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STUDY ON PRE-CONCENTRATION EFFICIENCY OF WOLFRAMITE FROM TUNGSTEN ORE USING GRAVITY AND MAGNETIC SEPARATIONS

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Abstract: Pre-concentration is effectively applied in recovering wolframite from tungsten ore, due to its benefits of further upgrading tungsten ore and improving separation efficiency. The most important pre-concentration techniques for tungsten ore include gravity separation and magnetic separation, based on the fact that there are appreciable differences, between the desired wolframite and the gangue minerals, in density and magnetic susceptibility. This study investigated the separation efficiency of gravity pre-concentration (Falcon Concentrator) and high-gradient magnetic pre-concentration (SLon VPHGMS) for the beneficiation of a Canada tungsten ore. It is a low-grade type of ore with high silica and arsenic content, and an average content of WO_3 is about 0.45%. The optimum conditions for different operational parameters of two pre-concentration separators were studied on this low-grade material. The results presented in this paper suggested that although both pre-concentration techniques were effective for producing pre-concentrates containing high WO_3, magnetic pre-concentration showed significantly better separation efficiency. Over 90% of the feed was rejected as the final tailings, meanwhile, over 85% of arsenic minerals were removed with tailings, while the WO_3 loss was less than 15%.

Keywords*: tungsten ore, pre-concentration, separation efficiency, gravity separation, magnetic separation*

Introduction

With increasing global demand of tungsten ores due to huge need for alloys all over the world, tungsten ore producing countries have increased their production by initiating steps to utilize the low-grade complex tungsten ores. Wolframite is the main mineral as a source of tungsten metal. The most commonly used beneficiation methods for tungsten ores are gravity separation and magnetic separation, which are widely used in mineral beneficiation practices for their low-cost, easy-to-control, and eco-friendly advantages (Burt, 1996; Srivastava et al., 2000).

The pre-concentration process is effectively applied in recovering wolframite from tungsten ore, due to its benefits of further upgrading tungsten ore and improving

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separation efficiency. The most important pre-concentration techniques for tungsten ore are Falcon centrifugal concentrator (Greenwood et al., 2013) and high-gradient magnetic separator, based on the fact that there are appreciable differences between the desired wolframite and the gangue minerals in density and magnetic susceptibility.

Falcon concentrators have found a wide number of applications in industry for separating and concentrating objective minerals on the basis of density difference. The enhanced gravity field created by their fast spinning bowl can reach several hundred times the earth's gravitational acceleration. The strong increase in differential settling velocities allows separators to handle significant tonnages of fine and ultrafine particle suspensions. High-gradient magnetic separation technique is the simplest method to separate weak magnetic minerals from non-magnetic minerals based on different behaviors of mineral particles in an applied magnetic field. This technique also has a variety of applications in different industries such as mineral beneficiation, food, textiles, plastic and ceramic processing (El-Midany et al., 2011; Ozan et al., 2015).

Although it is important to choose the high-efficiency pre-concentration technique for the final separation efficiency, there has not been studied and published previously about which technique has better pre-concentration efficiency. In this paper, the focus is to estimate the pre-concentration efficiency of recovering wolframite from tungsten ore, using Falcon concentrator (Matjie et al., 2005; Kroll-Rabotin et al., 2012) and the SLon vertical ring and pulsating high-gradient magnetic separator (SLon VPHGMS) (Zeng et al., 2003; Jordens et al., 2014; Chen et al., 2014). Moreover, the removal efficiency of arsenic minerals was also evaluated in the paper by using different pre-concentration separators.

Experimental

Materials

Mineral characterization and pre-concentration experiments were conducted on a sample containing about 0.45% WO_3. The sample was collected from New Brunswick, Canada. Around 100 kg of representative ore samples were well mixed and divided into 500 g each bag for mineralogical and mineral processing studies.

Test methods

Mineralogical survey of the head ore

The chemical analysis was performed with the Xios advanced X-ray fluorescence (XRF) analyzer. Sizing analysis was conducted on sub-samples of feed with using laboratory wet screening method.

Gravity separation

The feed was subjected to gravity pre-concentration by a Falcon L40 cyclic pilot-scale centrifugal separator. The process parameters were processing capacity of 500 g each batch, pulp density of 10 wt%, power frequency of 0–60 Hz, fluidization water of 3448-10343 Pa and feed flow rate of 0.8 dm^3/min.

