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Aerosol flotation of low-grade refractory molybdenum ores

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Abstract: The characteristics of aerosol flotation, which include the effect of the concentration and particle size of kerosene aerosol on the molybdenum (Mo) flotation index and the effect of kerosene aerosol dosing method on the kerosene dosage and flotation time, were studied in the flotation of low-grade refractory molybdenum ores using kerosene aerosol. The results revealed that the particle size and concentration of kerosene aerosol had little effect on the Mo grade but had significant effect on the Mo recovery. A smaller particle size and a lower concentration of kerosene aerosol were beneficial to the Mo aerosol flotation. For the received Mo ore samples, the optimized particle size of kerosene aerosol was 0.3-2 μm and the optimized aerosol concentration was 14 mg/L. The compressed air atomizer had a more uniform distribution of aerosol particles than the ultrasonic atomizer, and the aerosol concentration was controlled easily, so the compressed air atomizer was more suitable for the research of aerosol flotation. Compared with conventional flotation in which kerosene was directly added into the ore pulp, the flotation time was reduced by ~30%, and the dosage was decreased by ~20% in aerosol flotation, while the Mo flotation index was similar.

Keywords: molybdenum ore treatment; flotation; kerosene; aerosols; particle size

1. Introduction

Hidy [1], Lu [2], and Wang and Zhang [3] mentioned that aerosols refer to a multiphase decentralized system, where solid particulates and/or liquid particulates suspend in the gas medium. This decentralized system consists of two parts: one is the suspended particulates and the other is the gas dispersion medium [4-8]. The aerosol test group of Liaoning Metallurgy Institute [9] and Xu *et al.* [10] mentioned that aerosol flotation [11-15] could be understood that a flotation reagent (such as frother and collector) is added in the aerosol form during flotation. Generally, the above-mentioned gas medium is air. In fact, aerosol dosing method is applied in flotation to improve the effect of flotation reagents, accelerate the flotation speed, reduce the reagent consumption, and heighten the flotation index. Aerosol flotation technology can improve the flotation effects of sulfide ores, oxidized ores, and complex refractory ores.

Characterization parameters of aerosols abound. However, concentration and particle size are the most basic characteristic parameters of aerosols. They are the basis of the aerosol mechanics. Despite researches on the formation or the motion law of aerosols and researches about the various technologies of aerosols (such as sampling techniques, measurement technology, purification technology, ventilation, and dust control technology) or the various effects of aerosols (such as biological effect and atmospheric environmental effect), the above-mentioned two characterization parameters are studied necessarily. Therefore, aerosol flotation technology that utilizes aerosol properties is associated with these two characterization parameters of aerosol. In view of this, it is necessary to research the effect of the concentration and particle size of aerosols on the aerosol flotation index.

At present, the application of aerosol flotation technology in low-grade refractory molybdenum ores is little. This study focuses on the characteristics of aerosol flotation, including the effect of the concentration and particle size of kerosene aerosol on the aerosol flotation index of low-grade refractory molybdenum ores and the effect of kerosene

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aerosol dosing method on the kerosene dosage and flotation time.

2. Experimental

2.1. Materials

The multi-element analysis of the raw ore was performed and the results are shown in Table 1. It shows that the grade of molybdenum is only 0.062wt%. The contents of other elements that can be utilized comprehensively are low, excluding copper and sulfur. There also exists a small quantity of harmful element arsenic in the ore.

Table 1. Main chemical composition of the ore wt%

Mo	Cu	S	Fe	Pb	Zn
0.062	0.21	0.74	2.58	0.011	0.014
As	C	SiO_2	Al_2O_3	CaO	MgO
0.014	0.091	73.25	13.04	0.15	0.33
K_2O	Na_2O	Au*	Ag*		
0.95	0.33	0.04	3.24		

Note: * Au and Ag in g/t.

The phase analysis results of molybdenum are given in Table 2. The results show that the majority of molybdenum exists in molybdenum sulfide. The oxidation rate of molybdenum is high, which reaches 10.00%.

According to the results of microscope identification and X-ray diffraction analysis, the mineral composition of the ore is complex, and the elements of copper, molybdenum, and sulfur in the ore mainly exist as independent minerals. The independent minerals of copper include chalcopyrite, bornite, bluechalcocite, covellite, and tennantite; the independent minerals of molybdenum mainly exist in the form of molybdenite; and the independent mineral of sulfur is pyrite. Gangue minerals mainly include quartz, muscovite, feldspar, illite, kaolinite, etc., and the content of quartz is the highest in the gangue.

