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Application of a biconical dense medium cyclone to pre-treat a low-grade Pb-Zn sulfide ore

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Abstract: A biconical dense medium cyclone (BDMC) was applied to reject the gangue from a low-grade Pb-Zn sulfide ore for the first time. Based on mineralogy and heavy liquid separation tests, it was found that the rejection of gangue by the BDMC prior to grinding and flotation was promising. The results revealed that the particle size clearly affected the heavy liquid separation process. The effects of several parameters, such as medium specific gravity (SG), spigot diameter, tilt angle, cone angle and medium/ore mass ratio, on the yield of floats and on the metal recoveries in the floats were examined and the optimal parameters were determined. The results showed that 51.22% of floats were obtained with a lead recovery of 7.92% and a zinc recovery of 12.50%. The extended tests were further carried out with the BDMC being capable of throughputs about 3 t/h, which verified the results obtained in the laboratory experiments. The use of this equipment to pre-treat the refractory ore is promising.

Keywords: Pb-Zn sulfide ore, Low-grade ore, Pretreatment, Biconical dense medium cyclone

1. Introduction

Lead and zinc are important metals, that are mostly extracted from sulfide ores around the world (Peng et al., 2003; Lv et al., 2018; Zheng et al., 2018). With the continuous exploitation of major resources, high-grade ores have been gradually exhausted. Low-grade ores are now being utilized to supply market demand. There are abundant low-grade Pb-Zn sulfide ores in Yunnan Province, China. Flotation is a conventional way for the beneficiation of sulfide ores. However, it may not be economically feasible to treat low-grade ores, especially when the Pb-Zn prices decline. If the Pb-Zn grades in the ore are upgraded prior to grinding and flotation, it would be very beneficial to reduce the total cost for treating the ore by flotation.

Gravity separation methods, such as shaking tables, spirals and dense medium cyclones (DMCs), may be promising to achieve the above objective. They also cause relatively low environmental pollution (Wills et al., 2015; Hosseini et al., 2001; Guney et al., 2001; Cicek et al., 2002). Shaking tables and spirals are characterized by a simple structure and straightforward operation, but both have low processing capacities and occupy large footprints (Wills et al., 2015). DMCs, which mainly depend on a significant SG difference and centrifugal force, can usually reject considerable amounts of gangue, leading to a throughput increase in grinding and flotation systems. In addition, DMCs have many advantages, such as a large processing capacity and high separation efficiency (Wang et al., 2009a; Chu et al., 2009; Fourie et al., 1980). Considering the processing capacity and investment cost, a DMC was proposed to treat low-grade Pb-Zn sulfide ore.

In the available literature (Napier-Munn T J.,1991; Narasimha et al., 2007; O'Brien et al., 2014; Restarick and Krnic, 1991; He et al., 2001; Chen et al., 2014), DMC has been extensively applied in the

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mineral processing industry, especially the coal industry, for upgrading raw coal. O'Brien et al. (2014) investigated the effects of a medium composition on DMC operation and provided a method for quantifying the composition of a medium in terms of magnetite, clay, fine coal, and small coal. The results showed that the magnetite by itself at a feed medium density below 1.4 is less stable than a mixture containing magnetite, clay and fine coal and that the density of the underflow is the most affected. Restarick and Krnic (1991) reported closed-circuit tests with a 140 mm diameter DMC, which was operated at a relative density of less than 1.3 using a fine magnetite medium and density tracer. The effects of the diameter ratio of underflow to overflow above approximately 0.82 on the separation performance were also established. In addition, the hydrodynamic theory of particle movement in non-Newtonian fluids was discussed from a rheological perspective, and it could be concluded that the dense medium separation of fine and near density particles was mostly affected by the medium yield stress (He et al., 2001). Moreover, numerical experiments were performed by computational fluid dynamics and combination with the discrete element method to optimize the design and operation of a DMC (Chen et al., 2014; Kuang et al., 2012).

