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Preconcentration of a low-grade betafite ore by dense medium cyclone

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Abstract: In order to find an economical and feasible short process for betafite preconcentrating and to provide a reference for the development of similar low-grade uranium deposits, preconcentration of the betafite ore was investigated based on mineralogical characterization study, float-sink tests, and dense medium cyclone (DMC) separation experiments. The float-sink test results revealed that the gravity separation of the betafite ore was feasible, and the expected particle size range was chosen to be 3~0.3 mm. The effect of important parameters of the DMC experiment such as particle size, grade of the feed, separation density, and inlet pressure on the separation performance of betafite ore was studied. Under the optimal experimental conditions, the expanded experiments were performed and the heavy minerals contained 4557 ppm U and 5200 ppm Nb_2O_5 with a recovery of 88.86% and 79.73%, respectively, were obtained. Besides, the enrichment ratio (E) values of U and Nb_2O_5 were 14.24 and 12.78 severally, and the tailings discarding ratio (R) value was 93.76%. The results demonstrate that the preconcentration of low-grade betafite by DMC can remove a large number of tailings and obtain a high-grade uranium concentrate.

Keywords: preconcentration, betafite, dense medium cyclone, uranium, niobium

1. Introduction

Uranium is the basic raw material for nuclear power, which has the advantages of low greenhouse gas emissions and low electricity generation costs (Songqing et al., 2019; Yang et al., 2021). Up to now, most of the focus has been on uranium resources with high grade and ease of extraction such as uraninite (UO_2), pitchblende (U_3O_8), and coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$) (McMaster et al., 2015). However, as the number of high-grade uranium ore deposits has decreased in recent years, more and more attention has been paid to the processing of low-grade and refractory uranium-bearing minerals such as betafite (Nettleton et al., 2015).

Prior to hydrometallurgy, the tailings discarding pre-treatment of low-grade refractory uranium ore by mineral processing to improve the grade of uranium ore can effectively reduce the amount of ore and acid (alkali) consumption cost for subsequent hydrometallurgical treatment (Bhargava et al., 2015). In the 1980s, studies in the United States showed that the direct processing cost per pound of U_3O_8 can be saved by nearly half when the grade of U_3O_8 in the ore increases from 0.1% to 0.2% (Edwards and Oliver, 2000). Therefore, the use of mineral processing means to improve the grade of uranium ore before hydrometallurgy has been paid attention in many countries. At present, the mineral processing methods for different types of uranium ores mainly include radioactive sorting and conventional mineral processing (Chen, 1989). Radioactive sorting is mainly used for coarse tailings discarding of hard rock type uranium ores with uneven mineralization and low grade, which is currently adopted by many countries (Kidd and Wyatt, 1982; Lunt and El-Ansary, 2007). Conventional beneficiation methods mainly include gravity separation, magnetic separation, flotation, etc.

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A carbonatite-hosted U-Nb deposit in Huayangchuan is located in the Xiaofuyu-Huayangchuan-Huanglongpu metallogenic belt of the Lesser Qinling area, which is the first ultra-large hard rock type uranium-niobium-lead polymetallic deposit discovered in China (Bin-yue et al., 2018; Xue et al., 2020). It has the characteristics of large scale, multiple minerals, and low grade. The content of U in the ore is about 160 g/Mg ~ 300 g/Mg, and uranium mainly occurs in betafite, which is mainly scattered in the ore in star-shaped, irregular lumps and fine veins, and coexists with calcite, potash feldspar, aegirine, celestite, crystalline uranium ore in the form of mosaic, inclusion, and crystallization. The embedded particle size of betafite is mainly distributed in the range of 0.15~0.5 mm (SJ, 2020). Radioactive sorting is a method for the beneficiation of coarse-grained ores. Generally, the upper limit of ore size is 250~300 mm and the lower limit is 20~30 mm (Salter and Wyatt, 1991). Therefore, it is not suitable for Huayangchuan uranium polymetallic ore to subject to radioactive sorting. Meiyuan et al. (2005) used the method of jigging separation to discard tailings and high-intensity magnetic separation to recover betafite, discarding 80% tailings, but the enrichment ratio of uranium concentrate was below 5 (Mei-yuan, 2005). Songqing et al. (2020) conducted a study on the recovery of betafite by a combined process of chute gravity separation, magnetic separation, and flotation, and the enrichment ratio of uranium concentrate could reach 14-15 (Song-qin et al., 2020). However, the flotation-based process has problems such as long process, the large size of the flotation plant, difficulty in treating and reusing radioactive wastewater, and large-capacity tailing dam for storage and disposal of fine-grained tailings. This type of uranium ore has been lacking technical and economic reasonable preconcentration and tailings discarding methods to improve uranium enrichment ratio and tailings discarding rate.

Dense medium cyclone (DMC) has been widely used in mineral processing due to the advantages of large processing capacity, high separation efficiency, convenient operation, and easy automatic control (Chen et al., 2014; Yakup and Deniz, 2012; ZHAO et al., 2008). Since 1945, Dutch State Mines (DSM) has successfully developed the first DMC for separating fine coal, and the United States, Japan, Germany, Britain, France, the former Soviet Union, and other countries have developed DMC and applied it to industry. Nowadays, DMC has been proved to be an effective method that has been favourably applied in a variety of mineral plants for processing coal, iron ore, phosphate rock, lead-zinc ore, diamond, chromite, oil shale, and plastics, and so on (Aghlmandi Harzanagh et al., 2017; Chen et al., 2012; Dou et al., 2015; Ebtedaei and Farzanegan, 2020; Gent et al., 2018; Jian et al., 2019; Karami et al., 2019; Napier-Munn, 2017; Qi et al., 2015; Richard et al., 2011; Wang, 2009; Wei et al., 2011). However, to our knowledge, there is a little report of the application of DMCs in betafite beneficiation.

