PULSATING HIGH GRADIENT MAGNETIC SEPARATION FOR PURIFICATION OF QUARTZ

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Abstract: Pulsating high gradient magnetic separation (PHGMS) for removing trace amounts of iron impurities from a quartz ore was investigated using a lab-scale PHGMS separator, and its performance was further confirmed through a pilot-scale PHGMS separator. The results of this investigation indicated that PHGMS is effective for removing the iron impurities from the ore. By applying the lab-scale separator with a rod matrix of 1.5 mm diameter to the ore containing 0.063% Fe_2O_3, a concentrate assaying 0.0079% Fe_2O_3 with 89.82% iron removal rate was achieved through a two-step purification of PHGMS. It was found that the separation performance of this lab-scale separator was closely correlated with the wire diameter of matrix, pulsating frequency and background magnetic induction. Compared with the separation characteristics of PHGMS in beneficiating feebly magnetic metallic ores, it is clear that a much gentler pulsating intensity and a much higher background magnetic induction are both required to maintain a high iron removal rate. The comparison test of HIWGS further evidences the positive effect of pulsating energy in the high gradient magnetic separation. The purification performance of the lab-scale separator was well duplicated by the pilot-scale one, so that it was concluded that PHGMS provides an effective way for removing trace amounts of iron impurities from similar non-metallic ores.

Keywords: high gradient magnetic separation, purification, quartz

Introduction

Quartz is the most important raw material to produce fused silica, which is becoming an increasingly important material for several high technology applications (Vatalis et al., 2015). However, the quartz material always contains some harmful impurities, such as Fe, Cr, Al, Ti, Li, Na and K etc. The presences of impurities limit the application of quartz materials and reduce the economic value of them (Muller et al., 2007). Especially, iron oxide is the most harmful of them, it causes a series of

problems, such as impairing transmission of optical fibers, reducing the transparency of glasses, discoloring ceramic products and lowering the melting point of refractory (Veglio et al., 1999). For the production of colorless glass or higher premium ceramics, silica sands with less than 100 ppm (0.01%) iron is needed (Taxiarchou et al., 2007).

The iron content of industrial minerals can be reduced by a number of chemical, biochemical, physical and physicochemical methods. In the industrial production, leaching is the most cost-efficient method to remove the trace amounts of iron oxides from quartz minerals. And in recent years, the organic acids reportedly are more applied to improve indicators and reduce pollution in the leaching work of iron removal (Veglio et al., 1999; Lee et al., 2006; Li et al., 2010). However, those leaching methods are still hazardous for human health and the environment, because the discharge of acid wastewater is unavoidable in those technologies (Santos et al., 2015; Luo et al., 2016). Bioleaching is a new research trend in iron removal of silicate minerals and it is effective to convert some insoluble iron minerals. But most of related researches, as reported, are studied in laboratory and their products are still high iron content that are difficult to be used as qualified material (He et al., 2011; Styriaková et al., 2015; Dong et al., 2013). Flotation is a feasible separation method on the purification of quartz. Sodium petroleum sulfonate and fatty acid are often used as the collectors on such flotation works (Sun et al., 1992). However, the coarse quartz material is not purified well by flotation and the problem of pollution is also unavoidable on the flotation process. Magnetic separation is the best environment friendly method to remove iron from quartz, because it is a physical method without using any chemical agents (Liu et al., 2013; Newns and Pascoe, 2002). But most of traditional magnetic separators are incompetent on the purification for high-purity quartz, due to their insufficient magnetic force of impurity particles (Chen et al., 2016).

In fact, high gradient magnetic separation (HGMS) can produce a sufficiently strong magnetic force for impurity particles to separate. But the mechanical entrainment onto magnetic matrix and low-efficiency limited their applications (Svoboda et al., 2003). Therefore, for intensifying the separation effect, some researchers try to introduce different separation force on high gradient magnetic separation. They had designed and developed many different kinds of equipment. For example, a wet belt permanent HGMS separator was reported that it is effective in purifying quartz and feldspar (Chen et al., 2016). Moreover, a dry vibrating HGMS separator reportedly was also used for the purification of quartz and kaolin (Chen et al., 2012). Nowadays, pulsating HGMS (PHGMS) separators are widely used for separation of magnetic metallic ores such as hematite, limonite and ilmenite (Chen and Xiong, 2015). In the recent decade, PHGMS has been gaining numerous applications in the purification of non-metallic ores (Huang et al., 2016; Chen and Li, 2013). However, its effective performance in purifying quartz and similar non-metallic mineral was rarely reported and its separation characterizes for purification was

unclear. Therefore, in order to study its feasibility of removal iron from quartz and analyze the separation characterizes, a lab-scale PHGMS separator is used for purifying a quartz material in this work. Moreover, its performance was further confirmed through a pilot-scale PHGMS separator.

