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EFFECT OF TWO-STAGE STIRRED PULP-MIXING ON COAL FLOTATION

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Abstract: Stirred pulp-mixing is performed before coal flotation. In this study, a two-stage stirred pulp-mixing tank was designed based on the single-stirred process to intensify the mixing effect of pulp and flotation reagents. A tank has a pitched-impeller opening-type turbine. Stirred pulp-mixing and flotation experiments were conducted on a sample of anthracite fine coal (-0.5mm) from the Xuehu Coal Preparation Plant in Henan Province, China. The results of the two-stage stirred pulp-mixing were compared with those of a single-stage stirred pulp-mixing in terms of flotation performance. Compared with the single-stage stirred pulp-mixing, two mixing areas and double-layer impeller were able to strengthen the energy input to the stirred system, thereby improving the mixing efficiency of flotation reagents and coal particles in the pulp. The two-stage stirred pulp-mixing significantly increased the flotation feed rate of the cyclone-static micro-bubble flotation column and concentrate yield, enhanced the combustible matter recovery effect of coarse particles at a suitable flotation feed rate, and ensured the recovery effect of fine particles at high flotation feed rate.

Keywords: *mixing, stirred, two stage, fine coal, flotation*

Introduction

Stirred pulp-mixing is the first process in fine particle separation. With “poor, miscellaneous, and difficult” mineral characteristics, suitable conditions for mineralization are prerequisites for efficient recovery of fine and micro-fine mineral particles (Akdemir and Sonmez, 2003; Sun et al., 2006; Negri et al., 2007). The conventional mechanical cell, flotation column and Jameson cell are the main devices used in fine particle flotation. Mechanical flotation machines typically work as a mixing device. A high stirring intensity in flotation cell may lead to a low recovery of particles because of high detachment probability of mineral particles from bubbles (Cheng et al., 1998; Rubinstein, 2004). However, a highly turbulent environment is

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required for the sufficient mixing of particles and flotation reagents. These two distinct fluid environments cannot be provided simultaneously by the stirring mechanism of a flotation cell (Dobby and Finch, 1986). The flotation column has no stirring device, and thus, the mixing effect of pulp and reagents is particularly important for the subsequent separation process (Clayton et al., 1991; Harbort et al., 1994; Liu et al., 2000).

Stirred pulp-mixing is related to the dispersion of pulp and reagents, contact of mineral particles with reagents, and mineral surface modification. The adequacy of stirred pulp-mixing is directly related to the flotation effects. A lot of works were done and meaningful conclusions were obtained about mixing before mineral flotation. Strong pulp-mixing pretreatment significantly improves flotation performance, including the improvements in the selectivity and recovery of valuable metals (Engel et al., 1997). High-shearing pulp-mixing improves the flotation effect through the surface cleaning and shear flocculation of mineral particles (Chen et al., 1999). A shearing force is a key factor for separation efficiency (Valderrama and Rubio, 1998). Coal oxidation also has a significant effect on floatability. Feng et al. (2005) found that the hydrophilic oxide layer of a mineral particle surface can be removed effectively by high-shearing pulp-mixing. The oxidized coal is also difficult to float with the common collectors (Xia et al., 2012a, b, 2013). In fine coal flotation, higher combustible matter recovery can be obtained by enhancing the impeller speed of mixing operation prior to flotation. However, concentrate ash content also increases by different degrees (Li et al., 2009; Liu et al., 2009; Liang et al., 2011).

Considerable research and development were conducted on fine coal stirring equipment, particularly on pulp pre-processor (Yu, 2005), emulsifiers (Jiang et al., 2006), surface-modified separators (Wang, 2003), static mixers (Zhang et al,. 2006), and a variety of stirring tanks(Wang, 2004). These studies significantly improved pulp efficiency circulation and shearing and reduced the dosage of flotation reagents. Studies on stirred pulp-mixing focused mainly on the cycle efficiency, which significantly influences the macro-mixing of mineral particles and improves homogenization in a stirring tank. With the improvement in the proportion of mechanical coal-mining and the rapid development of heavy-medium coal preparation, the fine coal of China is characterized gradually by size reduction, ash increase, and higher intergrowth content (Xu et al., 2003). The fine coal separation problem became prominent (Li et al., 2013; Ding et al., 2006). A high fine coal particle content in stirred pulp-mixing can agglomerate the mixing system, pollute the micro-fine heterogeneous mud in clean coal flocs, and significantly affect the flotation reagents and coal particle surface. A short circuit in the stirred pulp-mixing process affects the recovery of flotation devices because parts of the flotation reagents and pulp would be overflowed by the surface material flow given a horizontal circulation of single-stage mixing (Gui et al., 2013). To solve this problem, the current study proposes a two-stage stirred pulp-mixing process. The effect of two-stage stirred pulp-mixing is compared with that of single-stage stirred pulp-mixing by analyzing their mixed characteristics. The results of this study can serve as references for new, efficient mixing mechanisms.