DMC has a relatively mature and extensive application in the field of coal preparation, but the usage of DMC in betafite may be quite different. Firstly, the properties of betafite differ significantly from those of coal, particularly in terms of density. The mineral density is much higher than that of coal, which increases the difficulty of configuring the dense medium suspension. The dense medium used in coal preparation is typically magnetite powder, whereas ferrosilicon powder should be used in betafite. These differences are significant in the performance of DMCs, especially in terms of the rheology and behavior of the medium (Napier-Munn, 2007). Secondly, coal has a simple mineral composition and low density, which allows for a relatively large space for density fluctuations of the dense media suspension, making it easy to separate; in contrast, the ore composition of the Huayangchuan uranium polymetallic ore is complex, and the specific gravity of some minerals is similar, necessitating precise configuration of the suspension density to achieve separation (SJ, 2020). Finally, because of the large concentration of dense medium suspension in the MDC, the motion law of betafite mineral particles differs significantly from that of coal (He et al., 2001). As a result, a comprehensive investigation of the separation performance of low-grade betafite ore by DMC is required.

In this study, the separation effect of DMC on low-grade niobium-titanium uranium ore was systematically studied according to the process mineralogy characteristics of the ore. And, the purpose of this study was to find an economical and feasible short process for betafite preconcentrating and to provide a reference for the development of similar low-grade uranium deposits. To achieve this goal, the float-sink tests were carried out to evaluate the feasibility of the density separation of betafite ore. Subsequently, the DMC tests were conducted on the preconcentration of the betafite ore, and the effects of several parameters such as particle size and grade of the feed, separation density, inlet pressure were investigated in detail, and then the optimal parameters were determined. Furthermore, the expanded experiments were developed using a 250 mm DMC with a processing capacity of 18.0 Mg/h. The objective was to demonstrate the separation performance of DMC on betafite preconcentration.

2. Materials and methods

2.1. Materials

The representative ore samples used in this study were obtained from the Huayangchuan deposit. It was originally crushed to less than 10 mm by a jaw crusher for the following experiments. The particle size distribution and U, Nb_2O_5 contents of the samples are shown in Table 1, and the cumulative particle size distribution is illustrated in Fig. 1, indicating that d_{50} and d_{80} (particle size at 50% and 80% cumulative undersize) of the samples are 4.07 mm and 6.77 mm, respectively. The chemical analysis of the samples is given in Table 2. X-ray diffraction patterns obtained using a Rigaku SmartLab X-ray diffraction spectrometer employing a graphite-filtered Cu Kα radiation (λ =1.5406 Å), operated at 40 kV and 40 mA with the scanning rate of 5°/min from 2° to 80°, are shown in Fig. 2. The distribution characteristics of betafite ore and the associated relationship of other minerals, as determined by the Mineral Liberation Analyzer (MLA 650F), are shown in Fig. 3.

Table 1. Particle size distribution and U, Nb_2O_5 contents of the samples

Size Fraction (mm)	Yield (%)	Grade (ppm)		Distribution Rate (%)	
		U	Nb_2O_5	U	Nb_2O_5
-10+5	40.51	47	73	8.26	9.4
-5+3	20.54	359	433	31.87	28.19
-3+2	4.25	296	392	5.44	5.28
-2+1	8.88	243	341	9.33	9.6
-1+0.5	6.07	556	697	14.59	13.41
-0.5+0.3	2.42	672	885	7.03	6.79
-0.3+0.15	6.08	505	653	13.27	12.58
-0.15+0.10	1.05	306	443	1.39	1.47
-0.10+0.074	2.82	239	379	2.92	3.39
-0.074	7.38	185	423	5.90	9.89
Raw ore	100.00	231	315	100.00	100.00

Table 2. Chemical analysis of ore samples (wt %)

U*	Nb_2O_5*	REO	TiO_2	Pb	TFe	Mn	P_2O_5	S
198	288	0.079	0.23	0.61	2.61	0.16	0.15	0.66
K_2O	Na_2O	CaO	MgO	Al_2O_3	SiO_2	BaO	SrO	Ag
4.82	1.44	6.87	0.78	8.93	61.87	1.91	0.89	0.0004