Table 2. Phase compositions of the ore

Phase	Content / wt%	Fraction / %
Molybdenum sulfide	0.0558	90.00
Molybdenum oxide	0.0062	10.00
Total	0.0620	100.00

The ore belongs to the low-grade refractory ore for molybdenum overall.

2.2. Devices and instruments

The ultrasonic atomizer aerosol flotation device is shown in Fig. 1. The compressed air atomizer aerosol flotation device is shown in Fig. 2.

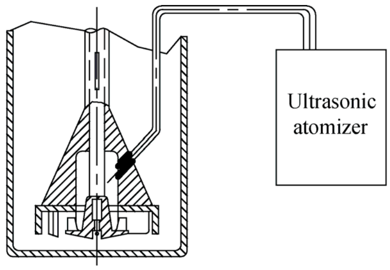

Fig. 1. Scheme of the ultrasonic atomizer aerosol flotation device.

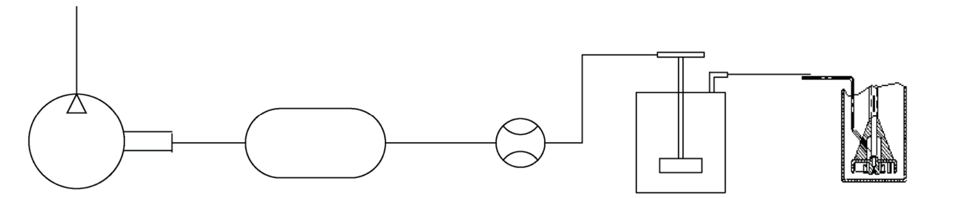

Fig. 2. Scheme of the compressed air atomizer aerosol flotation device.

In addition, the common glass apparatus for laboratory, pH meter, LAP-321 aerosol spectrometer, electronic analytical balance, and flotation equipment were also used in the test.

2.3. Primary flotation flowchart

The primary flotation flowchart is shown in Fig. 3.

2.4. Aerosol generator and measuring equipment

An ultrasonic humidifier (type: YC-E310B) was refitted as the ultrasonic atomizer. The working principle of the ultrasonic atomizer is that ultrasonic, which is from a piezoelectric crystal, is gathered in the liquid surface, the capillary wave is formed on the surface of the liquid, and then the fluid are shattered into the aerosol by the cavitation of the liquid surface. The droplet size depends on the frequency of the piezoelectric crystal.

The working principle of the Collison nozzle aerosol generator (type: CN-31) is that compressed air squirts at a certain speed from the Collison nozzle, and Bernoulli effect [16] produces low pressure in the nozzle exit, so the liquid in storage is inhaled in airflow and is shattered into an aerosol. The aerosol squirts to a surface directly, the larger particles disappear through collision at the surface, and the smaller particles stay in the airflow.

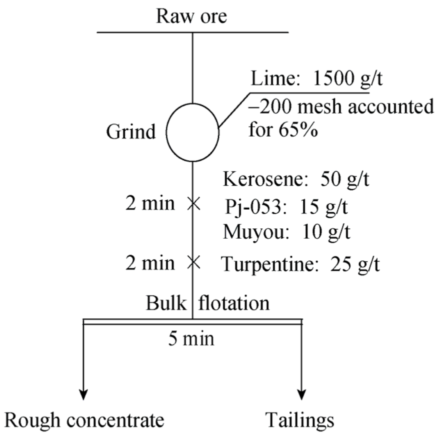

Fig. 3. Primary flotation flowchart.

Measuring the light scattering intensity of single particles is an efficient optical method to determine the particle size in a wide range. The laser aerosol particle size spectrometer (type: LAP-321) is a measuring instrument that determines the particle size distribution and concentration based on the principle of single particle measurement. The applied principle of this method is the physical effect that particles exposed to the light of a particular wavelength produce a certain scattered light signal depending on their size. The scattered light signals of the particles are converted to pulses and these are assigned to certain particle size classes. Using this method can gain information about the particle size distribution and at the same time measure the particle number concentration. The laser aerosol particle size spectrometer can provide results with high resolution and accuracy. The measurement software is PASWin software.

2.5. Method

In the aerosol flotation process, kerosene, the primary collector of molybdenum, was added into the ore pulp in the aerosol form, and other reagents were added according to a conventional dosing method, in which flotation reagents are added into the pulp directly. The effect of the concentration and particle size of kerosene aerosol on the aerosol flotation was studied by analyzing the flotation index of molybdenum. In addition, the kerosene dosage and flotation time were also studied in the aerosol flotation of the molybdenum ore.