However, there have been few studies on the application of DMCs to nonferrous metal ores. This paper focused on the application of a DMC to reject significant amounts of gangue from low-grade Pb-Zn sulfide ores prior to grinding. The DMC used in the experiments was devised by our research team (Li et al., 2011). It consists of two cones, which is referred to as BDMC. Generally, there are many factors, including the size range of the ore, equipment parameters and the medium SG, affecting its separation performance in industry (Wang et al., 2009b; He et al., 1994). In this study, several parameters, such as particle size, medium SG, spigot diameter, overflow diameter, tilt angle, cone angle and medium/ore mass ratio, were first examined and then the optimal parameters were determined. Extended tests were then carried out with the BDMC being capable of throughputs about 3.0 t/h. The aim was to explore the possibility that valuable metals, such as lead and zinc in low-grade Pb-Zn sulfide ore, could be recovered by physical separation. It was believed that the total cost for the recovery of lead and zinc would be reduced and that the method would show excellent potential for treating similar nonferrous ores.

2. Materials and methods

2.1 Materials

A representative sample was provided from the Lantsang mine in Yunnan Province, China. Chemical analyses were carried out to determine the chemical constituents of the sample, and inductively coupled plasma-atomic emission spectrometry (ICP, IRIS Intrepid II XSP) was used for the analysis. Table 1 shows the results of the chemical analyses of the sample, indicating that it was a low-grade Pb-Zn ore. The lead and zinc distributions in the ore are presented in Tables 2 and 3, respectively. The results show that lead and zinc occurred mainly as sulfides.

Table 1. Chemical composition of the low-grade Pb-Zn sulfide ore (wt. %)

Pb	Zn	Fe	S	As	Al_2O_3	SiO_2	CaO
3.17	0.97	2.54	2.52	0.18	7.17	64.57	7.38

Table 2. Phase composition of Pb in the the low-grade Pb-Zn sulfide or

Constituent	Silicate	Carbonate	Sulfide	Others	Total
Distribution (%)	4.82	6.75	86.50	1.93	100.00

Optical micrographs of the sample under reflected light are shown in Fig. 1. The poly-metallic sulfide minerals, which occurred in the form of compact aggregates, were unevenly distributed in the gangue. This finding indicates that it was feasible to separate the gangue from the ore by relying on the differences in the SG. In addition, these sulfide minerals are closely associated with each other, suggesting that fine grinding had to be carried out to achieve their liberation prior to flotation.

Table 3. Phase composition of Zn in the the low-grade Pb-Zn sulfide ore

Constituent	Silicate	Carbonate	Sulfide	Others	Total
Distribution (%)	10.86	1.37	86.80	1.17	100.00

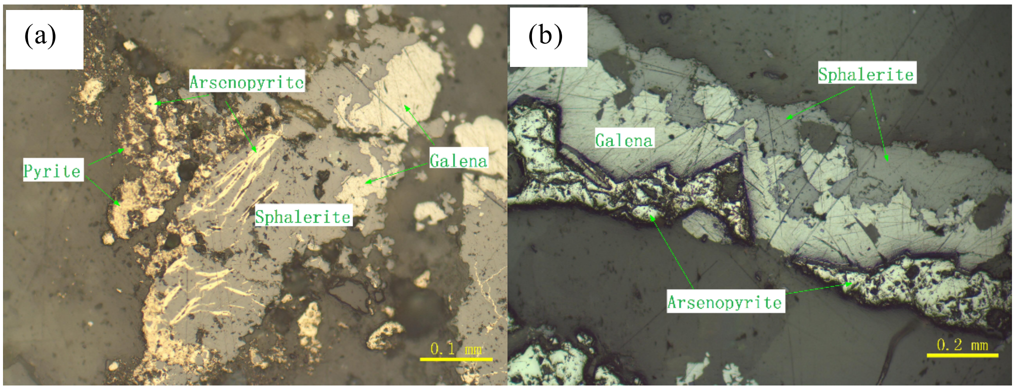

Fig. 1. Optical micrographs of the main minerals under reflected light

Table 4 presents the main mineral constituents, and in decreasing order of wt%, they were quartz, calcite, sericite, pyrite, kaolinite, galena, sphalerite and arsenopyrite. Gangue minerals, including quartz, calcite, sericite and kaolinite, accounted for 88.66% of the total minerals, but the valuable minerals accounted for approximately 11.34%. Therefore, it seemed unreasonable to directly recover these valuable minerals from the raw ore by flotation. If most of the gangue can be rejected before grinding and flotation, the grades of lead and zinc should increase.