* ppm

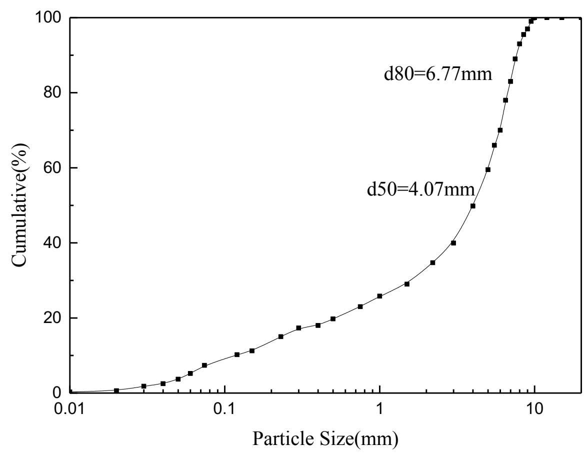

Fig. 1. The cumulative particle size distribution of samples

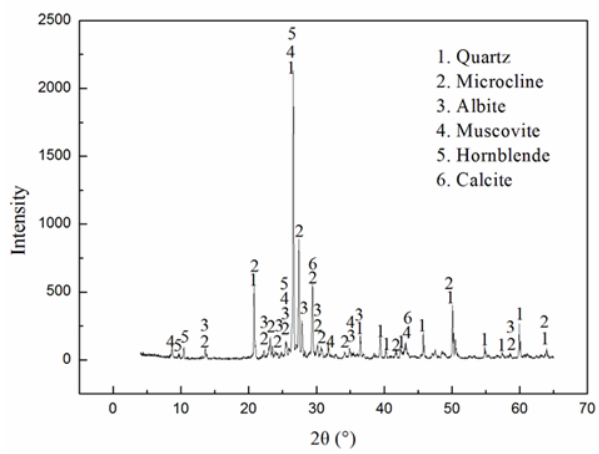

Fig. 2. X-ray diffraction patterns for ore sample

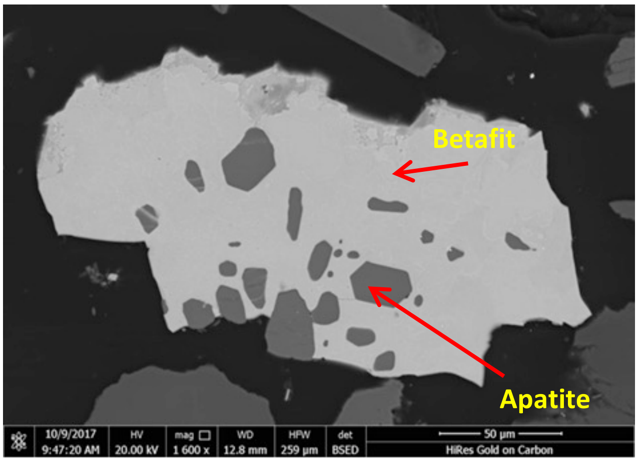

Fig. 3. MLA back-scattered electron image of betafite ore

2.2. Float-sink tests

Float-sink experiments were performed to evaluate the feasibility of gravity separation and DMC separation. According to the density difference of the valuable minerals and gangue minerals, heavy liquids of different densities, which prepared from tetrabromoethane (SG=2.97) and naphthalene bromide (1.48) were adopted as separating medium using in heavy liquid separation tests. At first, one part of the samples was sieved to give several size fractions and remove particles smaller than 0.1 mm, and then each size fraction was subjected to float-sink tests shown in Fig. 4. In the float-sink tests, each size fraction was placed in a large beaker filled with heavy liquid, respectively, standing and stratified. After that, the heavy minerals and light minerals were removed, washed and dried, weighed, analyzed for uranium and niobium, and the recoveries of metals were calculated. Finally, according to these experimental results, the suitability of gravity separation on the betafite ore was assessed.

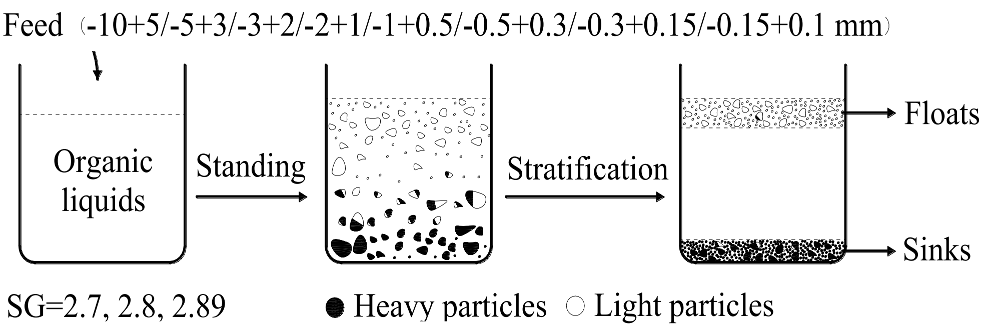

Fig. 4. Schematic diagram of float-sink tests

2.3. DMC separation experiments

In order to investigate the feasibility of preconcentration of a low-grade betafite ore from Huayangchuan deposit by using DMCs. The real ore separation experiments were conducted with a 250 mm gravity-fed two-product DMC, and the schematic flow chart is shown in Fig. 5. Ferrosilicon powder was used as a dense medium with a density of 6.8 g/cm^3, and the suspension density was adjusted to 2.2 to 2.9 g/cm^3 by Eq. (1) (Amini et al., 2016).

$$P = \frac{\delta_{\mathrm{dm}}(\delta_{\mathrm{su}}-1)}{\delta_{\mathrm{dm}}-1} V \tag{1}$$

where P is the weight of dense medium (Kg), δ_{dm} and δ_{su} refer to the specific gravity of medium and suspension, respectively, V represents the volume of the suspension (L).

In the separation process of gravity-fed DMC, the heavy medium with a certain specific gravity was pumped tangentially at the bottom of the 250 mm diameter separating chamber under a certain pressure to provide sufficient velocity and centrifugal force. The medium flow begins to form an upward external spiral flow along the inner wall of the cyclone from the inlet, and part of the medium flow forms a downward internal spiral flow near the cyclone axis. Betafite ore to be separated by density is fed into the upper feed inlet by gravity. The heavy minerals move to the wall of the cyclone with the external spiral flow due to the effect of centrifugal force and are discharged from the underflow port, while light minerals are discharged from the overflow port with the internal spiral flow. Both underflow products and overflow products were composed of minerals and dense medium (ferrosilicon powder), ferrosilicon powder was removed by sieve bend and sculping screen, and then recycled by magnetic separation. Finally, the heavy minerals and light minerals were obtained.

Dense medium separation is completed by using density difference of minerals in centrifugal force field based on Archimedes principle, and the centrifugal force (F) of materials in suspension can be calculated by Eq. (2).

$$F = V(\delta - \rho_{su})\frac{V_t^2}{r} \tag{2}$$

where V is the volume of the material (cm^3), δ and ρ_{su} are the density of the material and suspension, respectively (g/cm^3), V_t is the tangent velocity of the material at the rotation radius r (cm/s), r is the rotation radius of the material (cm).

When $\delta > \rho_{su}$, F value is positive, the materials will be centrifuged in the suspension and moved outward. Inversely, $\delta < \rho_{su}$, F value is negative, the materials will be centripetal in the suspension and concentrated in the inner layer. Moreover, in the process of DMC separation, the centrifugal force tending to separate heavy minerals and light minerals is much greater than gravity. Therefore, the heavy minerals and light minerals can be separated properly.