Kerosene aerosol was added into the pulp through the air pipe of a flotation machine by self-suction produced from impeller rotation. In the flotation process, first, the collectors were added into the pulp other than kerosene; second, the frothing agent was added; finally, kerosene aerosol was added and the addition of kerosene aerosol and flotation were carried out simultaneously. The reason why the frothing agent was added in front of kerosene is to provide a good bubble environment for kerosene aerosol dosing, which is beneficial to mass transfer of kerosene aerosol in gas phase. All tests were performed at room temperature (25°C or so).

3. Results and discussion

3.1. Effect of aerosol particle size

3.1.1. Measurement of aerosol particle size

The kerosene aerosol of two different particle sizes was produced by the ultrasonic atomizer and Collison nozzle aerosol generator, respectively. In order to ensure the accuracy of measurement, the measurement tests of aerosol particle size were performed in a clean room.

The measurement method of kerosene aerosol particle size is that, first, the particle size distribution of the clean room was measured with a laser aerosol particle size spectrometer; thus, the background value of the clean room was obtained, and the kerosene aerosol particle sizes were measured afterwards. The settling time was 5 s, the rate of gas flow was 3 L/min, every time the sampling time was 30 s, and the pause time after sampling was 5 s.

(1) Particle background value analysis of the clean room.

The results of the test are shown in Fig. 4.

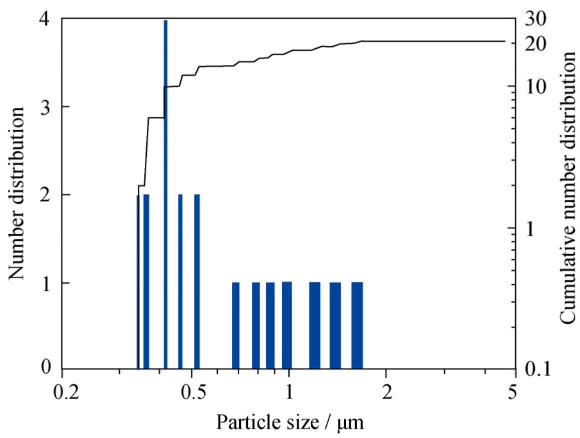

Fig. 4. Particle background values of the clean room.

As shown in Fig. 4, the size range of particles in the clean room air is mainly from 0.3 to 1.8 μm, and the particle size distribution is discontinuous. The number of particles that were collected in 30 s is below 20. Obviously, the number of particles in clean-room air is very little. Therefore, the air in the clean room does not cause adverse effect on the measurement of kerosene aerosol particle size.

(2) Particle size analysis of kerosene aerosol obtained by the Collison nozzle aerosol generator.

The results of the test are shown in Fig. 5. As shown in Fig. 5, the size range of kerosene particles obtained by the Collison nozzle aerosol generator is mainly from 0.3 to 2.0 μm, and the number of particles near 0.5 μm is maximum. The aerosol obtained by the Collison nozzle aerosol generator was assigned to aerosol I.

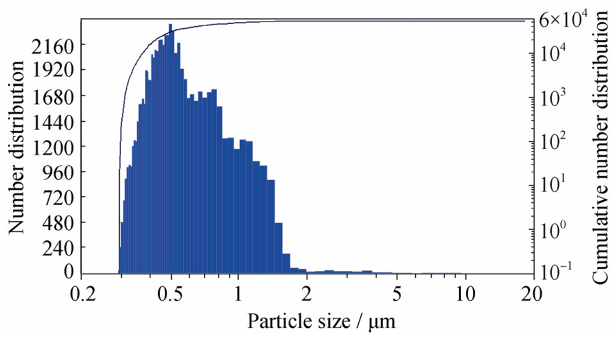

Fig. 5. Particle size distribution.

(3) Particle size analysis of kerosene aerosol obtained by the ultrasonic atomizer.

The results of the test are shown in Fig. 6. As shown in Fig. 6, the size range of kerosene aerosol particles obtained by the ultrasonic atomizer is from 0.3 to 20.0 μm and the number of particles at 1.8 and 5.0 μm is relatively more. Therefore, the size range of kerosene particles is mainly from 1.8 to 5.0 μm. The aerosol obtained by the ultrasonic atomizer was assigned to aerosol II.

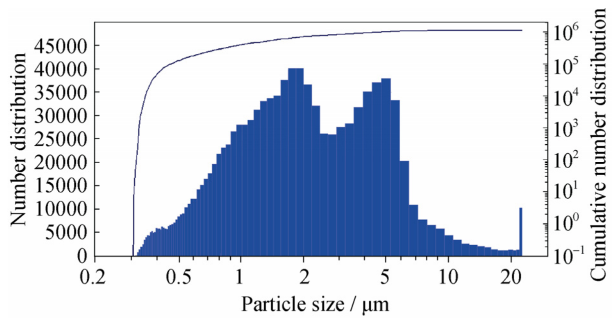

Fig. 6. Particle size distribution.