When the separator is in operation, fluidization water is introduced into the bowl (concentrate cone) through a series of fluidization holes at the top of its wall. Then feed slurry is introduced into the concentrate cone through the stationary feed tube at the bowl center. When the slurry reaches the bottom of the cone, it is forced to move outward and up under the influence of centrifugal force. During the course of the separation, tailings flow out from the top of the cone into the tailings launder. After finishing the separation process, concentrates are flushed from the cone into the concentrate launder.

Magnetic separation

The tungsten ore was subjected to magnetic pre-concentration by a SLon-100 cyclic pilot-scale separator (SLon VPHGMS), and the process parameters were processing capacity of 250 g each batch, pulp density of 10 wt%, magnetic field intensity of 0.75~0.95 T, rod matrix diameter of 2 mm and feed flow rate of 0.8 dm^3/min, pulsating stroke of 30 mm and stroke frequency of 100~250 min^{-1}. The products of SLon VPHGMS includes pre-concentrate and tailing.

The tailing and pre-concentrate were settled, collected, dried, weighed and chemically analyzed.

Results and discussion

Mineral characterization

Chemical composition analysis

The result of chemical composition analysis (Table 1) shows that the main components in the head ore are SiO_2 and Al_2O_3. The only useful element is tungsten. A characteristic of the ore is high content of As and low content of S. Based on the microscopy, it is inferred that As and S may originate from arsenopyrite and pyrite, respectively.

Table 1. Chemical composition of the head ore

Constituent	WO_3	SiO_2	Al_2O_3	CaF_2	K_2O	MgO	CaO	TFe
Weight (%)	0.45	67.81	9.02	6.21	1.33	0.31	4.13	3.83
Constituent	Zn	Cu	Sn	S	As	Pb	Na_2O	
Weight (%)	0.035	0.056	0.08	0.11	0.68	0.082	0.14	

Mineral composition analysis

The mineralogical composition presented in Table 2 indicates that wolframite is the main tungsten mineral, which is associated with silicate and arsenic bearing minerals in the sample. Arsenic is mainly present as arsenopyrite, while the bulk of the siliceous impurities are contributed by quartz and sericite. Besides, iron impurities are present as hematite and goethite.

Table 2. Mineral composition of the head ore

Mineral	Weight (%)
Quartz	61.70
Chlorite	2.00
Fluorite, calcite, hornblende	8.00
Sericite	20.00
Arsenopyrite	1.50
Pyrite	0.20
Feldspar	3.00
Wolframite	0.55
Scheelite	0.05
Iron minerals	3.00

Physical properties

Physical beneficiation process depends on the physical property differences of constituents in the sample. Separation efficiency for physical beneficiation process is influenced by many factors, such as differences of density and magnetic susceptibility among constituents, the grain size distribution of feed and the operational parameters of separators. Table 3 shows physical properties of various constituents in these materials. The physical properties of various constituents will affect separation efficiency of the gravity pre-concentration and magnetic pre-concentration directly and indirectly.

Table 3. Physical properties of various gangue constituents and wolframite

Mineral	Mohs hardness	Density ($1 \cdot 10^3$ kg·m^{-3})	Magnetic susceptibility ($1 \cdot 10^{-9}$ m^3·kg^{-1})
Quartz	7.0	2.65	-0.50
Hornblende	5.5	3.20	25.54
Chlorite	6.5	3.60	19.96
Mirrorstone	2.5	2.90	2.93
Fluorite	4.0	3.18	0.51
Feldspar	6.0	2.57	-0.33
Arsenicpyrite	5.5	5.89-6.20	0.63
Pyrite	4.0	4.60	26.98
Wolframite	5.0	7.30	39.42
Hematite	4.4	4.40	23.18

Occurrence of tungsten

The result of tungsten phase analysis is presented in Table 4. In the head ore, the main tungsten-bearing mineral is wolframite, which accounts for 88.44%. Scheelite accounts for 10.89%. The content of tungstite is very low, just 0.67%. Hence, by utilizing the contrasts of density and magnetic susceptibility between wolframite and the gangues, it could realize the recovering of tungsten.

Table 4. Phase analysis of tungsten in the head ore

Bearing minerals	WO_3 Grade (%)	WO_3 Content (%)
Tungstite	0.003	0.67
Wolframite	0.398	88.44
Scheelite	0.049	10.89
Total	0.450	100.00

Liberation study and tungsten size distribution

Wolframite was present as subhedral to anhedral grains with medium to very fine size. Wolframite grains disseminated among fracture/cleavage planes of quartz. Size of wolframite grains varied between 10 and 200 μm, and an average size was 50 μm. About 15% occurred as coarse inter-granular grains. Very fine grains with 10 to 15 μ m size constituted about 15% as inclusions within quartz.