The separation performance was characterized by the mineral processing recovery (ε), enrichment ratio (E), and tailings discarding ratio (R) in float-sink tests and DMC tests, as presented below.

$$\varepsilon = \frac{Q_1\beta}{Q_0\alpha} \times 100 \tag{3}$$

$$E = \frac{\beta}{\alpha} \tag{4}$$

$$R = \frac{Q_0 - Q_1}{Q_0} \times 100\% \tag{5}$$

where Q_1 and Q_0 refer to the mass of heavy minerals and raw ore, respectively (g); β and α represent the grade of metal in heavy minerals and raw ore, respectively (wt%).

3. Results and discussion

3.1. Characteristic of ore sample

As can be seen in Table 1, compared with other size fractions, the -10+5 mm size fraction accounts for 40.51 wt% of the total sample, which contains 47 ppm U and 73 ppm Nb_2O_5 with the distribution rate of 8.26% and 9.40%, respectively. The results show that it is feasible to discard tailings at a coarse size. Table 2 presents the chemical composition of the sample, indicating that the main components are SiO_2 (61.87%), Al_2O_3 (8.93%), CaO (6.87%), K_2O (4.82%), and TFe (2.61%), and other components are less than

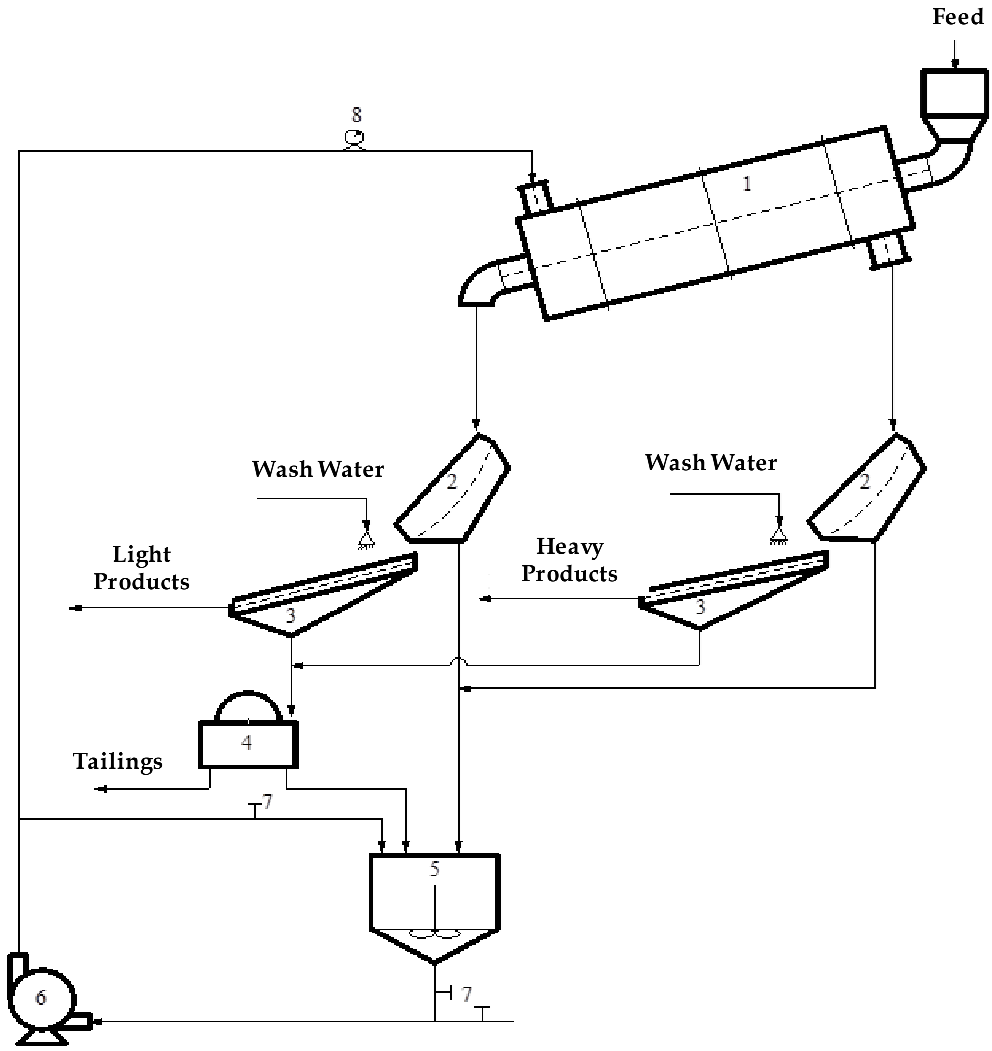

Fig. 5. Schematic diagram of betafite preconcentration using DMC (1, Gravity-fed two-product DMC; 2, Sieve bend; 3, Sculping screen; 4, Low-intensity magnetic separators; 5, Agitating vessel; 6, Pump; 7, Valve; 8, Pressure gauge)

2%. It can be noted that the contents of uranium and niobium oxide are 198 ppm and 288 ppm, respectively, indicating that the deposit is a low-grade uranium- niobium ore.

The X-ray diffraction patterns shown in Fig. 2 reveal that major minerals are quartz, microcline, calcite, albite followed by magnetite, hornblende, barite, muscovite, celestite, and limonite. The mineral composition and content of the ore sample were analyzed by MLA, and the analysis results are shown in Table 3. The results indicate betafite $(Ca, U)_2(Ti, Nb)_2O_6(OH)$ accounting for 0.13%, is the major (U, Nb)-bearing mineral in the Huayangchuan deposit, which is not reflected in the performed X-ray diffraction pattern for the content below the detection limit of XRD.