Experimental

Lab-scale PHMGS separator and its working principle

The investigations were carried out through a SLon-100 cyclic lab-scale PHGMS separator, as schematically shown in Fig. 1. Round bars made of magnetic stainless steel are used as rod matrix, as shown in Fig. 1.
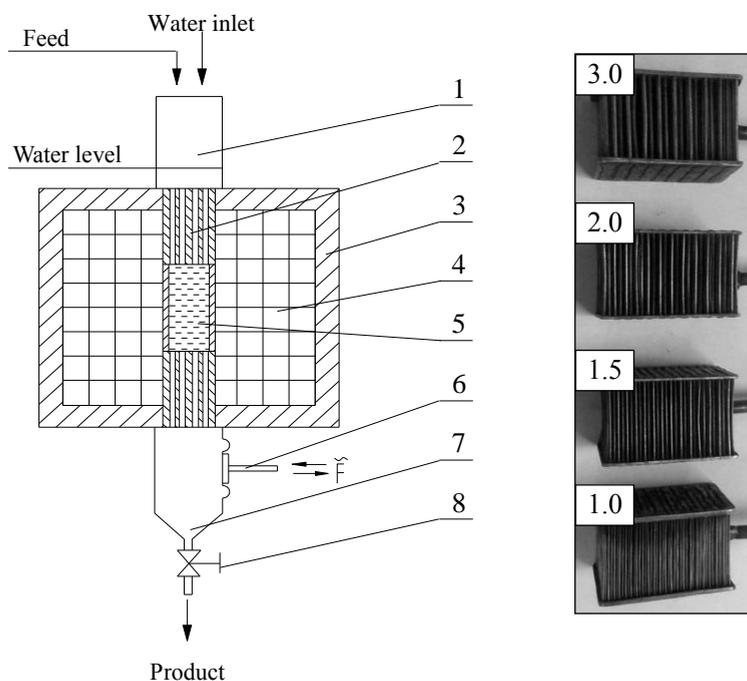

Fig. 1. Lab-scale PHGMS separator (left) and rod matrix of different wire diameters (right):
1. Feed box, 2. Magnetic pole, 3. Magnetic yoke, 4. Energizing coils, 5. Magnetic matrix,
6. Pulsating mechanism, 7. Product box, 8. Valve

While the lab-scale separator is being operated, a direct current flows through the energizing coils and a magnetic field is built up in the separating zone. Firstly, the separating zone is filled with flowing water so that the pulsating energy can be transmitted to the separating zone, in which the level of water and its flow rate is

adjustable through the valve below the pulsating mechanism. Then, the slurry is fed into the matrix in the separating zone through the feeding box. Magnetic particles are attracted from slurry onto the surface of the matrix, while non-magnetic particles pass through the matrix and go out through the product box to become concentrate under the combined actions of slurry pulsation, gravity and hydrodynamic drag. The lab-scale PHGMS is fed periodically. When a batch of feed is finished, the energizing current is switched off and the magnetic particles in the matrix are washed out to get a magnetic product (tailings). The pulsating mechanism drives the slurry in the separating zone up and down, keeping particles in the matrix in a loose state so that magnetic particles can be more easily captured by the matrix and non-magnetic particles can be more easily dragged out through the matrix.

Description of sample

The quartz material was obtained from a sandpit in Beihai of Guangxi Province in China. It has a particle size below 0.25 mm. As shown in Table 1, the sample has a SiO_2 grade reaching 99.70% with iron impurities assaying 0.063% Fe_2O_3. The dominant iron-bearing mineral in the material was detected as hematite.

Table 1. Chemical compositions of sample (%)

Element	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	Na_2O	K_2O	MgO	CaO
Assaying	99.700	0.063	0.056	0.049	0.044	0.038	0.029	0.021

Separation method

The sample (150 g) was fully mixed in a stir beaker at a 10% solid concentration and then was fed to the lab-scale PHGMS separator. The feed velocity of slurry through the separating matrix and the pulsating stroke were controlled at 400 cm^3/s and 6 mm, respectively. In the investigations, the wire diameter of rod matrix, pulsating frequency and background magnetic induction in the separator were adjustable in the ranges of 1.0 to 3.0 mm, 0 to 100 rpm and 0.9 to 1.5 T, respectively. When a batch of feed was finished in the separator, a concentrate (non-magnetic product) and a tailings (magnetic product) were respectively produced.

