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EXPERIMENTAL STUDY ON THE SLIME FLOTATION PROCESS OF LOW-RANK STEAM COAL BY THE SMALL CONE ANGLE HYDROCYCLONE GROUP

Considering that the clay content in the western Liaoning region is high, the dominant fraction is <0.045 mm high ash in fine-grained low thermal coal and coal slurry. Self-developed CMC (Cone type Multi-stage Cyclone) multiple multistage small cone angle hydrocyclone groups are used for desliming flotation experiment research, product particle size analysis, hydrocyclone underflow product order evaluation tests and flotability evaluation. The results showed that 150 mm hydrocyclones with small cone angles are more suitable as the main desliming equipment before flotation than those with 75 mm and 50 mm hydrocyclones with small cone angles, but the bottom abortion rate is lower, and the phenomenon of “overflow running” is more serious. In the deslime-flotation process of the CMC multistage and small-cone angle hydrocyclone groups, the removal rate of fine particles with ash contents of 69.82% <0.045 mm in the original coal slime reaches 64.43%, basically solved the problem of “overflow and coarse running” of cyclones, and high ash fine clay minerals such as kaolin were enriched in the overflow. The group of three kinds of CMC hydrocyclone underflow products due to their different size widths shows that the flotability of the three underflows can be mixed into the float. Compared with raw coal direct flotation plants, the yield and combustible recovery rate can increase 2-3 times, and the floatability level is increased from extremely difficult to float to difficult to float, which can also be used for the underflow product floatability. The flotation process is different, strengthening the graded plant recycling process and providing a technological reference for better realization of narrow slime flotation.

Keywords: Small cone angle hydrocyclone; Low-order power slime; Classification; Desliming; Narrow flotation; Flotability

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1. Introduction

It is a well-known fact that coal is the most abundant fossil fuel in the world and the known coal reserves are much more than both known gas reserves and oil reserves [1-2]. Generally, coarse coal (>0.5 mm) upgradation using physical beneficiation processes is the most common practice. The main available physical beneficiation equipments are hydraulic separation jigs, dense medium separators, hydrocyclones, shaking tables, spiral concentrators, etc. [3-4]. The physical beneficiation processes are usually utilized to upgrade good quality coals. On the other hand, coal fines (<0.5 mm) are inevitably produced during coal processing, mining, etc. and more coal fines will be produced with the maturity of mechanized mining and processing technology. These coal fines need to be utilized to reduce landfills. Froth flotation is the most effective way for recovery of coal fines based on differences of surface properties (hydrophobic/hydrophilic) between coal and gangue [5-6]. However, fine coal usually contains excessive levels of ultrafine gangue particles and other materials such as clays, known as slimes, as the quality of fine coal deteriorates. The slimes in turn leads to a major problem for handling fine coal, i.e., the slimes enter into the froth product and contaminate the clean coal during the flotation process, resulting in the high ash content of clean coal [7-9]. The contamination of slimes on clean coal is also the most serious problem in fine coal flotation to date. Fine mud with a high ash content contaminates cleaned coal by entrainment and covering with fine mud [10]. Because of its small inertia force, fine particles easily enter the foam layer through the Plante channel or turbulence around bubbles [11].

Examining the characteristics of high-ash fine-grained clay minerals in the flotation process, scholars at home and abroad have performed much research. Shu et al. [12] changed the surface properties of clay minerals to make them fully dispersed in the slurry to reduce the entrainment in the mineralized particle bubbles. Jameson [13] suggested that fine particles require a fluid environment with a high energy state to increase the probability of collision and attachment between particles and bubbles through strong shear and turbulence, while coarse-grained materials require low energy input but require high gas content at different particle sizes to ensure flotation efficiency. William J. Oats [14] focuses on the effect of mechanical and chemical removals of fine minerals by hydrocyclone and dispersants on coal flotation. The experimental results showed that the best way to increase the flotation recovery in the presence of clays was to remove these fine minerals by mechanical means such as hydrocyclones.

In this paper, according to the characteristics of high ash fine slime content of the test slime, a self-developed CMC multistage and small cone angle hydrocyclone group was used to carry out experimental research on the desliming flotation process to provide a reference for the washing process of low-quality steam coal slime with large fine content and high slime content.

2. Test

2.1. Analysis of slime properties

2.1.1. Analysis of slime mineral composition

Experimental coal samples were obtained from the filter press feed of the coal preparation plant in western Liaoning Province. The coal type is low-rank steam coal, and the ash content is 57.32%. To determine the mineral composition of coal slime, A D8 X-ray diffractometer of

Brock AXS Company was used in Cu target, tube voltage of 40 kV, tube current of 40 mA, the qualitative analysis of XRD phase was carried out under the diffraction angle of 5° – 80° , and the test results were analyzed by X 'Pert Highscore software. The results are shown in Fig. 1.