Table 3. The mineral composition and content of the ore sample (wt %)

Mineral	betafite	plumbobetafite	thorite	uraninite	fergusonite	galena	cerussite	celestite
Content	0.13	0.03	0.01	bit	trace	0.35	0.54	1.71
Mineral	orthite	monazite	barite	strontianite	magnetite	limonite	pyrite	calcite
Content	0.31	0.03	2.41	0.52	2.5	0.92	0.48	11.89
Mineral	albite	potash feldspar	quartz	hornblende	biotite	muscovite	apatite	sphene
Content	11.86	25.18	34.34	2.48	1.78	0.51	0.42	0.5
Mineral	chlorite	zircon	ilmenite	garnet	plagioclase	-	-	-
Content	0.65	0.04	0.01	0.25	0.15	-	-	-

3.2. Feasibility evaluation of gravity separation

3.2.1. Narrow range particle size tests

In order to assess the suitability of gravity separation on betafite ore, float-sink tests were separately carried out at different size fractions in separation density of 2.89 g/cm^3 for a more detailed study. The results of the float-sink tests for each size fraction are presented in Table 4.

Table 4. Results of float-sink tests on different size fractions in separation density of 2.89 g/cm^3

Size Fraction (mm)	Products	Yield (%)	Grade (ppm)		Distribution Rate (%)	
			U	Nb_2O_5	U	Nb_2O_5
-10+5	Sinks	2.27	101	143	4.96	4.32
	Floats	97.73	45	74	95.04	95.68
	Feed	100.00	46	75	100.00	100.00
-5+3	Sinks	5.72	1260	1535	58.56	49.90
	Floats	94.28	54	94	41.44	50.10
	Feed	100.00	123	176	100.00	100.00
-3+2	Sinks	9.07	2151	2956	71.17	68.12
	Floats	90.93	87	138	28.83	31.88
	Feed	100.00	274	394	100.00	100.00
-2+1	Sinks	9.38	4280	4939	86.93	80.73
	Floats	90.62	67	122	13.07	19.27
	Feed	100.00	462	574	100.00	100.00
-1+0.5	Sinks	11.90	4579	5685	91.20	88.48
	Floats	88.10	60	100	8.80	11.52
	Feed	100.00	597	765	100.00	100.00
-0.5+0.3	Sinks	15.65	4468	5667	94.62	91.16
	Floats	84.35	47	102	5.38	8.84
	Feed	100.00	739	973	100.00	100.00
-0.3+0.15	Sinks	17.14	2881	3666	93.01	86.93
	Floats	82.86	45	114	6.99	13.07
	Feed	100.00	531	723	100.00	100.00
-0.15+0.10	Sinks	15.44	1566	2111	89.91	78.59
	Floats	84.56	32	105	10.09	21.41
	Feed	100.00	269	415	100.00	100.00

As shown in Table 4, it is found that the sinks (heavy products) in the -10+5 mm size fractions contained 101 ppm U and 143 ppm Nb_2O_5 with a recovery of 4.96% and 4.32%, respectively. Theoretically, the poor separation performance of the -10+5 mm size fractions is due to insufficient mineral liberation of valuable minerals. Comparatively speaking, when the particle size range decreases from -10+5 mm to -5+3 mm, the grade of U and Nb_2O_5 increases from 101 ppm and 143 ppm to 1260 ppm and 1535 ppm, respectively, whilst the recovery of U and Nb_2O_5 increases from 4.96% and 4.32% to 58.56% and 49.90%, respectively. The *E* values of U and Nb_2O_5 are 10.24 and 8.72, respectively, and the R-value is 94.28%. It is observed that the separation performance is greatly improved by increasing mineral liberation. Whereas the recovery rates of U and Nb_2O_5 are relatively low and it indicates that mineral liberation is still incomplete.

As the particle size range further decreases to -3+2 mm, the results of sinks show similar trends to those seen in the -5+3 mm size fractions, and the contents and recovery rates of U and Nb_2O_5 are higher than those of -5+3 mm size fractions. It is noted that when the size fractions varied from -2+1 mm, -1+0.5 mm, -0.5+0.3 mm to -0.3+0.15 mm, the contents of U and Nb_2O_5 in sinks are varied in the range of 2881 ppm~4579 ppm and 3666 ppm~5685 ppm, respectively, and the recovery rates are varied in the range of 86.93%~94.62% and 80.73%~91.16%, respectively, whilst the R values are mainly concentrated in 90.62%~82.86%. Meanwhile, the float-sink tests of the -3+0.15 mm size fractions show satisfactory separation performance of gravity separation.

Based on the float-sink test of -0.15+0.1 mm size fractions, the results display that the sinks contained 1566 ppm U and 2111 ppm Nb_2O_5 with a recovery of 89.91% and 78.59%, respectively. Both the grade and recovery of U and Nb_2O_5 are beginning to decrease, indicating that the separation efficiency of fine particles is deteriorating.

A further float-sink test was performed at combined size fractions of 3-0.15 mm to evaluate the adaptability of gravity separation to betafite ore in a wide size range. Table 5 displays the results of float-sink tests of -3+0.15 mm size fractions in separation density of 2.89 g/cm^3. The sinks contained 3026 ppm U and 3882 ppm Nb_2O_5, as shown in Table 5, with a recovery of 87.09% and 83.24%, respectively. It still indicates a high level of separation performance.

