{r_{im}}{\overline{d}}\right) \cdot \exp\left(-\frac{r_{im}}{\overline{d}}\right)\right).$$

The number of poor (non-carbon) attachments is determined from the expression

$$P_{p\_att} = 1 - P_{cg} - P_{r\_att} - P_{asg}.$$

As follows from Fig. 1, the break in a curve occurs at the point of an average content of valuable mineral α_{av}, and rich

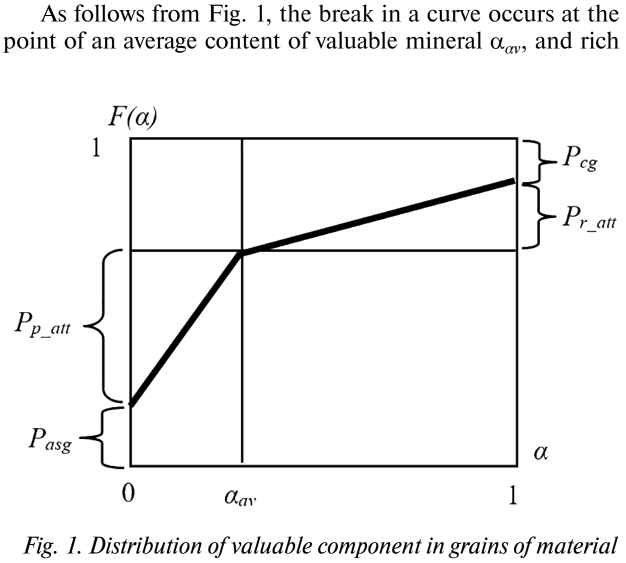

Fig. 1. Distribution of valuable component in grains of material after grinding [11]

attachments complement the content of released carbon grains to the value of this average grade. In turn, the content of non-carbon (pure) attachments complements the number of released aluminosilicate grains up to the indicator $(1 - \alpha_{av})$. Thus, in order to identify the release function, it is sufficient to know three of its indicators, namely: α_{av}, P_{cg}, P_{asg}.

From the point of view of statistics, it is necessary to represent the washability curve in a natural form, i.e. non-decreasing. In this case, the content of the rich attachments fraction will start from a zero coordinate value.

The coal fraction never has zero ash content (during the combustion of solid fuel, at best, ash always remains). Therefore, the beginning of the washability polyline will be at the point with the minimum ash content of the coal fraction – A_{min}. To calculate the parameters of coal release from ash, it is necessary to use the concept of average ash content instead of the average content of a valuable mineral. Let us make such a replacement.

The higher the ash content is, the higher the content of released aluminosilicate grains and non-carbon attachments will be, that is, there is an increase in P_{asg}. Obviously, with an increase in ash content, the distance between carbon grains of an impregnation – r_{im} increases, that is, there is also an increase in P_{asg}. As a result, it is sufficient to take the initial ash content A_i instead of the difference $(1 - \alpha_{av})$, and the expression for the amount of aluminosilicate grains will be converted to the form

$$P_{asg} = \frac{\grave{A}_i \cdot \bar{d}}{r_{im}} \cdot \left(1 - \left(1 + \frac{r_{im}}{\bar{d}}\right) \cdot \exp\left(-\frac{r_{im}}{\bar{d}}\right)\right), \tag{7}$$

where

$$r_{im} = d_{im} \cdot \left(\sqrt[3]{\frac{0.65}{1 - \grave{A}_i}} - 1\right). \tag{8}$$

Accordingly, to determine the indicators of the carbon fraction content, we take the value: $\alpha_{av} = (1 - A_i)$.

In this case

$$P_{cg} = \left(1 - A_i\right) \cdot \frac{\bar{d}}{d_{im}} \cdot \left(1 - \left(1 + \frac{d_{im}}{\bar{d}}\right) \cdot \exp\left(-\frac{d_{im}}{\bar{d}}\right)\right).$$

Then the distribution function of ash attachments will be transformed to the form shown in Fig. 2.

Let us determine the attachment-distribution function provided that $d_{im} = 0.05$ mm, $A_i = 0.7$.