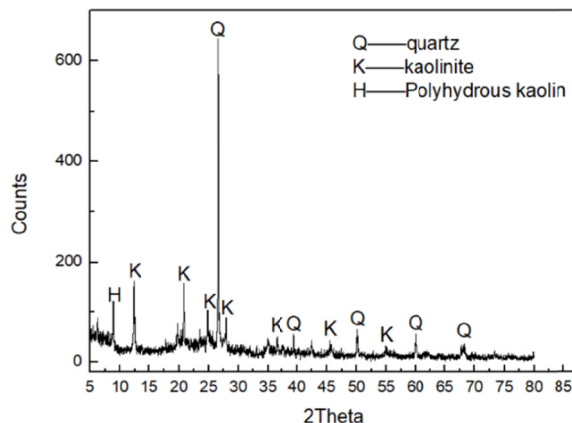


Fig. 1. XRD pattern of coal slime

The analysis of the XRD pattern indicates that the coal slime contains three minerals, quartz, kaolinite (kaolin) and halloysite. There is “steamed bread” in the range of 20 – 30° , indicating that there are also amorphous substances, mainly amorphous carbonaceous substances, and that quartz is a granular material with greater hardness. Due to the presence of kaolin, the surface and water quality viscosity of carbon particles will be increased, which is adsorbed on the surface of coal particles or engrained on bubbles during flotation, resulting in a fine mud cover, which reduces the selectivity of flotation and affects the cleaned coal yield and recovery rate. Therefore, slime containing a large amount of clay should be properly treated before flotation or during flotation to increase the selectivity of coal particles during flotation.

2.1.2. Analysis of slime morphology characteristics

The morphological characteristics of coal slime and coal slime ash were analyzed. The raw ore the samples were gold-plated prior to analysis and then analyzed by a JSM-7500F scanning electron microscope with an accelerated voltage of 5 kV, as shown in Fig. 2.

Fig. 2 shows that the microstructure of coal particles in the slime is lamellar, with an uneven surface, purified edges, and dense structure, which belongs to a typical bedding development structure, with some fine particles less than $1\ \mu\text{m}$ attached to the surface. In the coal slime ash, the flat lamellae changed into cracked and irregular bending lamellae, the gap between the layers increased, and the structure was loose. Combined with the XRD pattern, the lamellae were kaolin.

2.1.3. Analysis of particle size composition of coal slime

The study of the slime particle size distribution is a prerequisite for the separation of coal and noncoal [15]. Two hundred grams of dried slime sample was used. In accordance with the

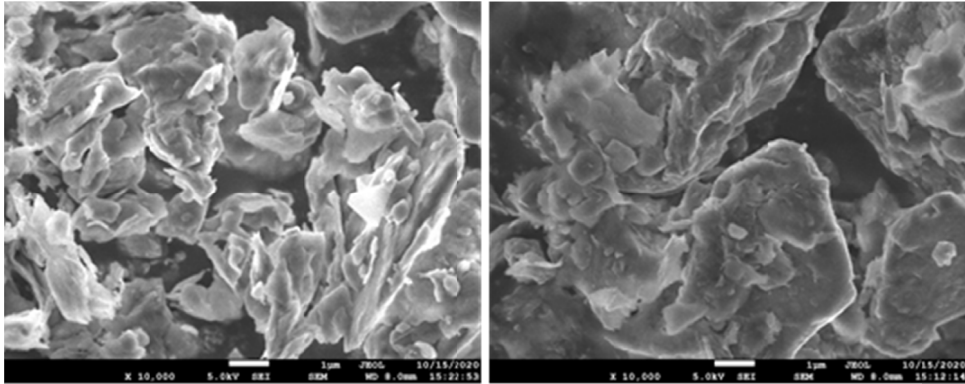


Fig. 2. Microscopic characteristics of the slime and slime ash

relevant provisions of GB/T 477-2008 “Coal Screening Test Method,” a wet small screening test was carried out [16]. A standard series of screen sets of 0.500 mm, 0.250 mm, 0.125 mm, 0.074 mm and 0.045 mm were used for the screening test. The particle size composition is shown in TABLE 1.

TABLE 1

Table of small screening test results of coal slime

Grade/mm	Yield/%	Ash/%	Upper product /%		Lower product /%	
			Yield/%	Ash/%	Yield/%	Ash/%
+0.500	7.05	23.35	7.05	23.35	100.00	57.25
0.500-0.250	10.64	29.53	17.69	27.07	92.95	59.82
0.250-0.125	10.85	42.35	28.54	32.88	82.31	63.74
0.125-0.074	9.42	56.45	37.96	38.73	71.46	66.99
0.074-0.045	10.98	62.84	48.94	44.14	62.04	68.58
-0.045	51.06	69.82	100.00	57.25	51.06	69.82
Total	100.00	57.25	—	—	—	—

TABLE 1 shows that the ash content of each particle size in the raw coal slime gradually increases with decreasing particle size. The coarse grain size of +0.250 mm has a lower content, with a yield of 17.69% and an ash content of 27.07%. The dominant very fine grain size of -0.045 mm has a yield of 51.06% and an ash content of 69.82%, which is 25.68% higher than the weighted ash content of each grain size of +0.045 mm, indicating that a large number of heterogeneous fine mud components are mixed in this grain size. These high-ash heterogeneous fine slimes will adhere to the surface of coal particles or bubbles in flotation, reduce the contact probability between coal particles and bubbles, or cause mechanical entrainment, which will have a great impact on the quality of flotation cleaned coal, which also provides a basis for the use of small cone angle hydrocyclones before flotation.