Table 4. Main mineral constituents in the ore (wt. %)

Galena	Sphalerite	Pyrite	Arsenopyrite	Calcite	Quartz	Sericite	Kaolinite
3.45	2.34	5.16	0.39	13.18	57.8	12.86	4.82

2.2. Heavy liquid tests

Heavy liquid separation tests play an important role in determining the required particle size, medium SG and expected rejection yield (Wills et al., 2015). First, the ore samples were crushed to -13, -20 and -28 mm. Screening was then carried out to remove particles finer than 1 mm. The remaining samples in the size fractions of -13+1, -20+1 and-28+1 mm were subjected to heavy liquid separation tests, as shown in Fig. 2. Two kinds of heavy liquids were prepared by mixing bromoform ($CHBr_3$) and ethanol (C_2H_6O) with different weight ratios. Both of them were close to the true SG of the ore (2.75). The sample was initially introduced into the heavy liquid with an SG of 2.6. The floats and the bottom products with an SG higher than 2.6 were obtained. The obtained bottom products were then placed in the heavy liquid with an SG of 2.7. The intermediate floats and sinks were finally obtained.

2.3 BDMC tests

An experimental flow chart for treating the low-grade Pb-Zn sulfide ore is shown in Fig. 3. Approximately 50 kg of the raw ore at a required size was mixed with the suspension at a desired weight ratio. The suspension was composed of ferrosilicon particles with a size of -0.043 mm. Then, the mixture was transported to the groove by a pump and introduced into the inlet of the BDMC, as shown in Fig. 4. The internal diameter of the BDMC increased and then decreased, which helped to obtain a higher centrifugal force. Moreover, the suspension composed of mineral particles with different SGs could stably exist at the sectional position. Generally, the BDMC could generate a higher centrifugal coefficient in comparation to that of an ordinary dense medium cyclone. It can also be observed that the diameter of the overflow was not easily adjusted. Therefore, the overflow diameter was fixed in the subsequent experiments.