According to the ore mineralogy, fine grinding was required to obtain a reasonable liberation. The liberation degree of the tungsten mineral was studied by the point counting technique. Polished sections of the different size fractions were prepared and studied under the microscope in reflected light mode. The wolframite grains in form of liberated particles and locked particles, both were counted in the microscope views. Then, the percentage of liberated wolframite grains relative to the sum of the two types of particles, it was calculated. Table 5 gives the distribution of WO_3 and the liberation degree of the wolframite mineral in different size fraction. More than 75% liberation degree was achieved by grinding to obtain 70% passing 74 μm size. When the sample was wet ground to obtain 70% passing 74 μm size in a rod mill, cumulative distribution of tungsten is showed in Fig.1 as a function of size fraction.

Table 5. Liberation degree of wolframite grains as a function of size fraction

Size Fraction (μm)	Distribution of WO_3 (%)	Degree of Liberation (%)
+74	36.03	65.77
-74+37	19.40	73.12
-37+19	21.19	75.25
-19+10	12.17	88.63
-10	11.21	94.56
Total	100.00	75.21

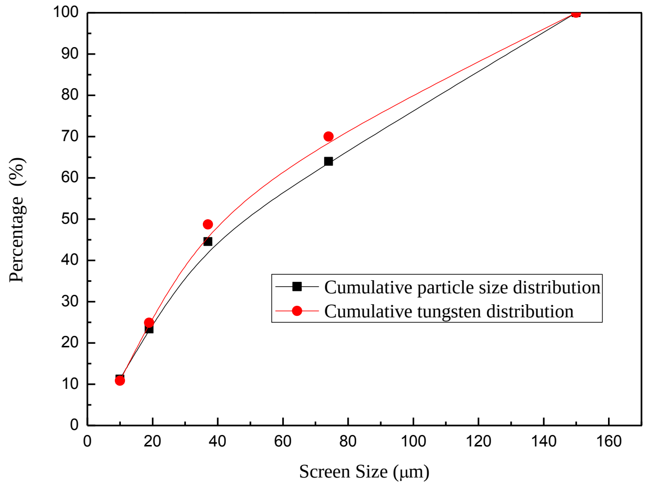

Fig. 1. Cumulative particle size distribution and cumulative tungsten distribution versus particle size

Effect of main parameters on centrifugal pre-concentration

Tests were conducted on the tungsten ore pulp at power frequency ranging from 50 to 70 Hz. Grinding fineness of ore pulp was fixed at 70% passing 74 μm size. At fixed water pressure of 6895 Pa, Table 6 shows the test results corresponding to the variation of power frequency. It is clear that raising power frequency can increase WO_3 recovery from 55.94 to 58.92%. On the other hand, the increase of centrifugal force decreases WO_3 grade from 4.35 to 3.14% in the pre-concentrate.

It is clear that separation performance of the centrifugal separator is affected by the power frequency. At low power frequency, the centrifugal force is low and this gives a chance for the light particles (quartz) and fine-grained wolframite to move into overflow (tailing launder). In other words, only a small amount of coarse wolframite particles go to underflow (concentrate launder) after passing through the fluidizing region. As a result, the lower recovery and the higher grade were observed at low power frequency. With increasing the power frequency, the wolframite particles are likely to stratify quickly before entering the fluidization zone. This stratification increases the particles packing, which makes the drag force exerted by fluidizing water be not enough to disturb the stratified particles and release the entrapped gangue mineral, consequently it reduces the WO_3 grade in pre-concentrate. As a result, the higher recovery and the lower grade were observed at high power frequency.

When the solid particles move towards the bowl periphery and encounter the fluidizing water passing through the orifices in the bowl periphery, the fluidization water exerts a drag force on the solid particles in the fluidization zone. The effectiveness of the fluidizing water appears when the fluid drag force assists the heavy particles (wolframite) to displace the light particles and reduces the mechanical entrapment. Hence, the high-density particles can be retained in the retention zone and collected in the pre-concentrate fraction.

The effect of fluidization water pressure on grade and recovery of tungsten ore was investigated. At fixed power frequency of 60 Hz, the tests results are given in Table 6 by changing the fluidization water pressure. Despite the WO_3 grade increasing from 3.21 to 4.52% with the water pressure increasing from 3448 to 10343 Pa, it significantly reduced the WO_3 recovery from 60.50 to 55.47% in pre-concentrate. Under the condition of high water pressure, the improvement of pre-concentrate grade can be attributed to the increased influence of the drag force, which diminished the mechanical entrapment of gangue minerals into pre-concentrate. However, the recovery of WO_3 is low at high water pressure, it can be referred to incomplete stratification of particles at such a relatively low power frequency. Lower centrifugal force leads to the escaping of fine wolframite within the tailings.