2.2. Test equipment and methods

1) Three kinds of small cone-angle hydrocyclones ($\Phi 150$, $\Phi 75$, $\Phi 50$ mm) were used separately for the desliming test. The equipment parameters are shown in TABLE 2. The test conditions were: test coal slime 30 kg, feed concentration 10%, and the frequency converter was adjusted to 40-50 Hz. After vigorous stirring for 10 min, the mixed slurry was carried out through $\Phi 150$ mm, $\Phi 75$ mm and $\Phi 50$ mm small cone angle hydrocyclones under 0.2 MPa. Classification and sorting effect and analysis of flotation effect was completed.

TABLE 2

Parameters of different diameter small taper angle hydrocyclones

Cyclone diameter /mm	Feed pressure /MPa	Diameter of underflow /mm	Sorting particle size / μm	Unit processing capacity /($\text{m}^3 \cdot \text{h}$)	Feed particle size /mm	Pulp concentration /%
150	0.15~0.50	14	60	12.5~15.0	≤ 1.2	≤ 25
75	0.15~0.50	8	40	5.0~8.0	≤ 0.8	≤ 25
50	0.15~0.40	6	10	2.5~4.0	≤ 0.5	≤ 30

2) Under the same conditions, a self-developed CMC multistage small cone angle hydrocyclone group was used to carry out classification, separation and flotation effect analyses. The equipment is shown in Fig. 3, and the cone generator is shown in Fig. 4. The CMC multistage small cone angle hydrocyclone group includes a first heavy hydrocyclone, a cone generator connected to it, and the cone generator passes through each horn-shaped tapered pipe mouth in a tangenti mud al direction with the corresponding diversion. The tubes are connected, and the end of the draft tube is connected to the

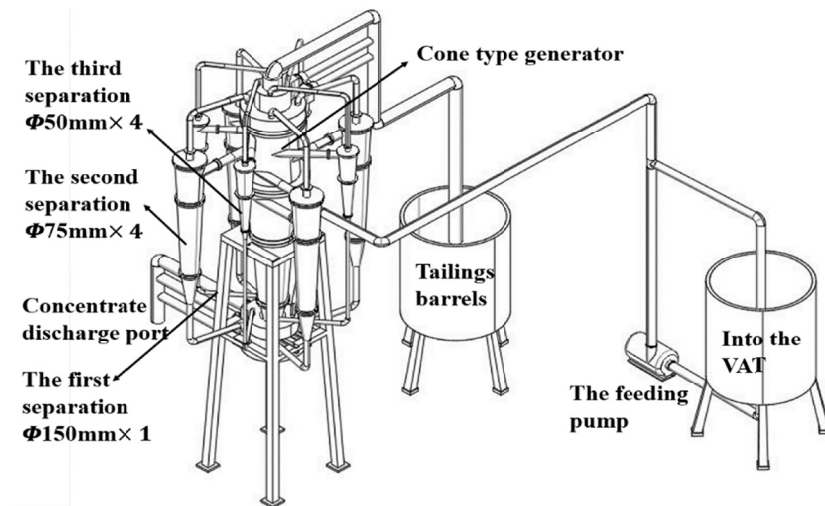


Fig. 3. CMC multistage small cone angle hydrocyclone group

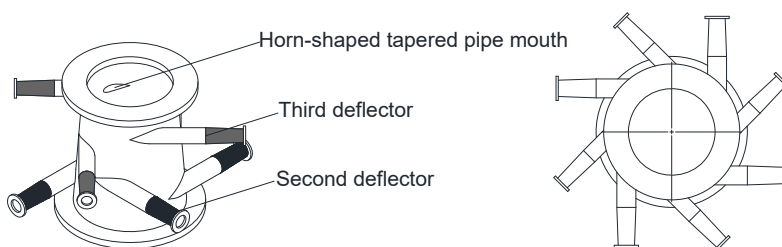


Fig. 4. CMC hydrocyclone group cone generator

second and third cyclones. The CMC cyclone group can guide the short-circuit flow and circulating flow in the multistage hydrocyclone into the draft tube to reduce the short-circuit flow and circulation. To reduce the probability of the flow entering the overflow pipe, the cone generator cooperates with the multiple cyclones, performs the classification and classification according to the gradation of the incoming materials, reduces the lower limit of the classification particle size step by step, improves the classification efficiency, enhances the classification and separation effect, and simplifies the selection. This operation process reduces sorting cost.