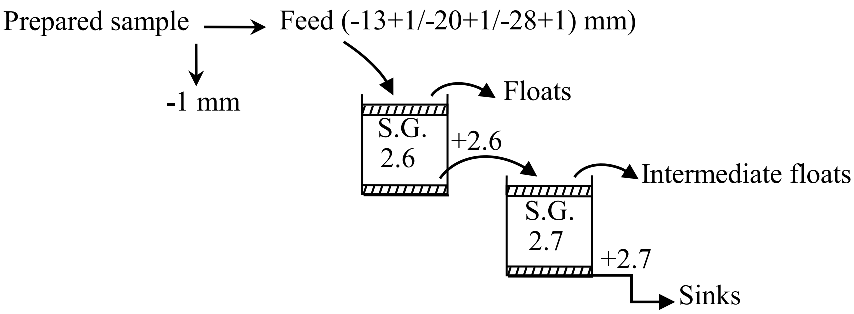

Fig. 2. The flow chart of heavy liquid tests

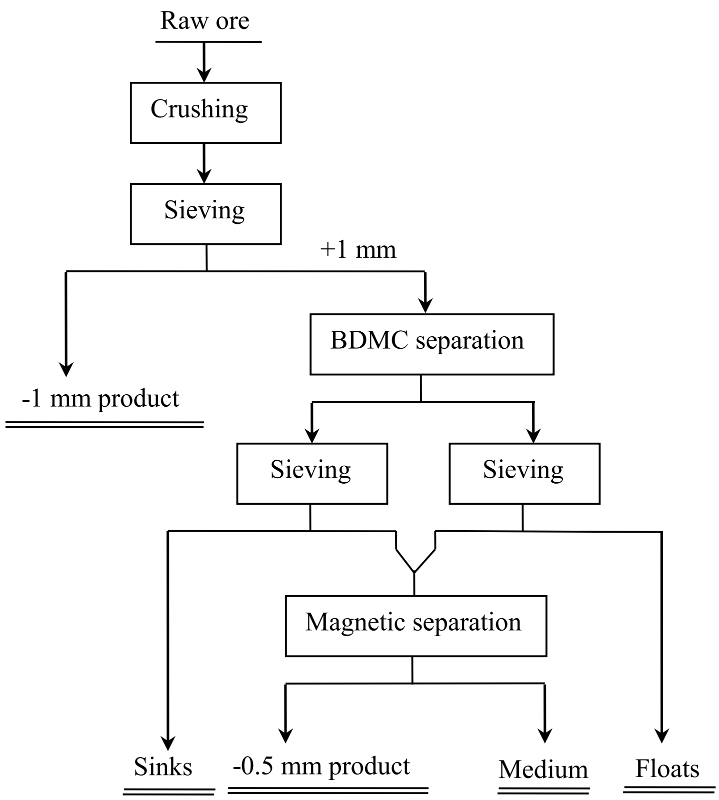

Fig. 3 Experimental flow chart for treating the low-grade Pb-Zn sulfide ore

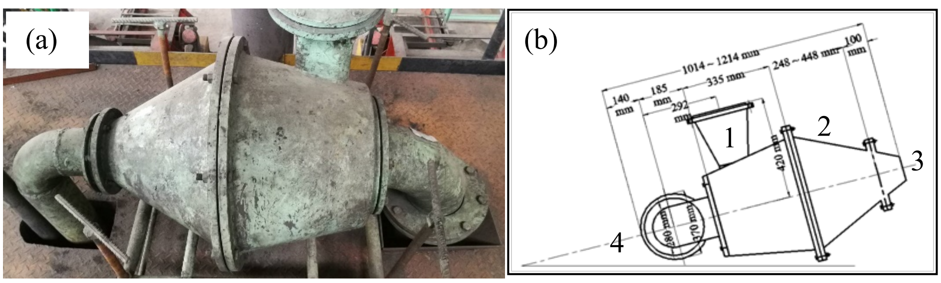

Fig. 4 Picture and schematic diagram of the BDMC (1: Inlet; 2: Vertebral body; 3: Overflow; 4: Spigot)

Once the BDMC started to run, large amounts of gangue and valuable minerals were obtained from the overflow and spigot, respectively, but both products contained ferrosilicon and mineral particles with a size of -0.5 mm. They were separated by screening, and finally, three products, including floats, sinks and particles with a size of -0.5 mm, were obtained. The latter were composed of ferrosilicon and mineral particles generated by abrasion, both of which would be separated by magnetic separation. The ferrosilicon was contained in the magnetic separation concentrate and it can be recycled in the process. To further verify the feasibility of the process, extended tests were carried out with the BDMC being capable of throughputs about 3.0 t/h. After two hours, the products were sampled, weighed and analysed.

3. Results and discussion

3.1. Heavy liquid tests

Table 5 shows the results of the sieving and heavy liquid tests. The weight percent of particles with a size of -1 mm and the distributions of lead and zinc significantly decreased when the crush size range increased from -13+1 to -20+1 mm. With a further increase in the crush size, the weight percent of the particles with a size of -1 mm and their distributions decreased. However, the increase in the crush size produced considerable amounts of coarse particles, resulting in a decrease in the grinding capacity. Therefore, it was very important to select a suitable crush size for treating the ore.