Experimental

Method

The experimental samples were fine anthracite coal from the Xuehu Preparation Plant in Henan Province, China. The feed slurry was a mixture of fine coal particles, water, and flotation reagents. The feed had solid concentration of 100 g/dm^3 to 120 g/dm^3 and pulp density of 1,035 kg/m^3 to 1,050 kg/m^3. The optimum flotation conditions were obtained in the experiment. Collector dosage was 320 g/Mg, frother dosage was 110 g/Mg, and feed concentration was 90 g/dm^3. Figure 1 shows the equipment flowchart.

With valves 1 and 3 opened and valves 2 and 4 closed, coal slime and flotation reagents were fed into a two-stage stirring tank with diameter of 2.5 m. With valves 1 and 3 closed and valves 2 and 4 opened, coal slime and flotation reagents were fed into a single-stage tank with diameter of 2.5 m. Impeller speed was changed by adjusting drive motor speed through the inverter. The strength of the flow field in the stirring tank was adjusted by replacing the stirring impeller with one of a different diameter. The coal slurry was fed into a FCSMC 3000×6000 cyclone-static micro-bubble flotation column after stirred pulp-mixing. The cyclonic-static micro-bubble flotation column (FCSMC) was researched by the China University of Mining and Technology widely used in coal preparation, polymetal sulfide flotation and magnetite/hematite reverse flotation, where higher separation efficiency, especially of fine and micro fine particles, was demonstrated. FCSMC is composed of the separation zone, cyclonic separation zone, bubble producer and pipe flow mineralized zone. The separation zone is on the top of the column. FCSMC is a combination of column flotation and cyclonic separation and is a multi-separation structure, combining column-separation, cyclonic-separation and pipe flow mineralization. It can maintain the selective superiority of flotation column separation and at the same time further improve the recovery and separation efficiency, which can make this kind of equipment highly efficient in fine and micro-fine particle separation. In this study, FCSMC 3000×6000 was used as a flotation equipment, which width and length are 3000 and 6000 millimeters, respectively (Cao et al., 2011; Zhang et al., 2013). The effect of two-stage stirred pulp-mixing on the flotation device was compared with that of single-stirred pulp-mixing by changing feed rate.

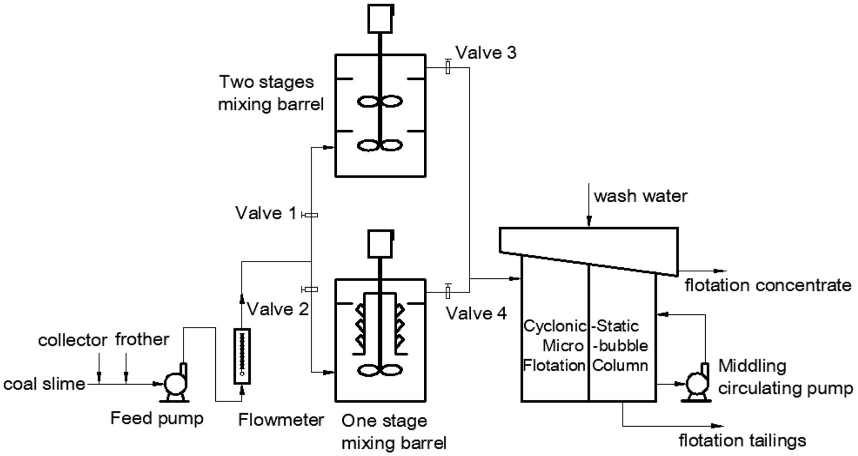

Fig.1. Equipment flow chart

Stirred mixing tank

The two-stage stirring tank consists of two mixing areas, tank, shaft, two impellers, baffles, and ring plate. Upper and lower impellers and ring plate are removable, allowing the switch from the two-stage stirring tank to the single one. In the preliminary tests, the impeller forms were fixed as pitched-impeller opening-type turbines, and the impeller number was 4 with alternating diameters (600, 650, and 700 mm). The motor and stirring shaft speeds were adjusted using the inverter. Table 1 shows the size of the stirring barrel and accessories.