The slime slurry enters the first hydrocyclone along the tangential direction from the feed port, and through strong centrifugal force, the inner swirl, outer swirl, zero-velocity envelope surface, short circuit flow and combustible matter combustible matter circulation flow are formed in the first hydrocyclone. The cyclone spirals in upward movement, through the first heavy overflow pipe, the outer cyclone spirals in a downward movement, through the first heavy sand discharge mouth, and the zero degree envelope is the boundary between inner and outer swirls. The short circuit flow and circulation flow forms in the conical generator, part of the short circuit flow and circulation flows through the horn

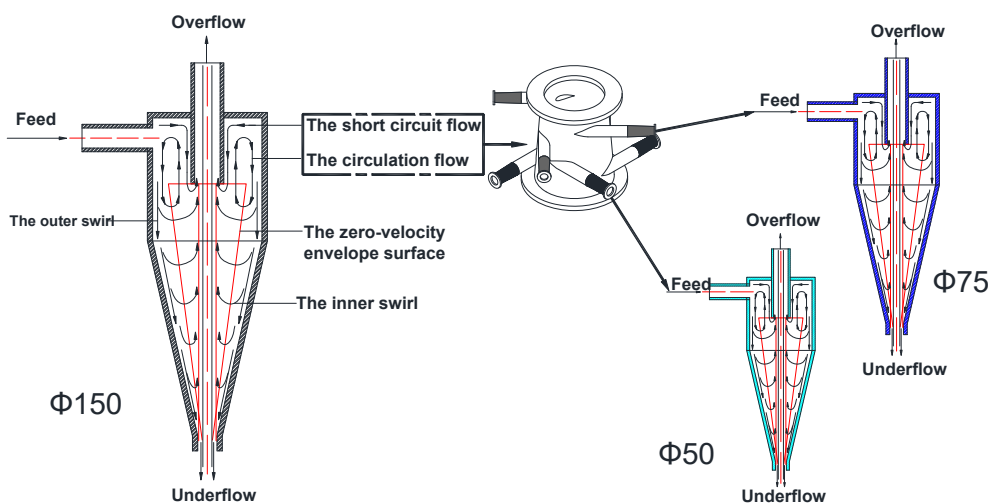


Fig. 5. Process flow chart of the CMC multistage small cone angle hydrocyclone group

mouth reducer and the second guide tube into the second hydrocyclone. After the second hydrocyclone classification, the second overflow pipe and the second desilting mouth discharge. After part of the classification of short circuit flow and circulation circulation through the horn type reducer and the third heavy guide tube the slime slurry passes into the third hydrocyclone. After the third hydrocyclone classification, the slime slurry passes through a third heavy overflow pipe and the third desilting mouth discharge. The specific technological process is shown in Fig. 5.

- 3) Unit flotation tests and sequence evaluation tests were carried out under the same conditions for raw coal slime and each underflow product of cyclone. According to GB-4757-84 “Coal Preparation Laboratory Unit Flotation Test Method” and GB/T 30046. 2–2013 “Coal (Pulverized) Flotation Test Part 1: Sequence Evaluation Test Method,” kerosene is selected as the catcher receiving agent, with a dosage 1,000 g/t, and pulp concentration 100 g/L. Sec-octanol was selected as the frother, with a dosage 100 g/t, impeller speed 1,500 r/min, scraper speed 24 r/min, aeration volume 0.25 m³/(m² · min), and scraping time 3.00 min.

3. Results and discussion

3.1. Analysis of the desliming flotation process of hydrocyclones with different diameters and small cone angles

Three kinds of small cone angle hydrocyclones of $\Phi 150$ mm, $\Phi 75$ mm and $\Phi 50$ mm were used to carry out the desliming and sorting effect of raw coal slime and the underflow flotation experiment research. The results are shown in TABLE 3.

TABLE 3

Predesliming separation results of different diameter hydrocyclones

Cyclone diameter/mm	Underflow of cyclones		The cyclone overflows		Ash difference /%
	Yield/%	Ash/%	Yield/%	Ash/%	
150	35.55	46.52	64.45	62.86	16.34
75	42.58	47.78	57.42	65.34	17.56
50	46.21	48.12	53.79	66.09	17.97

As shown TABLE 3, the underflow ash contents of the three types of hydrocyclone are 46.52%, 47.78% and 48.12%, which are lower than the test coal sludge ash content of 57.12%. The underflow overflow ash difference values are all larger than 15.00%, indicating that the small cone angle hydrocyclone has achieved a certain desliming and ash reduction effect, and the fine clay minerals are overflow discharged from each cyclone. From the cyclone bottom of the miscarriage rate and ash content change rule, with the decrease in the diameter of the cyclone, the ash content and yield increased. The high ash content of the fine mud removal rate decreased with the decrease in the diameter of the hydrocyclone because for the same particles, the greater the angle is, the particle concentration degree is higher, and it is easier to close to the axis, leading to a medium granularity separation efficiency being reduced. However, with the increase

in particle size, the particles are basically enriched on the wall and discharged from the underflow settling mouth. That is, when the cone angle is small, the phenomenon of „underflow pinching“ is easily caused by the large underflow shunt. When the cone angle is large, the phenomenon of „overflow running coarse“ is easily caused [17-20].