When the particle size range increased from -13+1 to -20+1 mm, the yield of rejects, including the floats and intermediate floats, increased from 56.77% to 65.03%, while the lead and zinc recoveries in the product increased from 3.59% to 4.55% and from 9.25% to 13.27%, respectively. With a further increase in the particle size range, there was a slight increase in the yield and zinc recovery in the rejects. Combined with the sieving results, the optimal crush size was determined to be -20+1 mm.

Table 5. The results of sieving and heavy liquid tests

size（mm）	Products	Yield （%）	Grade（%）		Recovery（%）	
			Pb	Zn	Pb	Zn
13	-1 mm	28.90	3.07	1.25	27.74	37.68
	Sinks	14.33	15.32	3.55	68.66	53.07
	Intermediate	18.63	0.33	0.21	1.92	4.08
	Floats	38.14	0.14	0.13	1.67	5.17
	Feed	100.00	3.20	0.96	100.00	100.00
20	-1mm	19.49	2.92	1.17	18.25	24.84
	Sinks	15.48	15.55	3.67	77.20	61.89
	Intermediate	33.49	0.32	0.26	3.44	9.49
	Floats	31.54	0.11	0.11	1.11	3.78
	Feed	100.00	3.12	0.92	100.00	100.00
28	-1mm	15.45	2.72	1.21	13.31	19.12
	Sinks	17.23	14.90	3.83	81.24	67.42
	Intermediate	37.20	0.41	0.25	4.77	9.53
	Floats	30.12	0.10	0.128	0.98	3.93
	Feed	100.00	3.16	0.98	100.00	100.00

3.2. BDMC tests

3.2.1 The effect of the medium SG

As mentioned before, the medium SG played an important role in the BDMC operation. Therefore, the effect of the medium SG on the removal performance of floats was initially examined. Experiments were carried out under these conditions: particle size of -20+1 mm, spigot diameter of 65 mm, overflow diameter of 120 mm, cone angle of 68 degrees, tilt angle of 0 degree and medium/ore mass ratio of 8.0. Fig. 5 shows that the medium SG affects the yield of floats and Pb-Zn recoveries in the floats. When the medium SG decreased from 2.5 to 2.2, the yield of floats decreased from 67.95 to 60.93% while the recoveries of lead and zinc in the floats decreased from 21.19 to 10.94% and from 30.32 to 23.83%, respectively. With a further decrease in the medium SG, there was less change in the yield of floats and the Pb-Zn recoveries in the floats. Therefore, the optimal medium SG was determined to be 2.2, and all subsequent experiments were carried out at this value.

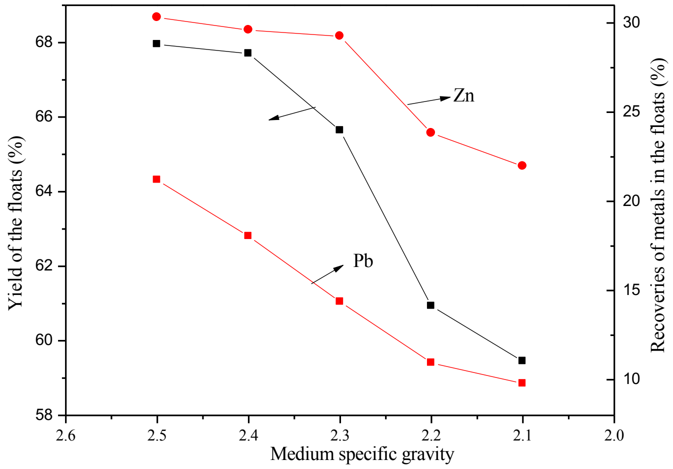

Fig. 5. The effect of medium SG on the yield of floats and Pb-Zn recoveries in the floats

3.2.2 The effect of the spigot diameter

Fig. 6 presents the yield of floats and metal recoveries in the floats with respect to the spigot diameter. From this figure, it can be seen that there was less change in the yield of floats and the Pb-Zn recoveries in the floats when the spigot diameter decreased from 70 to 65 mm. The yield of floats and the Pb-Zn recoveries increased when the spigot diameter was below 65 mm. Therefore, the optimal spigot diameter was determined to be 65 mm, and all the following experiments were carried out at this diameter.