To sum up, the effect of the clean-room air on the measurement of kerosene aerosol particle size could be ignored. The particle size of kerosene aerosol obtained by the Collison nozzle aerosol generator was smaller than that obtained by the ultrasonic atomizer.

3.1.2. Effect of kerosene aerosol particle size

The test aimed at researching the effect of aerosol particle size on the aerosol flotation index, and the results are shown in Table 3.

Table 3. Comparison between the flotation indexes of molybdenum

Aerosol	Product name	Yield / %	Mo grade / %	Mo recovery / %
I	Mo rough concentrate	4.543	1.08	82.37
II	Mo rough concentrate	4.338	1.09	80.47

As shown in Table 1, aerosol particle size has little effect on the molybdenum grade but has significant effect on the molybdenum recovery. The molybdenum recovery is 82.7% when the size range of kerosene particles is from 0.3 to 2.0 μm. The molybdenum recovery is 80.47% when the size range of kerosene particles is from 1 to 20 μm. Therefore, the kerosene aerosol of fine particles is more advantageous to the aerosol flotation. The effect of kerosene aerosol particle size on the aerosol flotation cannot be ignored.

3.2. Effect of aerosol concentration

For the compressed air atomizer, the structure (hole number, pore size, structure form, and so on) of the nozzle is the main influence factor on the dispersion degree. Once the nozzle structure is selected, the aerosol dispersion degree will not change. The aerosol concentration refers to the magnitude of some physical quantities of aerosols in unit air volume. Spray pressure is the main influence factor on the aerosol concentration. Generally speaking, with increasing spray pressure, the aerosol concentration increases, and both are a linear relationship. However, spray pressure does not affect the dispersion degree of aerosols [16]. Based on the above theory, for the study on the effect of aerosol concentration, it is suitable to adopt the Collison nozzle aerosol generator.

3.2.1. Measurement method of aerosol concentration

The tightness of the Collison nozzle aerosol generator is good. The aerosol concentration was calculated based on the mass change of the Collison nozzle aerosol generator before and after injection, gas flow and generator working time.

The aerosol concentration is computed as follows:

$$C_m = \frac{m}{Qt} \tag{1}$$

where C_m is the aerosol mass concentration, mg/L; m is the aerosol quality, mg; Q is the gas flow, L/min; and t is the dosing time, min.

The spray pressure and gas flow are related. The equation is as follows:

$$\frac{Q_1}{Q_2} = \frac{\sqrt{F_1}}{\sqrt{F_2}} \tag{2}$$

where Q_1 and Q_2 represent two different gas flows, and F_1 and F_1 represent two different spray pressures.

Therefore, the aerosol concentration is controlled by controlling the gas flow of the air compressor.

3.2.2. Test of the effect of aerosol concentration

The kerosene dosage was 50 g/t. In different gas flows, the aerosol concentration and dosing time are shown in Table 4.

Table 4. Gas flow, aerosol concentration, and dosing time in the test of the effect of aerosol concentration

Gas flow / ($m^3 \cdot h^{-1}$)	Aerosol concentration / ($mg \cdot L^{-1}$)	Dosing time / s
0.30	20	30
0.25	16	45
0.20	14	65
0.15	10	120

The test results are shown in Fig. 7. As shown in Fig. 7, with the increase of kerosene aerosol concentration, the molybdenum grade fractionally changes, but the molybdenum recovery shows a decreasing tendency. This reveals that the effect of aerosol concentration on the molybdenum recovery is significant and the effect of aerosol concentration on the molybdenum grade is little in aerosol flotation. In other words, the low aerosol concentration is more beneficial to aerosol flotation. In the experiment, the optimized aerosol concentration is 14 mg/L.

3.3. Kerosene dosage test

The test aimed at researching the effect of aerosol dosing method on the kerosene dosage compared with traditional dosing method, where the flotation reagent is directly added into the ore pulp. The kerosene dosage was 20, 30, 40, 50, and 60 g/t, respectively. The results of the test are shown in Fig. 8.

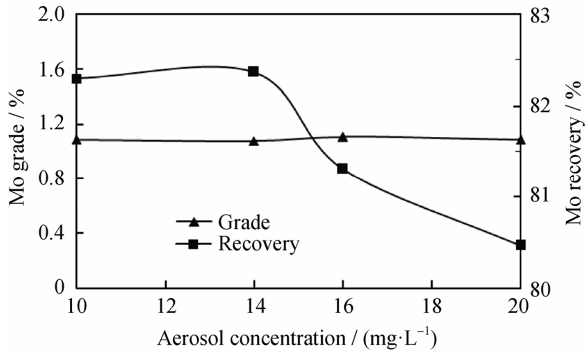

Fig. 7. Results of effect of aerosol concentration.