The effects of power frequency and fluidization water pressure on removal efficiency of arsenic were also investigated. The results in the Table 6 indicated that more than 60% minerals containing As entered into pre-concentrate with wolframite, grade and recovery of As were higher than tungsten in pre-concentrate, and that similar separation performance was presented in pre-concentration process of wolframite and arsenopyrite by using gravity separation. The results indicated that separating arsenopyrite from wolframite was not very promising due to their similar density.

Table 6. Results of the magnetic pre-concentration experiments

Test	Factors		Responses				
	Power frequency (Hz)	Water Pressure (Pa)	Weight of Concentrate (%)	WO_3 Grade in Conc. (%)	WO_3 Recovery in Conc. (%)	As Grade in Conc. (%)	As Recovery in Conc. (%)
1	50	6895	6.12	4.35	55.94	6.25	64.80
2	60	6895	7.57	3.63	57.74	5.82	74.64
3	70	6895	8.93	3.14	58.92	5.24	79.27
4	60	3448	8.97	3.21	60.50	5.11	77.65
5	60	10343	5.84	4.52	55.47	6.14	60.75

For further improving WO_3 recovery in pre-concentrate, two-stage scavenging were employed after centrifugal pre-concentration. As shown in Table 7, the scavenging times had a very significant effect on the WO_3 and As recovery of pre-concentrate. Recovery of WO_3 and As were increased with increasing scavenging times. The WO_3 recovery of 81.02% was obtained in pre-concentrate1-3. The As content in pre-concentrate was not promising. The rejection rate and WO_3 loss in the tailings were 72.72% and 18.98%, respectively.

Table 7. Results of two scavengers after centrifugal pre-concentration

Product	Weight (%)	Grade (%)		Recovery (%)	
		WO_3	As	WO_3	As
WO_3 Pre Concentrate 1	7.57	3.63	5.82	57.25	74.67
WO_3 Pre Concentrate 2	10.85	0.61	0.58	13.79	10.67
WO_3 Pre Concentrate 3	8.86	0.54	0.16	9.98	2.40
WO_3 Pre Concentrate 1-3	27.28	1.43	1.90	81.02	87.74
Tailings	72.72	0.125	0.10	18.98	12.36
Head (calculated)	100.00	0.48	0.59	100.00	100.00

Effect of main parameters on magnetic pre-concentration

Tests were conducted on the tungsten ore pulp at magnetic field intensity ranging from 0.75 to 0.95 T. Grinding fineness of ore pulp was fixed at 70% passing 74 μm size. Firstly, at fixed pulsating stroke of 200 min^{-1}. Table 8 gives the tests results corresponding to variation of the magnetic capture force and area, which are adjusted by changing the magnetic field intensity. It is clear that raising magnetic field intensity can increase WO_3 recovery from 76.44 to 80.35%, and the WO_3 grade, which is about 7%, was not changed obviously.

Secondly, the effect of pulsating stroke on grade and recovery of WO_3 was investigated. At magnetic field intensity of 0.95 T, the tests results are given in Table 8 under conditions of changing the pulsating stroke. Despite the WO_3 grade increasing from 6.32 to 7.12% with changing the pulsating stroke from 150 to 200 min^{-1}, it significantly reduced recovery of WO_3 from 80.35 to 74.65% in pre-concentrate.

Table 8. Results of the magnetic pre-concentration experiments

Test	Factors		Responses					
	Magnetic Field Intensity (T)	Pulsating Stroke (min^{-1})	Weight of Concentrate (%)	WO_3 Grade in Conc. (%)	WO_3 Recovery in Conc. (%)	As Grade in Conc. (%)	As Recovery in Conc. (%)
1	0.75	200	4.67	6.94	76.44	1.21	8.03
2	0.85	200	4.81	7.01	80.28	1.26	8.66
3	0.95	200	4.86	6.95	80.35	1.35	9.36
4	0.95	250	4.62	7.12	74.65	1.06	6.88
5	0.95	150	5.22	6.32	78.98	1.06	7.68

The effect of magnetic field intensity and pulsating stroke on removal efficiency of arsenic was also investigated. The results in the Table 8 indicated that less than 10% minerals containing As entered into pre-concentrate with wolframite, the grade and recovery of As were lower than WO_3 in pre-concentrate, and that the different separation performance was presented in pre-concentration process of wolframite and arsenopyrite by using magnetic separation. The results indicated that separating arsenopyrite from wolframite was very encouraging due to their significant differences of magnetic susceptibilities.