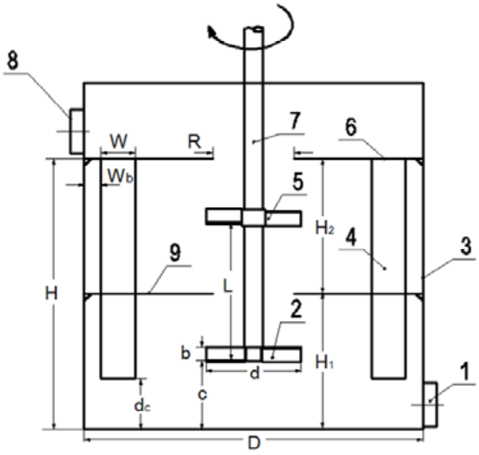

Fig. 2. Schematic diagram of two-stage compulsory-stirred tank. 1 – Feed inlet; 2 – Lower impeller; 3 – Mixing tank; 4 – Baffle; 5 – Upper impeller; 6 – Upper ring-plate; 7 – Stirring shaft; 8 – Discharge port; 9 – Low ring-plate

The coal slurry was mixed in different axial positions through stirred pulp-mixing by two impellers in two different positions in two sections of the tank area. Figure 2 shows the structure diagram of the two-stage stirring tank. The coal slurry was fed into the first stirring section through feed inlet 1. The coal slurry then entered the second stirring section after the stirring action of lower impeller 2. Then, the second mixing process was completed by the action of upper impeller 5. The material was forced-modified by the mechanical fluid force. The modified pulp was discharged from discharge port 8. When the upper impeller 5 and lower ring plate were removed and a loop sleeve was added, the two-stage stirred pulp-mixing was changed to single mixing, allowing for comparative tests on the two stirring forms. Figure 3 shows the schematic diagram of the single-stage stirring tank

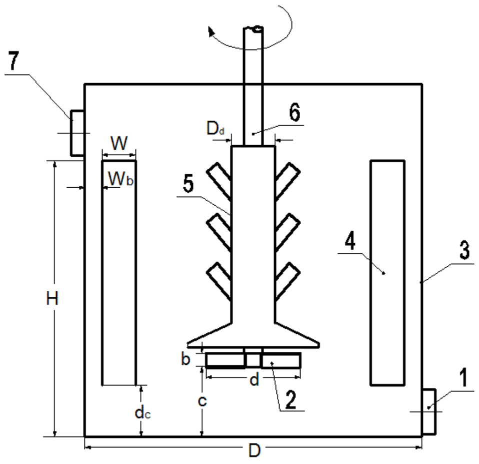

Fig. 3. Schematic of single-stage stirred tank. Feed inlet; 2 – Impeller; 3 – Mixing tank; 4 – Baffle; 5 – Circulation sleeve; 6 – Stirring shaft; 7 – Discharge port

Table 1. Structure size of two- and single-stage stirring tanks. Symbols: *D* – Tank diameter; *H* – Tank height; W_b – Distance between baffle and tank; *W* – Width of baffle; *C* – Distance between lower impeller and bottom of the tank; *L*, *d* – Impeller diameter; D_d – Cycle sleeve diameter; *b* – Impeller height; *R* – Inner circle radius of the ring plate; H_1 – Distance between lower ring plate and bottom of the tank; H_2 – Distance between the two ring plates; *θ* – Blade angle

Dimension (mm)	*D*	*H*	W_b	*W*	*C*	*L*	*d*	D_d	*b*	*R*	H_1	H_2	*θ*, °
Two-stage	2500	2500	125	250	500	1000	600/650/700	/	100	600	1000	1000	45
Single-stage	2500	2500	125	250	500	/	600/650/700	324	100	/	/	/	45

Results and discussion

Effect of stage stirring on coal flotation index

Figure 4 shows a relationship between flotation index and stirring speed. Test conditions were characterized by a dry fine coal with 30 Mg/h and pulp feed rate of 380 m^3/h. Concentrate yield and ash content increased with increasing shaft speed, although the increasing trend slowed down. The previous studies showed that coal floatability decreases in the flotation cell and that the flotation rate constant is reduced gradually with the flotation process (Li et al., 2013). In other words, many materials of low ash content float during early flotation, and only a few materials of high ash content and poor floatability float during late flotation. Thus, the increase in the shaft speed is equivalent to increase in energy input in the stirring system. The excess energy is reflected mainly in the recovery of coal particles that are difficult to float. Impellers with large diameters can obtain higher concentrate yield at the same coal ash content or obtain lower ash content at the same concentrate yield. The concentrate yield can be increased and high-quality clean coal can be obtained by increasing energy input in the stirred system.