We take the calculated ratio of the amount of released coal particles in discrete form

$$P_{cg} = \left(1 - A_i\right) \cdot \sum_{0}^{d_{im}} \left(1 - \frac{d}{d_{im}}\right) \cdot \Delta F\left(d\right).$$

The distance between two impregnations will be determined from the expression (8)

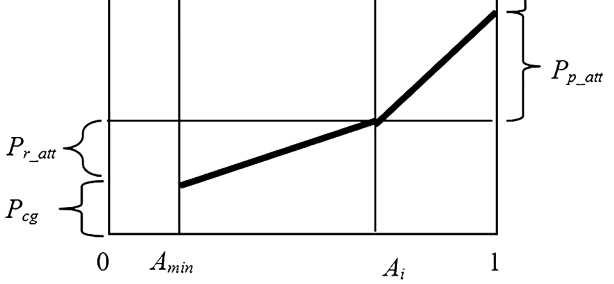

Fig. 2. Distribution of fractions of grinded ash

$$r_{im} = d_{im} \cdot \left(\sqrt[3]{\frac{0.65}{1 - A_i}} - 1\right) = 0.05 \cdot \left(\sqrt[3]{\frac{0.65}{1 - 0.7}} - 1\right) = 0.02.$$

As can be seen, the distance between the two impregnations amounts to 0.02 mm.

Similarly, in discrete form, we write down the ratio for calculating the number of released aluminosilicate particles

$$P_{asg} = A_i \cdot \sum_{0}^{r_{im}} \left(1 - \frac{d}{r_{im}}\right) \cdot \Delta F\left(d\right).$$

The results of calculation of a number of released coal grains are shown in Table 1, and the results for the total number of released aluminosilicate grains are in Table 2. For convenience, intermediate calculations are also given here.

As can be seen from the calculation results, the total number of released coal grains amounts to $P_{cg} = 0.1172$.

As can be seen from the calculation results, the total number of released aluminosilicate grains amounts $P_{acg} = 0.2246$.

The calculated attachment-distribution function is presented in Table 3.

Thus, dependencies have been found that make it possible to calculate the indicators of the release of the coal fraction in ash.

Now let us start calculating the separation parameters in the scheme of flotation with recycle (Fig. 3), provided that the separation characteristics of the operations are known.

Ash suspension enters the aerator under pressure through a special nozzle. A vacuum is formed in the upper part of the aerator, so the air is sucked in through the adjusting device. In

Table 1

Ash disclosure calculation – released coal grains

Narrow grain size classes, mm	Average particle size, *d*, mm	Differential particle distribution function, $\Delta F(d)$	$1-\frac{d}{r_{im}}$	Number of particles by size
1	2	3	4	5
0–0.005	0.0025	0.1782	0.95	0.0508
0.005–0.015	0.01	0.1471	0.80	0.0353
0.015–0.025	0.02	0.1139	0.60	0.0205
0.025–0.035	0.03	0.0882	0.40	0.0106
0.035–0.055	0.045	0.0	0.10	0.0
Total				0.1172

Table 2

Ash disclosure calculation – released ash grains

Narrow grain size classes, mm	Average particle size, *d*, mm	Differential particle distribution function, $\Delta F(d)$	$1-\frac{d}{r_{im}}$	Number of particles by size
1	2	3	4	5
0–0.005	0.0025	0.178	0.125	0.1092
0.005–0.01	0.0075	0.157	0.375	0.0686
0.01–0.015	0.0125	0.138	0.625	0.0362
0.015–0.020	0.0175	0.121	0.875	0.0106
Total				0.2246

Table 3

Calculated particle-distribution function by ash content

Ash content, A	0.1	0.3	0.5	0.7	0.9	1.0
$F(A)$	0.12	0.2	0.29	0.48	0.78	1
$\Delta F(A)$	0.12	0.08	0.09	0.19	0.3	0.22

the aerator, the air is divided into small bubbles that adhere to hydrophobic particles. In the flotation cell, air bubbles with hydrophobic particles float and form a froth product. Hydrophilic particles form cell product, or flotation tails, part of which forms a recycle flow through the bypass. Another part of the flotation tails is removed from the cell.

The separation characteristic shows the probability P, with which a particle is extracted into an enriched product at a given content of the useful component.

This flotation scheme can be represented by a technological scheme with a basic and control operation (Fig. 4).