TABLE 4 shows that the coal after the small cone angle hydrocyclone desliming flotation effect improved significantly. Three kinds of swirl bottoms of abortion rate, ash content, and combustible recovery compared with raw coal flotation indicators are significantly enhanced directly. Fine ash removes impurities before flotation of fine clay and reduces extremely fine clay particles in coal slime and the lid of cleaned coal particles. This is the key to improving the flotation effect to enhance the hydrophobicity of the coal particle surface. The underflow flotation recovery of cleaned coal with a $\Phi 150$ mm cyclone is 72.28%, the cleaned coal ash is 17.83%, the tail coal ash is 72.59%, and the cleaned coal yield is 47.14%. All indicators are better than those of $\Phi 75$ mm and $\Phi 50$ mm, but the cleaned coal yield only accounts for 16.76% of the total grade of raw slime. This result is lower compared with the other two types of cyclone. This is because in the desliming process of the $\Phi 150$ mm cyclone, a large amount of high-ash fine-grained clay minerals were removed to achieve a better flotation effect, but compared with $\Phi 75$ mm and $\Phi 50$ mm cyclones, the phenomenon of overflow „running thick“ is more serious. More coarse cleaned coal particles enter into overflow, resulting in the reduction of overflow ash and bottom abortion rate, resulting in the reduction of flotation feed, thus affecting the yield of flotation cleaned coal in the whole class.

TABLE 4

Flotation test results of different hydrocyclone diameters under flow

Product Name	Raw coal slime		150-Underflow of cyclone		75-Underflow of cyclone		50-Underflow of cyclone	
	Yield/%	Ash/%	Yield/%	Ash/%	Yield/%	Ash/%	Yield/%	Ash/%
Flotation clean coal	36.32	33.95	47.14	17.83	44.12	19.10	42.23	20.52
Flotation tail coal	63.68	70.38	52.86	72.59	55.88	71.20	57.77	69.02
Total	100.00	57.15	100.00	46.78	100.00	48.21	100.00	48.54
Combustible recovery rate/%	55.98		72.28		68.92		65.22	
Clean coal yield (accounting for the whole stage)/%	36.32		16.76		18.79		19.51	

3.2. Analysis of the desmudding and separation effects of the CMC multistage and small cone angle hydrocyclone

According to the experimental study in Section 2.1, compared with the $\Phi 75$ mm and $\Phi 50$ mm hydrocyclones, the $\Phi 150$ mm small cone angle hydrocyclone is more suitable as the main equipment for desliming before flotation. However, due to the low bottom abortion rate, there is a serious phenomenon of “running rough” in overflow, which affects the yield of flotation cleaned coal in the whole class. To solve this problem, the self-developed CMC multistage and small cone angle hydrocyclone group is used for stripping under the same test conditions as in Section 2.1. The results of the sludge process test are shown in TABLE 5.

TABLE 5

Desliming and separation effect of the CMC multistage small cone angle hydrocyclone group

Cyclone diameter /mm	Underflow of cyclones		The cyclone overflows		Ash difference /%
	Yield/%	Ash/%	Yield/%	Ash/%	
150	61.69	46.97	38.31	64.85	17.88
75	38.99	49.41	61.01	66.34	16.93
50	39.41	52.69	60.59	68.33	15.64
Comprehensive	49.51	48.63	50.49	66.39	17.75

TABLE 5 shows that, compared with the single desliming effect of each cyclone diameter, the comprehensive bottom abortion rate of the CMC cyclone was 49.51%, which was 13.96% higher than that of the $\Phi 150$ mm cyclone. The overflow ash content is 66.39%, which is 3.52% higher than that of the $\Phi 150$ mm cyclone. The comprehensive underflow overflow ash difference is increased by 1.37%. This shows that the CMC multistage small cone angle hydrocyclone group can achieve a higher underflow yield while ensuring the desliming and ash reduction effect.