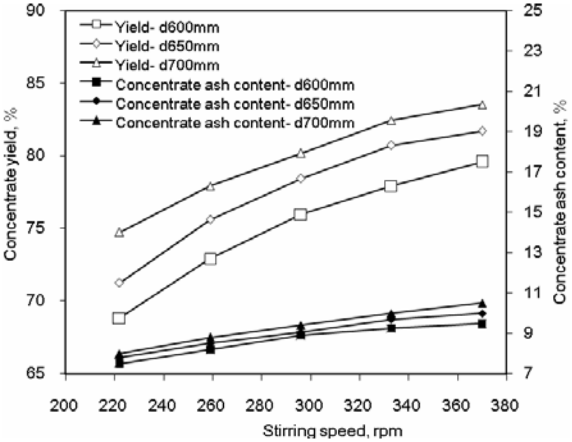

Fig. 4. Relationship between flotation index and stirring speed

Figure 5 shows the relationship between the power consumption of the unit volume and the flotation index. The power consumption of the unit volume in a stirred tank (P_V) can be expressed as:

$$P_V = \frac{P}{V} \tag{1}$$

where P_V is the input power of fluid in the tank (W) and V is the effective volume of the tank (m^3). Figure 5 shows that the power consumption of unit volume reached the maximum value of 2877, 3415, and 4140 W/m^3 with the maximum speed of 370 rpm at the corresponding impeller diameter of 600, 650, and 700 mm, respectively. The flotation concentrate yield and ash content increased with increasing power input per unit volume, but the rate of increase gradually slowed. The power input per unit volume with the same speed increased and the concentrate yield increased with larger impeller diameter. However, with the same power input per unit volume, the smaller impeller diameter generated higher concentrate yield and lower ash content. These results indicate that more energy is required in the late stage of the flotation process of hard-to-float particles. In actual production, flotation index requirements and the power consumption of unit volume are considered comprehensively to determine impeller diameter and speed in the two-stage stirring tank.

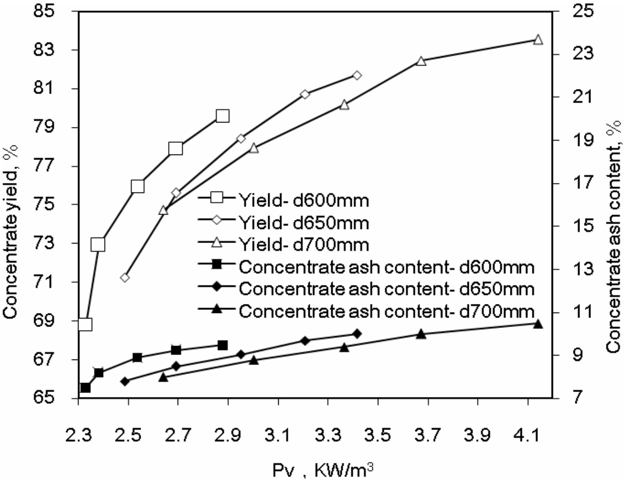

Fig. 5. Relationship between concentrate ash content, yield, and power consumption of unit volume in a stirred tank P_V

Mixing characteristics were evaluated comprehensively by investigating the flow and power dimensionless numbers, shearing and cycle characteristics, and mixing efficiency of the two-stage compulsory-stirred system. Efficient mixing means that the same mixing level was achieved at the lowest energy consumption. Thus, mixing efficiency of different stirring mechanisms is combined with the mixing time and energy consumption. The mixing time per unit of energy consumption is characterized by K (dimensionless). Smaller K indicates shorter mixing time with the same energy consumption and higher mixing efficiency. K can be expressed as follows (Wang and Yu, 2003; Zhang et al., 2003; Li, 2010):

$$N=\left(\frac{\rho N_P d^5}{P}\right)^{-\frac{1}{3}} \tag{2}$$

$$\theta_m=\frac{N_\theta}{N}=N_\theta N_P^{\frac{1}{3}} d^{\frac{5}{3}}\left(\rho/P\right)^{\frac{1}{3}}=N_\theta N_P^{\frac{1}{3}}(d/D)^{\frac{5}{3}}(D)^{\frac{5}{3}}\left(\rho/P\right)^{\frac{1}{3}} \tag{3}$$