Table 9. Results of one scavenger after magnetic pre-concentration

Product	Weight (%)	Grade (%)		Recovery (%)	
		WO_3	As	WO_3	As
WO_3 Pre Concentrate 1	4.81	7.01	1.26	80.28	8.66
WO_3 Pre Concentrate 2	2.02	1.34	1.32	6.44	3.81
WO_3 Pre Concentrate 1-2	6.83	5.33	1.28	86.72	12.47
Tailings	93.17	0.060	0.66	13.28	87.53
Head ore (calculated)	100.00	0.42	0.70	100.00	100.00

For further improving WO_3 recovery in pre-concentrate, a scavenging stage was employed after magnetic pre-concentration, as shown in Table 9. The scavenging had a very significant effect on the WO_3 and As recovery of pre-concentrate. The WO_3 recovery of 86.72% was obtained in pre-concentrate 1-2. The As content in pre-concentrate 1-2 was 1.28%. The rejection rate and the WO_3 loss in the tailing were 93.17% and 13.28%, respectively.

Comparison of separation performance

It can be seen from Table 10 that tungsten separation efficiency increased and grade decreased as WO_3 recovery increasing in pre-concentrate. It was apparent that the application of magnetic pre-concentration had resulted a better and cleaner pre-concentrate. Comparing to centrifugal separation, the obtained pre-concentrate by magnetic separation had the higher WO_3 grade and recovery. Table 10 indicated that although both two technologies can achieve the aim of removing mostly gangue minerals as tailings, high gradient magnetic separation had better separation efficiency in pre-concentration process.

It was apparent that arsenic grade decreased as arsenic recovery increasing in pre-concentrate. Compared to centrifugal separation, the obtained pre-concentrate by magnetic separation had the lower grade and recovery of arsenic. Therefore, Table 10 indicated that a better efficiency in removal of arsenic which was obtained by high gradient magnetic separation in pre-concentration process, it is because there has a significant magnetic susceptibility differences rather than density differences between wolframite and arsenopyrite.

From Table 10, the arsenic recovery increased as the WO_3 recovery increasing in pre-concentrate by using two separation technologies. When the WO_3 recovery of 81.02% was obtained by using centrifugal pre-concentration, more than 85% minerals containing arsenic entered into WO_3 pre-concentrate, it is due to the small density differences between wolframite and arsenopyrite. When the WO_3 recovery of 86.72% was obtained after magnetic pre-concentration, less than 15% minerals containing arsenic entered into WO_3 pre-concentrate, it is due to a significant magnetic susceptibility differences between wolframite and arsenopyrite. Therefore, the pre-concentration process by magnetic separation can not only reject mostly gangue minerals and improve the WO_3 grade, but also obviously decrease the arsenic content in pre-concentrate of tungsten.

Table 10. Performance comparison of magnetic and centrifugal pre-concentration under optimum condition

Separator	Product	Wt. (%)	Grade (%)		Recovery (%)	
			WO_3	As	WO_3	As
SLon-100	WO_3 Pre Conc. 1	4.81	7.01	1.26	80.28	8.66
	WO_3 Pre Conc. 1-2	6.83	5.33	1.28	86.72	12.47
Falcon L40	WO_3 Pre Conc. 1	7.57	3.63	5.82	57.25	74.67
	WO_3 Pre Conc. 1-2	18.42	1.85	2.73	71.04	85.34
	WO_3 Pre Conc. 1-3	27.28	1.43	1.9	81.02	87.74

Conclusions

This study described a research on efficiency of gravity pre-concentration (Falcon) and high-gradient magnetic pre-concentration (SLon VPHGMS) for the beneficiation of a Canada tungsten ore, which is a low-grade type of ore with high silica and arsenic content, and an average tungsten content of about 0.45% WO_3. Comparing to centrifugal separation, the obtained pre-concentrate by magnetic separation had higher WO_3 grade and recovery. Pre-concentration process of magnetic separation can not only reject mostly gangue minerals and improve the WO_3 grade, but also obviously decrease the arsenic content in WO_3 pre-concentrate. Through pre-concentration process of magnetic separation, over 90% of the feed ore was rejected as the final tailings, meanwhile, over 85% of arsenic minerals with tailings were removed, while the WO_3 loss was less than 15%.

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