Table 5. Results of float-sink tests of -3+0.15 mm size fractions in separation density of 2.89 g/cm^3

Size Fraction (mm)	Products	Yield (%)	Grade (ppm)		Distribution Rate (%)	
			U	Nb_2O_5	U	Nb_2O_5
-3+0.15	Sinks	12.14	3026	3882	87.09	83.24
	Floats	87.86	62	108	12.91	16.76
	Feed	100	422	566	100.00	100.00

3.2.2. Separation density tests

Float-sink tests with different separation densities were conducted to study the response of the -3+0.5 mm size fractions to the gravity separation, and the results are shown in Table 6 which depicts the variation of the grades and recoveries of U and Nb_2O_5 with the change of separation density. It is seen that when separation density varies from 2.70 g/cm^3, 2.80 g/cm^3, 2.89 g/cm^3, to 2.97g/cm^3, the metal grade in the sinks is increased and the metal recovery rate is slightly decreased. When the separation density is 2.89 g/cm^3, the sinks containing 3620 ppm U and 4082 ppm Nb_2O_5 with a recovery of 81.00% and 79.71%, are obtained. Uranium and niobium are well enriched and recovered. Therefore, it can be concluded that gravity separation of the betafite ore is feasible. And the separation density can be determined to be 2.89 g/cm^3.

Table 6. Results of float-sink tests of -3+0.5 mm size fractions at different separation densities

Size Fraction (mm)	Products	Yield (%)	Grade (ppm)		Distribution Rate (%)	
			U	Nb_2O_5	U	Nb_2O_5
2.70	Sinks	15.85	1610	1860	81.90	80.96
	Floats	84.15	67	82.4	18.10	19.04
	Feed	100.00	311.53	364.11	100.00	100.00
2.80	Sinks	8.38	3146	3710	81.37	80.76
	Floats	91.62	65.9	80.9	18.63	19.24
	Feed	100.00	324.14	385.16	100.00	100.00
2.89	Sinks	7.02	3620	4082	81.00	79.71
	Floats	92.98	64.1	78.4	19.00	20.29
	Feed	100.00	313.62	359.33	100.00	100.00
2.97	Sinks	6.52	3776	4227	80.01	79.38
	Floats	93.48	65.8	76.6	19.99	20.62
	Feed	100.00	307.74	347.25	100.00	100.00

3.3. Separation performance of DMC

3.3.1. Effect of feed particle size range

The lower size limit of DMC for coal preparation is generally accepted to be 0.5 mm. However, in order to improve the betafite ore processing ratio, it is necessary to study the influence of the change of the lower size limit on DMC separation performance. DMC tests in different particle size ranges were carried out under these conditions, the upper size limit of 3 mm, separation density of 2.89 g/cm^3, and inlet pressure of 0.14 MPa, and the results are presented in Fig. 6.

It can be seen from Fig. 6 that although the grades of U and Nb_2O_5 decrease with a decrease in the lower size limit, both U and Nb_2O_5 recoveries increase, which is conducive to improving the ore processing ratio and valuable metals recoveries. Moreover, the discarding amount of tailings in each particle size range is above 94%. When the particle size range varies from 3~0.3 mm to 3~0.15 mm, the grade of U and Nb_2O_5 reduce from 5352 ppm and 6592 ppm to 4303 ppm and 5590 ppm, respectively. While the recoveries of U and Nb_2O_5 increase from 78.86% and 74.05% to 79.21% and 74.85%, which are not obvious. Therefore, the expected particle size range was chosen to be 3~0.3 mm, and all the following experiments were carried out in this particle size range.

It reveals that the separation performance begins to deteriorate when the particle size becomes smaller than 3~0.3 mm. Because of their slower settling rates, fine particles generally separate less efficiently than coarse (Wills et al., 2015). The separation performance of fine particles is more sensitive to changes in medium rheology (He et al., 1994) and it is thought that there is a size below which the recovery efficiency for the smaller particles begins to drop "significantly" (De Korte et al., 2014). This is referred to as the 'breakaway' size because it is the smallest size that can be processed efficiently in a specific cyclone under certain conditions (Napier-Munn, 2007).

3.3.2. Effect of the separation density

Separation density is one of the most important factors affecting DMC separation performance (Vakamalla et al., 2015). Hence, the effects of different separation densities on the separation performance of DMC were investigated under the conditions of the particle size range of 3~0.3 mm and inlet pressure of 0.14 MPa, and the results are shown in Fig. 7.

Analysis of the results obtained from Fig. 7 indicates that when the separation density increases from 2.23 g/cm^3 to 2.65 g/cm^3, both the grade and recovery of valuable metals are improved. However, once the separation density increases to 2.79 g/cm^3, the recovery of valuable metals decreases, which may be explained by the fact that the higher the separation density (ferrosilicon content is higher), the higher viscosity affects the performance of the DMC. While the R-value increases from 82.26% to 95.12% with the separation density ranging from 2.23 g/cm^3 to 2.79 g/cm^3 and then tends to be stable. Based on the data shown in Fig. 7, the optimum separation density can be selected as 2.65 g/cm^3.

It has to be noted that the separation density of 2.65 g/cm^3 from DMC tests is lower than that of 2.89 g/cm^3 obtained from the float-sink tests. In the dynamic separation of DMCs, the considerable centrifugal force acts not only on the mineral particles to be separated but on the medium as well, which causes uneven distribution of suspension density in the cyclone for the strong concentration effect. The tangential velocity distribution reveals that the suspension density increases with increasing radius from the cyclone center to the wall (Cui et al., 2016; Shen et al., 2009), and the density of the medium flowing with the external spiral flow (heavy minerals) is significantly higher than that of the inlet, conversely, the density of the medium with the internal spiral flow (light minerals) is significantly lower than that of the inlet. That is to say, the real separating density is between overflow density and underflow density, and higher than that of the inlet. Therefore, a higher separation density can be achieved by using a lower medium density.