In addition, a high intensity wet magnetic separator (HIWGS) of Boxmag Rapid Limited under the optimized conditions was used as comparison equipment for the sample. Furthermore, the pilot-scale PHGMS investigation was performed to the material, through a SLon-500 pilot-scale PHGMS separator under the optimized conditions.

Evaluation

The Fe_2O_3 content, iron removal rate (*IRR*) and iron removal efficiency (*IRE*) of concentrate were used for evaluating the purification performance. *IRR* and *IRE* were calculated using:

$$IRR = T \cdot \frac{\theta}{\alpha} \tag{1}$$

$$IRE = IRR \left(1 - \frac{\alpha}{\theta} \cdot \frac{\delta - \theta}{\delta - \alpha}\right) \tag{2}$$

where, T is the tailing yield, α and θ are Fe_2O_3 content of feed and tailings, respectively, δ is the maximum content of Fe_2O_3 (100%).

Results and discussion

Determination of wire diameter of rod matrix

The uniform magnetic field was de-homogenized by magnetic matrix, which led to the high magnetic field gradient on the matrix, so that weakly magnetic particles are separable in HGMS separator (Zheng et al., 2016). It is generally believed that HGMS is a deep bed filtration process (Svoboda, 2001), onto which an external magnetic field is imposed, and the efficiency of magnetic capture is dominantly determined by the collision efficiency of particles with magnetic matrix. Thus, the matrix presents a decisive role in the operation of PHGMS separator. In view of this, the determination of wire diameter of rod matrix was firstly investigated using the lab-scale PHGMS separator, at a low pulsating frequency of 50 rpm and at a relatively high background magnetic induction of 1.0 *T*. From Fig. 2, the wire diameter has a significant effect on the purification performance of the separator; the increase in the wire diameter of rod matrix from 1.0 to 3.0 mm has greatly increased the Fe_2O_3 content of concentrate; meanwhile, the *IRR* and *IRE* are both decreased.
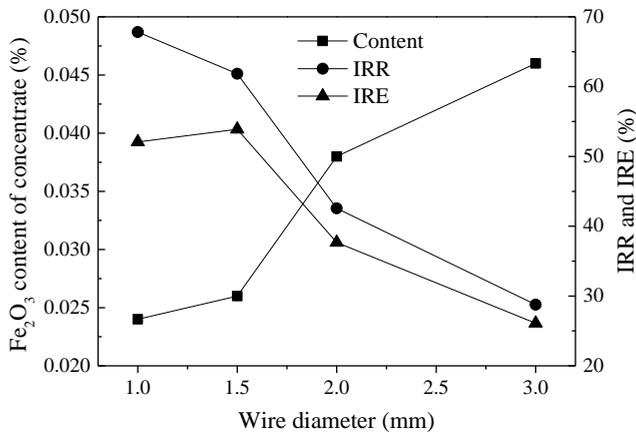

Fig. 2. Determination of wire diameter of rod matrix on performance.
Conditions: background magnetic induction = 1.0 T
and pulsating frequency = 50 rpm

Generally, a finer matrix tends to give a higher yield and iron recoveries for magnetic product, while a coarser matrix gives a higher iron grade of the product (Svoboda et al., 1988). From Fig. 2, the finest 1.0 mm rod matrix has achieved the highest IRR, and almost the highest IRE and the lowest Fe_2O_3 content of magnetic concentrate; this is due to the fact that this matrix produces a highest magnetic gradient and magnetic force to magnetic particles. As the purification performance of 1.5 mm rod matrix is near to that of the 1.0 mm one and it has a superior advantage in mechanical strength to the latter one, the 1.5 mm rod matrix is adopted in the present investigation.

Effect of pulsating frequency

The pulsating energy in the separating zone of the separator is adjustable by selecting the pulsating stroke or frequency, and the frequency is commonly used to control the pulsating energy in industrial productions (Xiong et al., 1998). Thus, the lab-scale separator applied to the quartz material as a function of pulsating frequency was investigated, with the results as shown in Fig. 3. It can be seem that the Fe_2O_3 content of concentrate has decreased with the increase of pulsating frequency at the beginning; however, the Fe_2O_3 content has remarkably increased while the pulsating frequency is over 50 rpm. The IRR and IRE have both increased and reached different plateaus at 50 rpm, and then they have decreased with the continual increase of pulsating frequency. Therefore, the pulsating frequency of 50 rpm is most favorable for the ore.
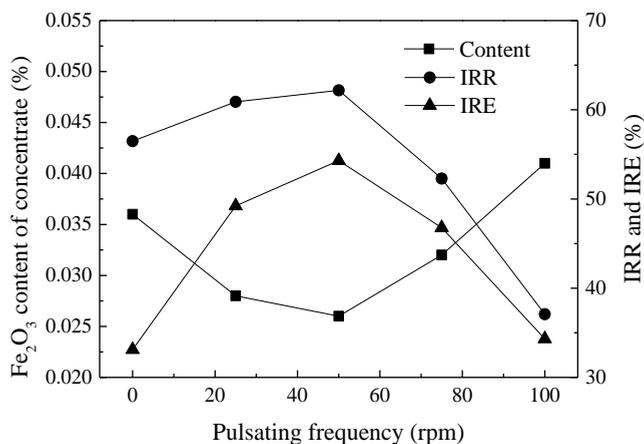