If the separation characteristics of the operations are known, then the separation characteristic of the scheme is determined from the expression [10, 11]

$$P_{sc1} = \frac{P_1}{1 - P_2 \cdot \left(1 - P_1\right)},$$

where P_1, P_2 are separation characteristics of circuit operations.

It is known that a series connection of technological devices enhances the output quality indicators; therefore, let us

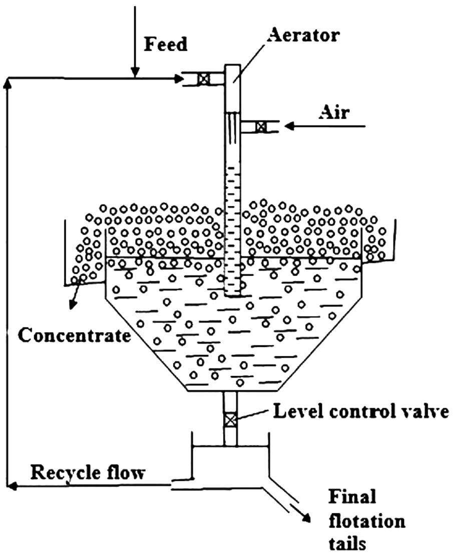

Fig. 3. Schematic diagram of the Jameson Cell recycling flotation machine operation

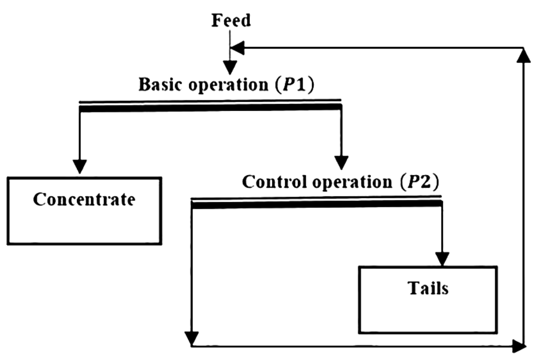

Fig. 4. Technological scheme with two separation operations (scheme 1)

try to estimate the separation indices for combining three and four separation operations, that is, using a control and recleaning operation (Fig. 5) and one control and two recleaning operations (Fig. 6). The separation characteristics of the control and recleaning operations are assumed to be equal.

The separation characteristic of the circuit with three separation operations (Fig. 5) is determined from the expression

$$P_{sc2} = \frac{P_1 \cdot P_3}{1 - P_2 \cdot (1 - P_1) - P_1 \cdot (1 - P_3)},$$

where P_1, P_2, P_3 are separation characteristics of circuit operations: basic, control and recleaning ones, respectively.

The separation characteristic of the circuit with four separation operations (Fig. 6) is determined from the expression

$$P_{sc3} = \frac{P_1 \cdot P_3 \cdot P_4}{1 - P_2 \cdot (1 - P_1) - P_1 \cdot (1 - P_3) - P_1 \cdot P_3 \cdot (1 - P_4)},$$

where P_1, P_2, P_3, P_4 are separation characteristics of circuit operations: basic, control and recleaning ones, respectively.

The results of calculating the separation characteristics are shown in Table 4.

Determine the separation indices from the following ratios [11], and summarize them in Table 5

$$\gamma = \sum_{A=0}^{A=1} P(A) \cdot \Delta F(A);$$

$$A_f = \frac{1}{\gamma} \cdot \sum_{A=0}^{A=1} A \cdot P(A) \cdot \Delta F(A);$$

$$A_t = \frac{1}{1-\gamma} \cdot \sum_{A=0}^{A=1} A \cdot \left(1 - P(A)\right) \cdot \Delta F(A),$$

where γ is yield of the carbon containing fraction, which is concentrated in the froth product of flotation, %; A_f is ash content of the froth product, %; A_t is ash content of the flotation tale (product, which remains in the cell of flotation machine), %.