$$K=N_\theta N_P^{\frac{1}{3}}\left(\frac{d}{D}\right)^{\frac{5}{3}}. \tag{4}$$

Combination of $N_\theta=\theta_m N$, $N\theta_m=5\left(\frac{2H_L}{d}+\frac{D}{d}\right)\frac{C}{d}$ and $N_p=\frac{P}{\rho N^3 d^5}$, then

$$K=\frac{5\left(2\frac{H_L}{d}+\frac{D}{d}\right)\frac{C}{d}}{N}\left(\frac{P}{\rho D^5}\right)^{\frac{1}{3}} \tag{5}$$

where N is the stirring speed (rpm), ρ pulp density (kg/m^3), d impeller diameter, N_P power dimensionless number, P input power in the tank (W), H_L liquid height in the tank, D tank diameter and C is the distance between impeller and bottom of the tank .

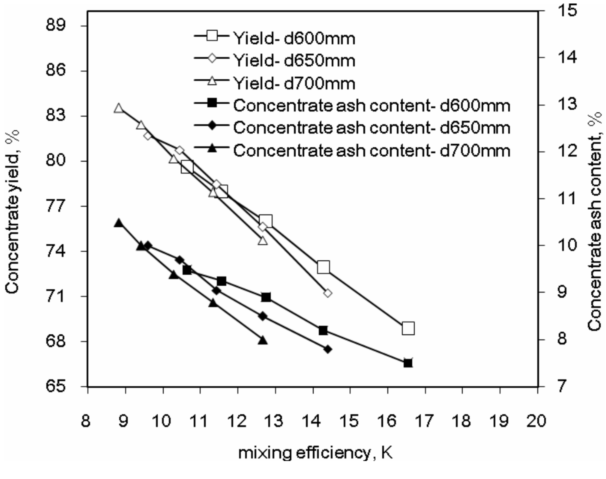

Fig. 6. Relationship between concentrate ash, yield, and mixing time per unit of energy consumption K

Figure 6 shows a relationship between the mixing efficiency and flotation index. The yield and ash content of flotation concentrate decreases with increasing mixing time per unit of energy consumption K. Higher K is detrimental to concentrate flotation, while smaller *K* is more conducive to concentrate flotation. Based on the relationships between blade diameter, rotational speed, and *K*, the mixing time per unit of energy consumption is small when blade diameter is large. With the same *K*, larger blade diameter could obtain lower ash content of concentrate as well as concentrate yield.

Effect of stirred form on the feed rate of the flotation column

Stirred pulp-mixing and flotation experiments were conducted in the single- and two-stage stirring tanks at different feed rates to investigate the effect of stirred form on the feed rate of flotation column. The flotation concentrate ash content was controlled as qualified ash with intervals of 8.5% to 10% through forth overflow operation. The ash content of the flotation tailings of the two-stage stirred pulp-mixing was compared to that of the single-stage stirred pulp-mixing at different feed rates. The results of the prediction tests show that shaft speed was fixed at 333 rotation per min (rpm) (Fig. 7). The ash of the flotation tailings significantly decreased with the increasing feed rate of the cyclone-static micro-bubble flotation column. At a low feed rate, the ash content of the flotation tailings of two-stage stirred pulp-mixing did not exhibit obvious advantages over the single-stage stirred pulp-mixing.