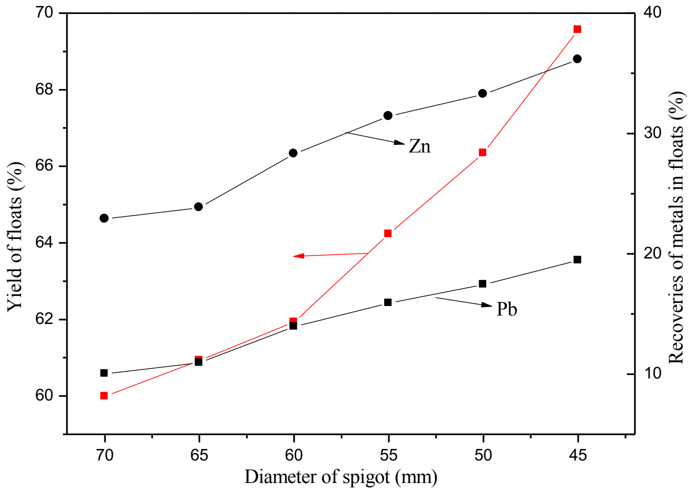

Fig. 6. The effect of spigot diameter on the yield of floats and metal recoveries in the floats

3.2.3 The effect of the tilt angle

In the available literature, the tilt angle of the hydro-cyclone or similar gravity separator obviously affects the metal recoveries, especially when the spigot is worn (Liu et al., 1994; Aslan et al., 2008). Fig. 7 shows the effect of tilt angle on the yield of floats and metal recoveries in the floats. According to this figure, the yield of floats and the Pb-Zn recoveries in the floats decreased when the tilt angle increased from 0 degree to 15 degrees. There was less change in the yield and metal recoveries when the tilt angle increased beyond 15 degrees. Accordingly, the optimal tilt angle was determined to be 15 degrees and all subsequent experiments were carried out at this tilt angle.

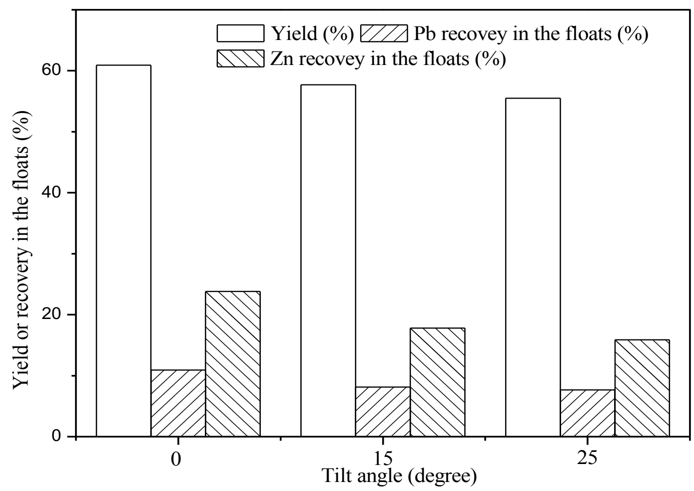

Fig. 7. The effect of tilt angle on the yield of floats and metal recoveries in the floats

3.2.4 The effect of the cone angle

Fig. 8 shows the effect of cone angle on the yield of floats and metal recoveries in the floats. When the cone angle decreased from 68 degrees to 56 degrees, the yield of floats decreased from 57.69 to 51.22%, while the lead and zinc recoveries in the floats decreased from 8.15 to 7.92% and from 17.80 to 12.50%, respectively. With a further decrease in the cone angle, there was no obvious change in the yield and metal recoveries. Thus, the optimal cone angle was determined to be 56 degrees, and all further experiments were carried out at this cone angle.