The particle size analysis of each product in the desliming-flotation process of the CMC multistage and small cone-angle hydrocyclone groups is shown in Fig. 6. The particle size content of <0.045 mm in $\Phi 150$ -underflow is 22.71%, which is 28.35% lower than that in raw coal slime. The particle size of $\Phi 150$ -overflow >0.045 mm is 25.64%, and the overflow has a serious phenomenon of „running coarse.“ The particle sizes of >0.045 mm in $\Phi 75$ -underflow and $\Phi 50$ -underflow were 65.09% and 46.35%, respectively. The particle sizes of <0.045 mm in $\Phi 75$ -overflow and $\Phi 50$ -overflow were 94.91% and 98.86%, respectively. This shows that $\Phi 75$ mm and $\Phi 50$ mm cyclones have achieved a good „cut off“ effect. If $\Phi 75$ - overflow and $\Phi 50$ - overflow are used as fine mud tailings, the removal amount is 32.90% of the total slime. Compared with the original slime, the particle size yield of <0.045 mm is 51.06%, and the desliming efficiency reaches 64.43%.

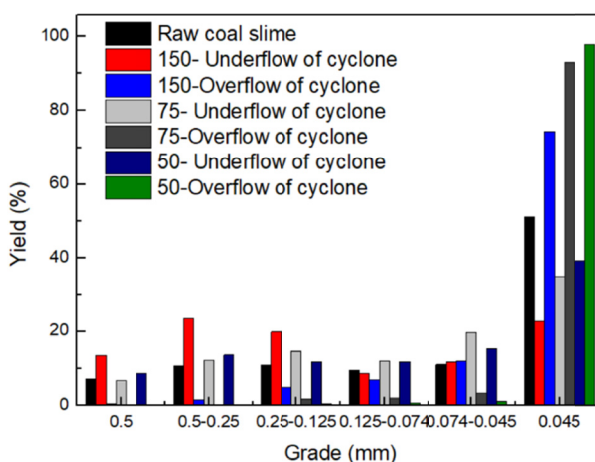


Fig. 6. Particle size analysis of the CMC multistage small cone angle hydrocyclones

Fig. 7 shows more intuitively that Φ 150-underflow, Φ 75-underflow, and Φ 50-underflow particle size composition are different. The coarse grain content of Φ 150-underflow >0.25 mm is 37.10%, and the medium grain content of Φ 75-underflow 0.074-0.125 mm is 31.15%. In the Φ 50-underflow, the content of fine particles of 0.045 mm-0.074 mm and very fine particles of <0.045 mm is 53.65%, indicating that the CMC multistage and small cone-angle hydrocyclone can not only improve the recovery of coarse granular coal in the process of desliming but also provide ideas for accomplishing narrow particle flotation [21,22] of slime.

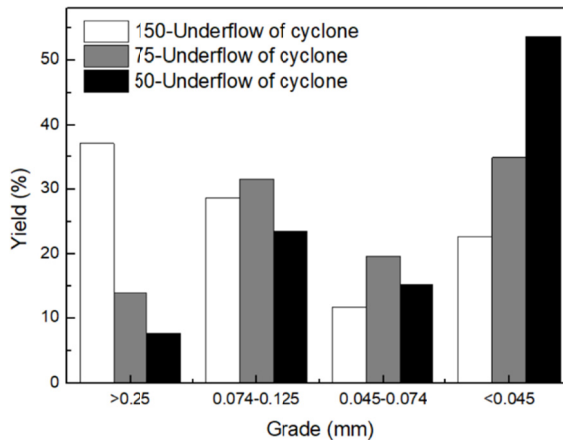


Fig. 7. Composition of the underflow particle size of the CMC multistage and small-cone angle hydrocyclone

3.3. Underflow sequence evaluation test and floatability evaluation of the CMC multistage and small cone angle hydrocyclone groups

The floatability of slime is an important index to characterize the properties of slime. According to the relevant requirements of GB/T 30047-2013 “Assessment Method [23] for Floatability of Pulverized Coal (slime),” the floatability of slime is evaluated by calculating the recovery rate of a cleaned coal combustible matter. The formula for the recovery rate of a cleaned coal combustible matter is as follows:

$$\varepsilon = \gamma_c \frac{100 - \vartheta}{100 - \alpha} \tag{1}$$

where: γ_c – yield of concentrate, α – content of ash in feed, ϑ – content of ash in concentrate.

The theoretical cleaned coal yield should be determined according to the yield-cleaned coal ash relation curve drawn from the slime sequence evaluation test results. The sequential evaluation test is a new flotation method for coal preparation laboratories. It can reflect the flotation characteristics of slime more comprehensively through the test process of one rough selection, several sweeps and selective selection [24,25]. The sequential evaluation test sequence is shown in Fig. 8. In Fig. 8, “C” represents clean coal, “T” represents tailing coal, and the numbers represent

the operation sequence of the flotation test. Clean coal C1 and tailing coal T1 are obtained after coal slime roughing, and then the rough tailings coal T1 is swept. Clean coal C2 and tail coal T2 were obtained, the tail coal was swept four times in turn, and then the clean coal was selected. The number of selections is shown in Fig. 8.