3.3.3. Effect of the inlet pressure

The level of pump pressure directly affects the stability of the internal flow field of the cyclone and the separation performance of DMC. Therefore, the effect of inlet pressure on the separation performance of DMC was studied under the conditions of the particle size range of 3~0.3 mm and separation density of 2.65 g/cm^3, as shown in Fig. 8. As seen from Fig. 8, the grade and recovery of valuable metals increase slowly with the increase of inlet pressure from 0.10 MPa to 0.17 MPa, and the R-value remains at a high level above 94%. When the inlet pressure reaches above 0.14 MP, there is little difference in separation performance of DMC as the pressure increases (Liu et al., 2018). Thus, the optimal inlet pressure can be 0.14 MPa. At this level, the grades of U and Nb_2O_5 are 4693 ppm and 5626 ppm with the recovery of 77.08% and 72.56%, respectively.

3.3.4. Effect of the grade of feed

Ore grade is vital to the economic feasibility of ore mining and processing costs. It is apparent from Fig. 9, which shows the effect of ore grade on DMC separation performance, that when the ore grade increases from 110 ppm U to 430 ppm U, the grade and recovery of valuable metals in heavy minerals are significantly improved. On the other hand, although the *R*-value presents a very slow downward trend, it is kept at a high level of more than 94%. The results demonstrate that the higher the feed grade, the better the economic feasibility.

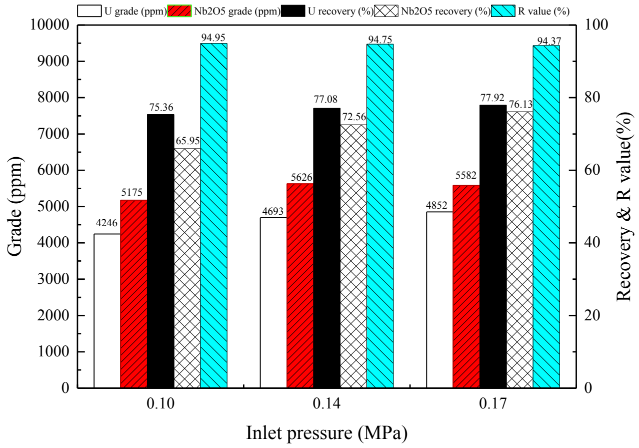

Fig. 6. The effect of particle size range on DMC separation performance

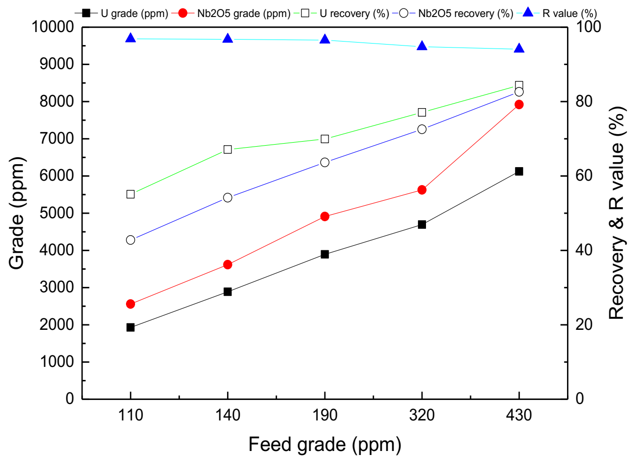

Fig. 7. The effect of separation density on DMC separation performance

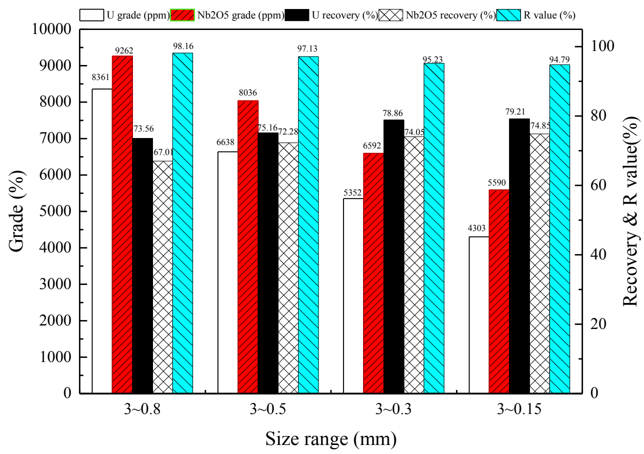

Fig. 8. The effect of inlet pressure on DMC separation performance

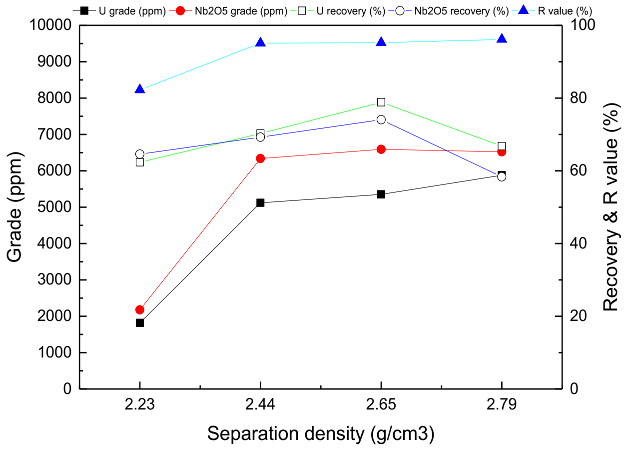

Fig. 9. The effect of ore grade on DMC separation performance

3.4. Expanded experiments of gravity-fed two-product DMC

In order to verify the feasibility of DMC separation on betafite preconcentration, expanded experiments were performed using a 250 mm gravity-fed two-product DMC with a processing capacity of 18.0 Mg/h. Operating conditions for betafite preconcentration were: particle size range of 3~0.3 mm, separation density of 2.65 g/cm^3, the inlet pressure of 0.14 Mpa and feed grade of 320 ppm U. The results are presented in Table 7. As seen, the heavy minerals contained 4557 ppm U and 5200 ppm Nb_2O_5 with a recovery of 88.86% and 79.73%, respectively, were obtained. The E values of U and Nb_2O_5 are 14.24 and 12.78 respectively, and the R-value is 93.76%. The results demonstrate that the gravity-fed two-product DMC has good separation performance for betafite preconcentration.