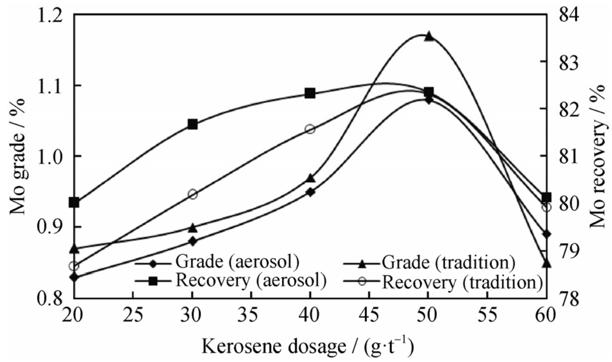

Fig. 8. Results of kerosene dosage test.

As shown in Fig. 8, with the increase of kerosene dosage, the molybdenum grade of molybdenum rough concentrate in aerosol flotation is a little lower than that in conventional flotation. However, the recovery of molybdenum changed obviously. When the kerosene dosage is from 20 to 40 g/t, the recovery of molybdenum in aerosol flotation is higher than that in conventional flotation. When the kerosene dosage is 50 g/t, the two recoveries are the same. When the kerosene dosage is 60 g/t, the two recoveries are reduced. When the kerosene dosage is 40 g/t, the recovery of molybdenum in aerosol flotation corresponded to that in conventional flotation at the kerosene dosage of 50 g/t. Compared with conventional flotation, it can be deduced that the kerosene dosage in aerosol flotation can be decreased by ~20%, while the recovery of molybdenum is similar. In addition, the test demonstrated that aerosol dosing method improves the effect of the kerosene collector.

3.4. Flotation time test

In the test, kerosene was added in the aerosol form and the kerosene dosage was 50 g/t. The flotation foam was collected in batches at different times. Compared with conventional dosing method, the effect of aerosol dosing method on the flotation time was studied through analyzing the grade and recovery of molybdenum rough concentrate. The results are shown in Fig. 9.

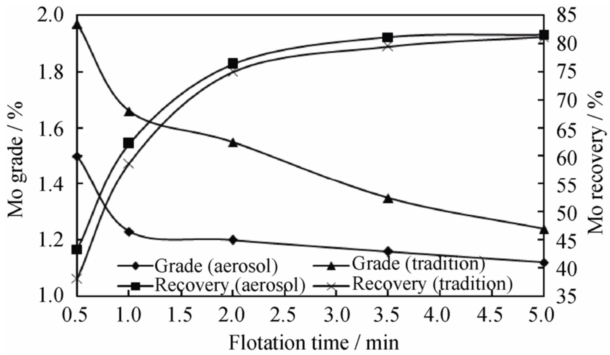

Fig. 9. Results of flotation time test.

As shown in Fig. 9, with the increase of flotation time, the molybdenum grade of molybdenum rough concentrate in aerosol flotation decreases gradually, while the molybdenum recovery rises gradually. When the flotation time is 3.5 min, the recovery of molybdenum in aerosol flotation corresponded to that in conventional flotation at the flotation time of 5 min. Therefore, compared with conventional flotation, it can be deduced that the flotation time in aerosol flotation can be reduced by ~30%, while the recovery of molybdenum is similar. According to the discussion above, aerosol flotation method can improve the flotation efficiency and save the flotation devices.

4. Conclusions

(1) The particle size of kerosene aerosol obtained by the compressed air atomizer (Collison nozzle aerosol generator) is smaller than that obtained by the ultrasonic atomizer. The compressed air atomizer has a more uniform distribution of aerosol particle than the ultrasonic atomizer and the aerosol concentration is controlled easily, so the compressed air atomizer is more suitable for the research of aerosol flotation.

(2) The particle size and concentration of kerosene aerosol have little effect on the Mo grade but have significant effect on the Mo recovery. A smaller particle size and a lower concentration of kerosene aerosol are beneficial to Mo aerosol flotation. For the received Mo ore samples, the optimized particle size of kerosene aerosol is 0.3-2.0 μm and the optimized aerosol concentration is 14 mg/L.

(3) Compared with conventional flotation, in which kerosene is directly added into the ore pulp, the flotation time is reduced by ~30% and the kerosene dosage is decreased by ~20% in aerosol flotation, while the Mo flotation index is similar.

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