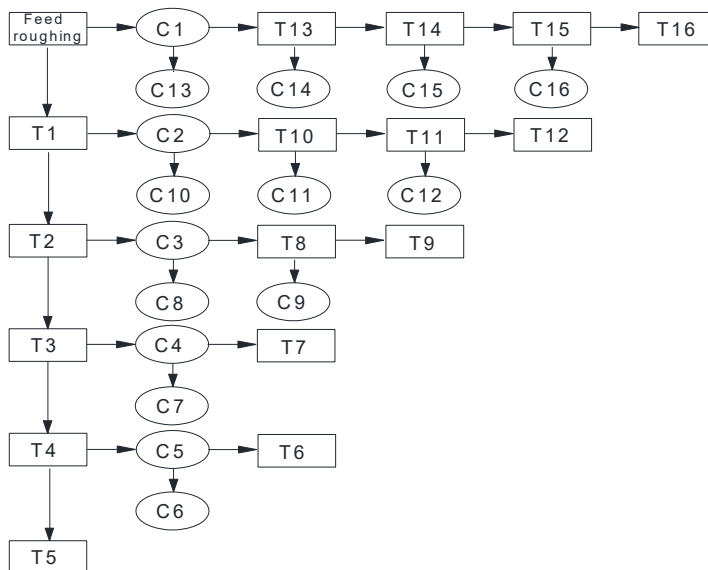


Fig. 8. Sequence evaluation test sequence

Sequential evaluation tests were carried out on each underflow of raw coal slime and the CMC multistage small conical angle hydrocyclone group. According to GB/T 30046.2-2013 “Pulverized Coal (mud) Flotation Test Part I: Sequence Evaluation Test Method,” the sequence evaluation test conditions are determined as follows: the slurry concentration is 100 g/L, the stirring speed is 1,500 r/min, the aeration rate is 0.25 m³/(m²·min), the amount of frother suoctanol is 100 g/t, and the amount of collector kerosene is 1,000 g/t. The amount of collector is increased by 5%-25% in each stage except for rough separation. The test products are ranked according to the ash content from small to large. The ash-yield curve is shown in Figs. 9 and 10.

According to the calculation of theoretical cleaned coal products based on the mixed underflow products of raw coal slime and CMC cyclone set, the ash content of qualified cleaned coal was determined to be 17.83%. According to the curve shown in Fig. 9, the theoretical cleaned coal yield (accounting for this grade) of raw slime is 12.75%, the recovery rate of the combustible matter is 24.45%, and the floatability is evaluated as extremely difficult to float. The theoretical cleaned coal yield (accounting for this grade) of the mixed products of the underflow after desliming is 37.56%, which is 24.81% higher than that of the direct flotation of raw slime. The recovery rate of the combustible matter is 57.42%, which is 32.97% higher than that of the direct flotation of raw coal, and the floatability level is increased from extremely difficult to float to difficult to float. This indicates that in the CMC multistage and small cone angle hydrocyclone desliming-flotation process, the high-ash fine mud is separated from the

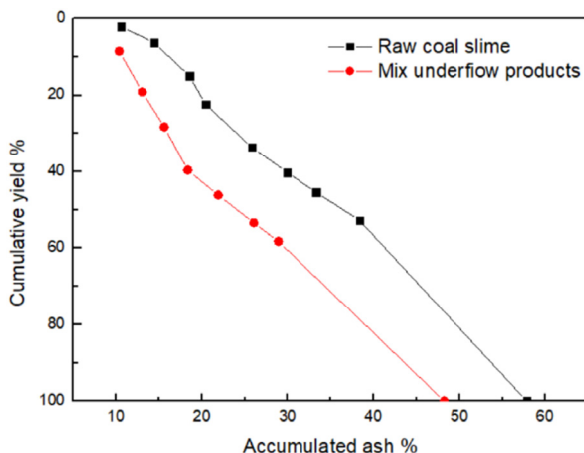


Fig. 9. Relationship between raw coal ash content and yield

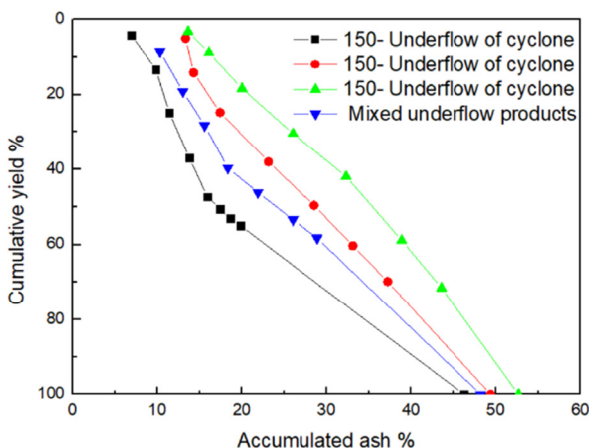


Fig. 10. Relationship between the ash content of the underflow and yield of the cyclone group

cleaned coal particles, the flotation environment of the slime is greatly purified, and the flotation efficiency is improved.