Fig. 3. Effect of pulsating frequency on performance.
Conditions: rod matrix = 1.5 mm diameter wire
and background magnetic induction = 1.0 T

When the pulsating stroke was constant, the higher is the pulsating frequency, the more adequate is the pulsating energy in the separating zone of PHGMS separator (Xiong et al., 1998). From Fig. 3, the purification performance is not effective when

the frequency was controlled at very low levels, due to the insufficient pulsating energy to relax the particles in the separator. But, as the frequency is slightly increased, the performance is significantly improved and this is much gentler than that for concentrating metallic ores. Such a difference is resulted from the much lower iron content in non-metallic ores.

Effect of background magnetic induction

From Fig. 4, the Fe_2O_3 content and *IRR* of concentrate have both improved with the increase of background magnetic induction and the *IRE* has increased with the increase of the induction from 0.9 to 1.3 T, beyond which, the Fe_2O_3 content of concentrate is slightly decreased as the magnetic induction is increased.
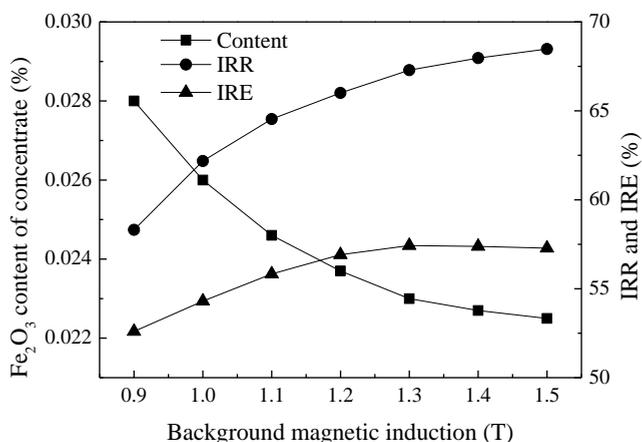

Fig. 4 Effect of background magnetic induction on performance.
Conditions: rod matrix = 1.5 mm diameter wire
and pulsating frequency = 50 rpm

The magnetic induction has a significant effect on the purification of quartz when all the other variables were constant; and this in turn was reflected in the *IRE*. As can be seen from Fig. 4, as the magnetic induction increases, more iron impurities go into the magnetic product and the separation performance is greatly improved. However, when the magnetic induction reached a high level of 1.3 T, the purification performance of the separator approaches to steady values; and under such a magnetic induction (1.3 T), this lab-scale PHGMS separator produced a non-magnetic product assaying 0.023% Fe_2O_3, at an iron removal rate of 67.29% and an iron removal efficiency of 57.43%.

Comparison test by HIWGS

The HIWGS is a classic lab-separator of high gradient magnetic. In this investigation, a HIWGS was also used for purification of the sample. The one time separation results of PHGMS and HIWGS under each optimized conditions are shown in Table 2.

Table 2. Performance comparison between PHGMS and HIWGS (%)

Separator	Fe_2O_3 content of feed	Operation conditions		Concentrate			
		Size of matrix (mm)	Magnetic induction (T)	Mass weight	Fe_2O_3 content	IRR	IRE
PHGMS	0.0633	1.5	1.3	90.02	0.0230	67.29	57.43
HIWGS	0.0631	1.5	1.6	80.39	0.0224	71.47	51.89
Difference	+0.0002	0.0	-0.3	+9.63	+0.006	-4.18	+5.54

As seen from Table 2, the Fe_2O_3 content of HIWGS concentrate is close to the PHGMS concentrate. The magnetic induction of HIWGS is 0.3 T higher than PHGMS. However, the IRR of HIWGS is much lower than PHGMS. The main reason of lower IRR is that the mass weight of HIWGS concentrate is significantly less than PHGMS concentrate. In fact, the structure and operating principle of HIWGS are similar to the PHGMS separator. But the HIWGS does not have the pulsating mechanism, and this is the biggest difference between the two kinds of equipment. The HIWGS only relies on the nature flow of water to wash the matrix at work. Thus, the same as the test result of pulsating frequency on the PHGMS separator, the performance of purification is significantly improved with the appropriate pulsating energy.