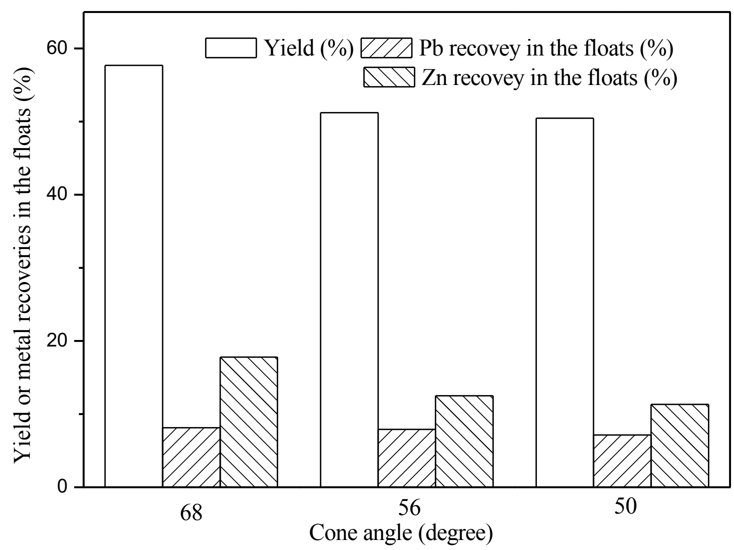

Fig. 8. The effect of cone angle on the yield of floats and metal recoveries in the floats

3.2.5 The effect of the medium/ore mass ratio

Fig. 9 shows the medium/ore mass ratio affecting the removal performance of the gangue. The yield of floats and the Pb-Zn recoveries in the floats fluctuated slightly in the medium/ore mass ratio range of 4~12, confirming that the medium/ore mass ratio selected in the previous experiments was reasonable.

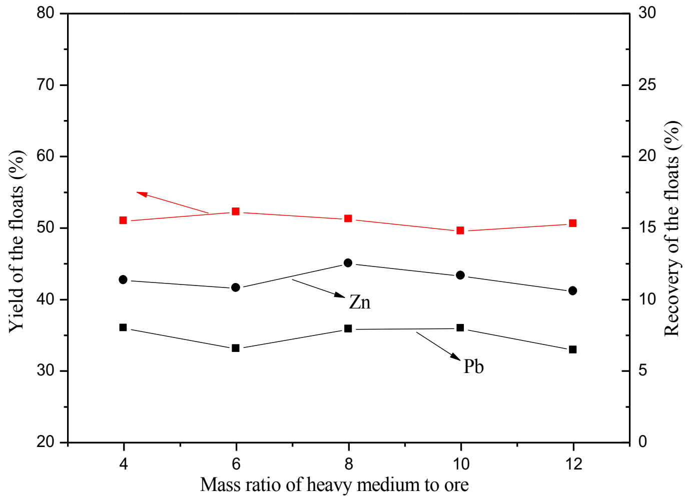

Fig. 9. The effect of medium/ore mass ratio on the yield of floats and metal recoveries in the floats

Table 6 shows the results of BDMC separation tests obtained under the optimal conditions. According to this table, 51.22% of the floats could be obtained with a lead recovery of 7.92% and a zinc recovery of 12.50%. Meanwhile, the grades of lead and zinc increased in other products, which would be beneficial to reduce the total cost for treating the ore. Therefore, it was promising to reject a large amount of gangue using the BDMC prior to grinding and flotation.

Table 6. The results of BDMC separation tests obtained under the optimal conditions

Products	Yield (%)	Grade (%)		Recovery (%)	
		Pb	Zn	Pb	Zn
-1 mm	16.93	4.65	1.17	27.68	21.97
Floats (-20+1 mm)	51.22	0.44	0.22	7.92	12.50
Sinks (-20+1 mm)	22.72	6.19	2.13	49.45	53.67
-0.5 mm	9.14	4.65	1.17	14.94	11.86
Feed	100.00	2.84	0.90	100.00	100.00

3.3. Extended tests

To further verify the feasibility of the proposed technology, extended tests were carried out with the BDMC being capable of throughputs about 3.0 t/h. The flow chart for pretreatment using the BDMC is shown in Fig. 10, and the results are presented in Table 7. Compared with the results in Table 6, it was found that the results obtained in the extended tests were very close to the results obtained in the laboratory experiments.