Table 7. Expanded experimental results of betafite preconcentration by DMC

Size Fraction (mm)	**Yield (%)**	**Grade (ppm)**		**Distribution Rate (%)**	
		U	**Nb_2O_5**	**U**	**Nb_2O_5**
Heavy minerals	6.24	4557	5200	88.86	79.73
Light minerals	93.76	38	88	11.14	20.27
Feed	100.00	320	407	100.00	100.00

3.5. Mineralogical composition of DMC products

The Mineral Liberation Analyzer (MLA) was used to determine the mineralogical composition of heavy products and light products. The compositions of heavy products are shown in Table 8 and Fig. 10(a). The results show that the compositions of heavy products are mainly barite, calcite, galena, and betafite, and most of the betafite have been dissociated from a monomer or in the form of rich association as shown in Fig. 10(b).

Table 8. The mineral composition and content of heavy products (wt %)

Mineral	betafite	plumbobetafite	thorite	uraninite	fergusonite	galena	cerussite	celestite
Content	2.16	0.12	0.1	0.01	trace	9.37	13.44	1.09
Mineral	orthite	monazite	barite	strontianite	magnetite	limonite	pyrite	calcite
Content	0.93	0.08	42.15	4.44	2.58	1.12	2.94	3.47
Mineral	albite	potash feldspar	quartz	hornblende	biotite	muscovite	apatite	sphene
Content	11.99	4.27	4.86	2.14	0.42	0.06	0.37	0.7
Mineral	chlorite	zircon	ilmenite	garnet	plagioclase	-	-	-
Content	0.14	0.06	0.04	0.46	0.02	-	-	-

The compositions of light products are shown in Table 9 and Fig. 11(a). The results show that the compositions of light products are mainly gangue minerals like quartz, potash feldspar, albite, and calcite, and the content of useful minerals such as betafite is very low, and most of them are monomer dissociation as seen in Fig. 11(b). The best separation performance of DMC on betafite preconcentration was further verified.

Table 9. The mineral composition and content of light products (wt %)

Mineral	betafite	plumbobetafite	thorite	uraninite	fergusonite	galena	cerussite	celestite
Content	0.03	0	0.01	0	trace	0.01	0.15	0.04
Mineral	orthite	monazite	barite	strontianite	magnetite	limonite	pyrite	calcite
Content	0.7	0.01	1.08	0.07	0.91	1.15	0.02	15.17
Mineral	albite	potash feldspar	quartz	hornblende	biotite	muscovite	apatite	sphene
Content	12.86	29.9	31.97	2.36	1.8	0.57	0.24	0.29
Mineral	chlorite	zircon	ilmenite	garnet	plagioclase			
Content	0.29	0.03	0.02	0.08	0.19			

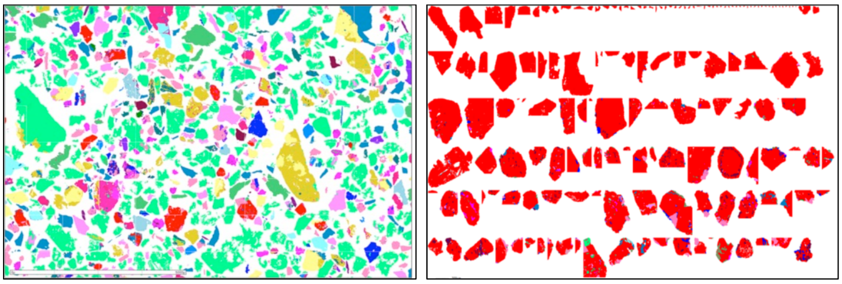

Fig. 10. MLA image of (a) heavy products of DMC tests (b) of betafite particles

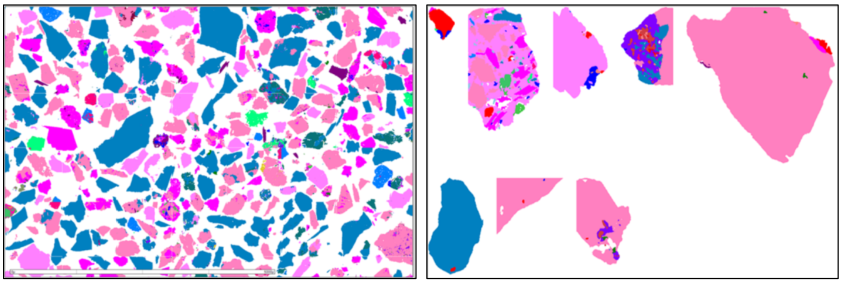

Fig. 11. MLA image of (a) light products of DMC tests (b) of betafite particles

4. Conclusions

The preconcentration of a low-grade betafite ore by DMC was investigated. Mineralogical characterization of the betafite ore indicates that it is feasible to discard tailings at a coarse size. Float-sink test results show that the gravity separation of the betafite ore is suitable. Based on the results of DMC experiments, the optimal parameters were determined as below: particle size range of 3~0.3 mm, separation density of 2.65 g/cm^3, the inlet pressure of 0.14 Mpa. Under these conditions, expanded experiments were performed using a 250 mm gravity-fed two-product DMC for betafite preconcentration， and the heavy minerals contained 4557 ppm U and 5200 ppm Nb_2O_5 with a recovery of 88.86% and 79.73%, respectively, were obtained. Besides, the *E* values of U and Nb_2O_5 are 14.24 and 12.78 respectively, and the *R*-value is 93.76%. The results demonstrate that the preconcentration of low-grade betafite by DMC can remove a large number of tailings and obtain a high-grade uranium concentrate. The process of preconcentration of a low-grade betafite ore by DMC has the advantages of the short process and good separation and enrichment effect.

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