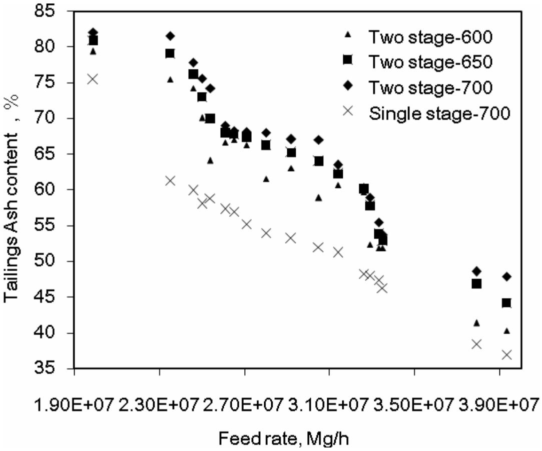

Fig. 7. Effect of different stirred mechanisms on flotation feed rate

For more in-depth analysis of superiority of the two-stage stirred mixing to the single-stage stirred mixing, the particle sizes of flotation tailings of the two stirring modes were analyzed at different flotation feed rates and at an impeller diameter of 700 mm. Figure 8 shows the ash distribution of the flotation tailings in different size fractions. In each grain size and feed rate, the ash content of tailings in the two-stage stirred pulp-mixing was higher than that of single-stage stirred pulp-mixing. In the two-stage stirred mode, fine particles (-0.074 mm) exhibited a good recovery effect with low flotation feed rate, and tailings with higher ash content were obtained with coarse fractions (+0.125mm). The two-stage stirred pulp-mixing obtained tailings with higher ash content, when the flotation feed rate was high. Fine particle recovery was better in the two-stage stirred pulp-mixing than in the single-stage pulp-mixing. These results show that the two-stage stirred process strengthens the sufficient contact of micro-grain and flotation reagents in fine-coal flotation and intensifies flotation.

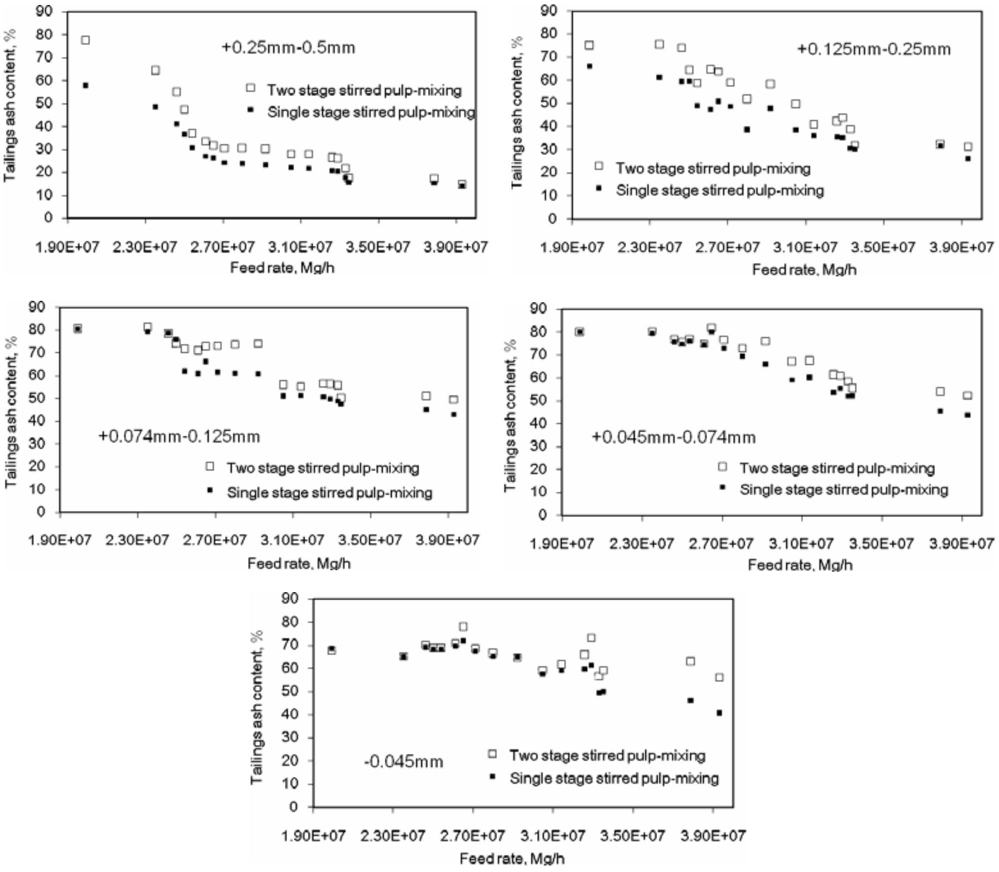

Fig. 8. Ash distribution in grain size of flotation tailings for different stirring mechanisms

Conclusions

In this study, the two-stage stirred pulp-mixing system was found to strengthen the mixing efficiency of pulp and flotation reagents and significantly increase the flotation concentrate yield and feed rate of the cyclone-static micro-bubble flotation column. Moreover, recycling of poor-floatability particles in the latter part of the flotation process in the two-stage stirring process could be strengthened with increasing impeller diameter and shaft speed. Unlike the single-stage stirred pulp-mixing, the two-stage stirred pulp-mixing enhanced coarse particle recovery at a suitable flotation feed rate and ensured fine particle recovery at a high flotation feed rate.

Future research could focus on the relationships between the impeller diameter and stirring tank diameter, and the effect of distance of two stirring impellers. These relationships can possibly improve unsuitable mixing zones, reduce energy consumption and optimize the tank structure.

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