Pilot-scale PHGMS investigation

According to Fig. 4, under the optimized conditions, the two-stage PHGMS process achieved a non-magnetic concentrate assaying 0.023% Fe_2O_3, which does not reach the quality standard for quartz product not higher than 0.01% Fe_2O_3. Therefore, this primary concentrate is further cleaned by the same separator with the same test conditions, except the background magnetic induction is improved to 1.5 T, and the results are illustrated in Table 2. Obviously, with a two-stage PHGMS process, a high-quality quartz concentrate assaying as low as 0.0079% Fe_2O_3 is achievable from the quartz ore assaying 0.063% Fe_2O_3, at a high iron removal rate of 89.82%.

To investigate the possibility of the PHGMS process in industry, a two-stage pilot-scale process is applied to the quartz ore by a pilot test. In the process, the primary non-magnetic product is dewatered and then it is further processed with the separator. In addition, in the pilot test, the throughput is 0.1 Mg/h, the solid of feed is 20% and the pulsating stroke is 8 mm. It should be noted that the background magnetic induction, the wire diameter of the matrix and pulsating frequency of pilot separator

are same as the lab-scale separator. The pilot-scale PHGMS process achieved a nearly identical purification performance to that of the lab-scale one (Table 3).
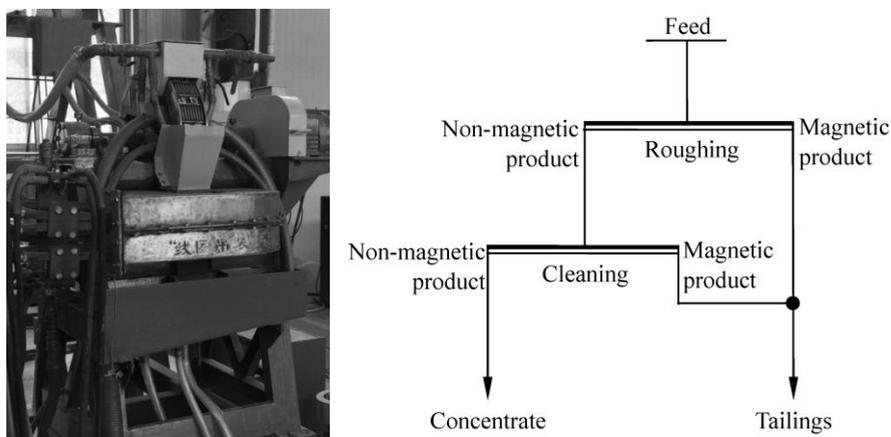

Fig. 5. SLon-500 pilot-scale PHGMS separator (right) and two-stage PHGMS process for purification of quartz ore (left). Conditions: rod matrix = 1.5 mm, background magnetic inductions = 1.3 T (for roughing) and 1.5 T (for cleaning)

Table 3. Performance comparison between lab-scale and pilot-scale PHGMS processes (%)

Separation methods	Fe_2O_3 content of feed	Concentrate of roughing stage				Concentrate of cleaning stage			
		Mass weight	Fe_2O_3 content	IRR	IRE	Mass weight	Fe_2O_3 content	IRR	IRE
Lab-scale	0.0633	90.02	0.0230	67.29	57.43	81.65	0.0079	89.82	71.51
Pilot-scale	0.0634	91.25	0.0265	61.86	55.94	81.17	0.0085	89.12	70.33
Difference	-0.0001	-1.23	-0.0035	+5.43	+1.49	+0.48	-0.0006	+0.700	+1.18

Conclusions

The PHGMS separators are effective in purification of quartz, and the investigation provides a common criterion for the operation of PHGMS separator while they are intended for purification of similar non-metallic ores. Compared with the separation characteristics of metallic ores by PHGMS, a much gentler pulsating intensity and a much higher magnetic induction are both required to maintain a high iron removal rate in the purification of quartz. The tests of pulsating frequency and the comparison test of HIWGS evidence that the presence of pulsating energy improves the separation performance of HGMS separator. Thus, it is an effective method to improve the separation efficiency of high gradient magnetic separation by introducing different separation force in the separation zone. Further, some of other force should be

introduced and investigated in the HGMS separator, such as centrifugal force and high-frequency vibration of magnetic matrix etc.

Acknowledgment

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