As shown in TABLE 4 and Fig. 9, when the ash content of qualified cleaned coal is determined to be 17.83%, the theoretical cleaned coal yield (accounting for the whole grade) of mixed underflow products of the CMC cyclone group is 18.60%. When the $\Phi 150$ mm small cone angle hydrocyclone is used alone, the underflow cleaned coal yield (accounting for the whole stage) is 16.76%, indicating that compared with the $\Phi 150$ mm small cone angle hydrocyclone CMC multistage small cone angle hydrocyclone group, it can ensure clean coal ash and has higher clean coal recovery.

Fig. 10 shows that when the ash content of qualified clean coal is determined to be 17.83%, the theoretical clean coal yields (accounting for this level) of $\Phi 150$ -underflow, $\Phi 75$ -underflow,

Φ 50-underflow and mixed underflow products are 51.96%, 26.92%, 15.20% and 37.56%, respectively; and the recovery rates of combustibles are 79.43%, 43.72%, 26.40% and 57.42%, respectively. Each underflow product was evaluated for flotation, as shown in TABLE 6.

TABLE 6

Evaluation results of floatability of CMC hydrocyclone group products

Product Name	Feed ash/%	Theoretical yield of clean coal/%	Combustible recovery rate /%	Flotability
Φ 150-Underflow of cyclone	46.97	51.96	79.43	Medium floatable
Φ 75-Underflow of cyclone	49.41	26.92	43.72	Difficult to float
Φ 50-Underflow of cyclone	52.69	15.20	26.40	Extremely difficult to float
Mixed underflow products	48.63	37.56	57.42	Difficult to float

As shown in TABLE 6, Φ 150-underflow, Φ 75-underflow and Φ 50-underflow show different floatability, among which the floatability of Φ 150-underflow is better than the other two kinds of underflow products because the fine mud content in the feed of Φ 75 mm and Φ 50 mm cyclone is relatively high, and when the cone angle is smaller, the enrichment degree of fine mud particles in sorting is lower. The less easy it is to get close to the axis, the more likely the phenomenon of „underflow pinching“ appears, which leads to the low underflow floatability. Combined with the particle size analysis of the underflow products of the CMC cyclone set in Fig. 6, it can be seen that there are more coarse particles in the Φ 150-underflow, more particles in the Φ 75-underflow, and more fine particles in the Φ 50-underflow, indicating that different particle size widths in the float show different floatability. Four kinds of underflow flotation clean coal accounted for 14.71%, 3.18%, 1.42%, and 18.60% of the whole class. The sum of clean coal yield of Φ 150-underflow flotation, Φ 75-underflow flotation and Φ 50-underflow flotation alone was higher than that of mixed underflow flotation. This indicates that narrow flotation is more beneficial to enhance the recovery of slime. The desliming-flotation process of the CMC multistage and small cone-angle hydrocyclone group has very good flexibility, which can be mixed into flotation or separate flotation into different flotation processes according to the different properties of the underflow products. This process can provide a technological reference for better realization of narrow slime flotation.

4. Conclusions

- (1) In the original coal slime, the dominant particle size is -0.045 mm, the yield is 51.06%, and the ash content is 69.82%. This particle size contains a large amount of clay minerals such as kaolin. After predesliming with a small cone-angle hydrocyclone, the high-ash fine-grained clay minerals are enriched in the overflow, which reduces the pollution of high-ash fine-grained slime to the quality of flotation cleaned coal.

- (2) In the process of the CMC multistage and small cone-angle hydrocyclone, the removal efficiency of high-ash fine particles <0.045 mm reaches 64.43%. This process can strengthen the recovery of coarse cleaned coal and basically solve the problem of “overflow running coarse” in cyclones.
- (3) In the CMC multistage and small cone-angle hydrocyclone group flotation process, after CMC hydrocyclone group desliming, the clean coal yield in mixed underflow flotation (accounting for this class) increased by 24.81% compared with the direct flotation of raw coal slime. At the same time, the recovery rate of the combustible matter was increased by 32.97%, and the floatability level was increased from extremely difficult to difficult to float. Compared with the single use of the $\Phi 150$ mm small cone angle hydrocyclone, the CMC cyclone group can better purify the flotation environment and ensure clean coal yield and quality.
- (4) The CMC multistage and small cone angle hydrocyclone group desliming-flotation processes have very good flexibility. Three underflows can be mixed into the float, and compared with the direct flotation of raw coal, the cleaned coal yield and the recovery rate of the combustible matter can be increased by 2-3 times. According to the different floatability of each underflow product, different flotation processes can be adopted separately to perform flotation feeding to strengthen the recovery of cleaned coal of each particle size. This process can provide a technological reference for better performance of narrow particle slime flotation.

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