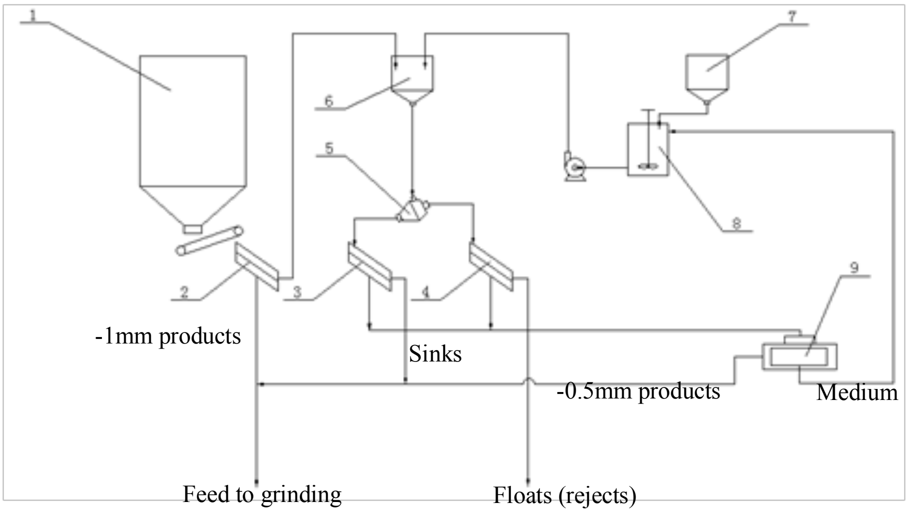

Fig. 10. The flow chart of pretreatment using BDMC (1, Ore bin; 2, Vibrating screen; 3 and 4, Screening for removing medium; 5, BDMC; 6, Groove; 7, Medium; 8, Mixing tank; 9, Magnetic separator)

Table 7. The results of extended tests using BDMC

Products	Yield (%)	Grade (%)		Recovery (%)	
		Pb	Zn	Pb	Zn
-1 mm	18.43	4.38	1.17	27.15	20.54
Floats	48.22	0.47	0.28	7.62	12.86
Sinks	22.44	6.47	2.62	48.83	55.99
-0.5 mm	10.91	4.47	1.17	16.40	12.16
Feed	100.00	2.97	1.05	100.00	100.00

4. Conclusions

It was promising to reject the gangue from a low-grade Pb-Zn sulfide ore using the BDMC. Mineralogical analyses showed that the sample contained 88.66% of gangue and 11.34% of valuable minerals. Poly-metallic sulphides, such as galena, sphalerite and pyrite, were unevenly distributed in the gangue in the form of compact aggregates, indicating that it was feasible to separate the gangue from the ore.

The crush size clearly affected the heavy liquid separation process. The increase in the particle size range from -13+1 to -20+1 mm was advantageous to the rejection of the gangue. A further increase in the particle size range resulted in an increase in the metal recoveries in the floats, and an increase in the amounts of coarse particles.

The medium SG, spigot diameter, tilt angle and cone angle had significant effects on the BDMC operation process, but the medium/ore mass ratio in the range of 4~12 seemed to have little effect. The optimal parameters were determined as follows: a medium SG of 2.20, a spigot diameter of 65 mm, a tilt angle of 15 degrees and a cone angle of 68 degrees. Under these conditions, 51.22% of the floats were obtained with a lead recovery of 7.92% and a zinc recovery of 12.50%. The results obtained in the extended tests further confirmed the results obtained in the laboratory experiments. In addition to the floats and sinks, products with particle sizes of -0.5 and -1 mm were simultaneously obtained from the proposed process.

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