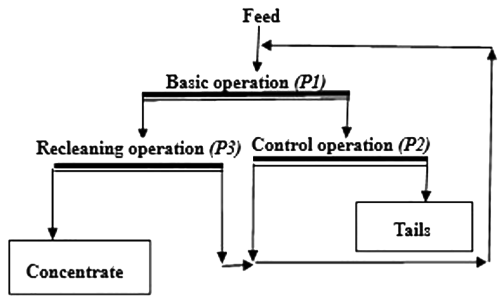

Fig. 5. Technological scheme with three separation operations (scheme 2)

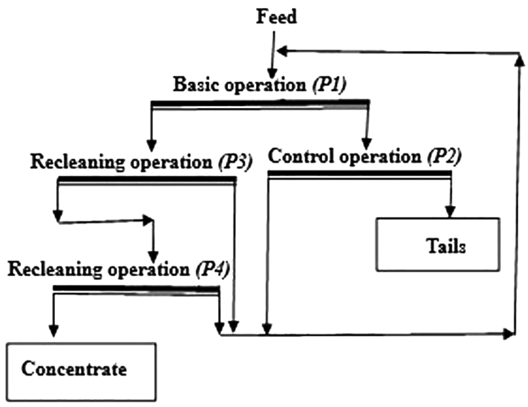

Fig. 6. Technological scheme with four separation operations (scheme 3)

Table 4

Indicators for calculating the separation characteristics of technological schemes

Ash content, A	Separation characteristics				
	Basic separation (P_1)	Control separation (P_2)	Scheme with two operations (P_{sc1})	Scheme with three operations (P_{sc2})	Scheme with four operations (P_{sc3})
1	2	3	4	5	6
0.1	0.82	0.9	0.9785	0.9762	0.9736
0.3	0.77	0.85	0.9571	0.9499	0.9416
0.5	0.55	0.4	0.6707	0.4490	0.2458
0.7	0.4	0.12	0.4310	0.0833	0.0108
0.9	0.25	0.05	0.2597	0.0172	0.0009
1.0	0.17	0.02	0.1729	0.0042	0.0001

Table 5

Results of calculating separation indices

Separation scheme	Separation indices			
	Concentrate		Tailings	
	Yield	Ash content	Yield	Ash content
1	2	3	4	5
Scheme 1	0.4522	0.50947	0.5478	0.8646
Scheme 2	0.2555	0.27937	0.7445	0.8497
Scheme 3	0.2166	0.21713	0.7834	0.8386

As can be seen, applying the flotation scheme with recycle (scheme 1), it is possible to obtain 45.2 % of concentrate with an ash content of 50.9 %. Application of one recleaning operation allows reducing the ash content in the concentrate to 27.9 % (the yield will amount to 25.5 %), and two recleanings – up to a standard value of less than 24 %, namely, up to 21.7 % with a concentrate yield of 21.7 %.

Conclusions. Thus, connecting the devices in series changes the separation indicators significantly and makes it possible to bring the quality indicators to the standard values.

The article shows that to predict the indicators of TPPs ash enrichment, it is possible to use three values of release, provided that the separation characteristics are preliminarily determined experimentally. Analytical dependencies have been obtained that make it possible to calculate the release indices and predict the quality indices of separation, provided that the grinding indices are known.

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Збагачувальні властивості золошлакових відвалів

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Мета. Розробка математичної моделі розрахунку показників розділення золошлакових відходів ТЕС флотаційним способом з використанням замкнутих циклів при застосуванні перечисних операцій збагаченого продукту.

Методика. Використана методика розрахунку показників розділення за допомогою сепараційних характеристик розділових процесів і обчислення показників розкриття цінного мінералу за допомогою статистичних співвідношень між розміром вкраплення, зольністю та функцією розподілу частинок за крупністю.

Результати. Попередньо експериментально визначені сепараційні характеристики флотаційного розділення й замкнутих циклів, визначені співвідношення, що дозволяють розрахувати показники розкриття вугільних частинок у золошлакових відвалах, на підставі яких знайдені функції розподілу частинок за вмістом у них цінного мінералу – фракційний склад. Визначені сепараційні характеристики з'єднань розділових блоків, що складаються з декількох операцій перечисток збагаченого – пінного продукту. Виконано розрахунок із визначення кількісних і якісних показників розділення.

Наукова новизна. Отримані аналітичні залежності для визначення показників розкриття вугільних включень при подрібненні матеріалу золошлакових відвалів.

Практична значимість. Встановлені залежності дозволяють виконати обґрунтування необхідної крупності подрібнення для досягнення заданих показників збагачувального процесу на підставі значень збагачувальних ознак золошлакових відвалів.

Ключові слова: *теплові електростанції, зола виносу, золошлакові відвали, розкриття вугільних включень, сепараційні характеристики, флотація*

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