Modern Physics Letters B
Vol. 32, No. 30 (2018) 1830005 (8 pages)
© World Scientific Publishing Company
DOI: 10.1142/S0217984918300053

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High-temperature superconducting magnetic separation technology in China

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Received 1 October 2018
Accepted 4 October 2018
Published 30 October 2018

This paper makes a prospect of the future development in applications of superconducting high-magnetic separation technology to the mining industry with the analysis of domestic status quo of researches and applications in China.

Keywords: Magnetic separation; mining industry; high-temperature superconductor.

1. Introduction

More and more attention has been given to high-efficient utilization of mining resources and environmental quality with economic restructuring as well as the setup and completion of laws and regulations in China. Correspondingly, requirements for techniques of ore separations have become more and more strict. In the ores that are massively used in the glass, paper and ceramic industries, etc. the amount of ferromagnetic minerals will affect the whiteness and simpering characteristics of non-metallic ores. Therefore, the requirement for the content of ferromagnetic minerals is high. Even for the non-magnetic metallic ores, such as monohydrallite and porphyry Cu-Mo ores, the superconducting separation technology plays an important role in raising the grade of concentrates. Thus, in the mining industry, purification and separation of ferrous elements are very important in the technique requirements.[1]

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2. History and Progress of Development

The permanent magnets were selected to be the source of a magnetic field in the earliest techniques of the magnetic separation, and then changed to the electromagnetic separation that has been playing an irreplaceable role in separation techniques. However, the intensity of the magnetic field of an electromagnetic separator is arranged from 10,000 Gs to 20,000 Gs due to the limitation of the magnetic core and thermal resistance. Since the first superconducting magnet was born in 1961, several types of superconducting separators were investigated and manufactured[2] and put into industrial utilization. The equipment of magnetic separation has also been gradually improved and the separating results of magnetic separators in a concrete field were raised up as well. The discovery of superconducting separators breaks up the limitation of needing cooling of regular magnetic separators due to thermal effects and obtain a background magnetic field with much higher intensity than regular magnetic separators.[3,4]

In general, the superconducting separation techniques, in comparison to others, possess obvious advantages: (a) high efficiency of removing impurities, which works for weak magnetic particles and even for gel granules; (b) low consumption of energy, which produces a great saving of energy and deduction of consumption; (c) green and friendly environment and no chemical additives, which do not break down features of soils; (d) capacity of rapid excitation of magnetization and demagnetization, which reduces time of separation and washing impurities and thus obviously increases the quantity of treatment and (e) high level of automation. Therefore, taking into account the huge amount of poor sources of ores in China, superconducting magnetic separation possesses better environmental and economical benefits. However, the utilization of the techniques remains limited in China due to the high manufacturing costs and thus sale prices.

The first low-temperature superconducting magnetic separator of the industrial level, made by Weifang's Xinli Superconducting Magneto-electric S&T Co. Ltd. in China, with a room temperature aperture diameter of 300 mm and the central magnetic field of 5.5 T that is as high as more than 2.5 times that of a regular electromagnetic separator.[5,6] Since it was put into operation, it has experienced several hundreds of tests for a variety of non-metallic ores. In 2017, the comprehensive experimental platform of the first high-temperature superconducting separator, made by Chongqing Center for Superconductive Science and Technology (CCSST) affiliated to Chongqing Academy of Science and Technology in China, was used which had a room temperature aperture diameter of 100 mm and a magnetic field of 3.5 T. It was designed firstly for high purification of non-ferrous metallic poor monohydrallite and will be extended to separate metallic, non-metallic ores as well as to carry out treatments of urban contaminated water and wastes with addition of relevant facility. Now, it is in the process of testing and adjusting the equipment as a whole (Fig. 1).

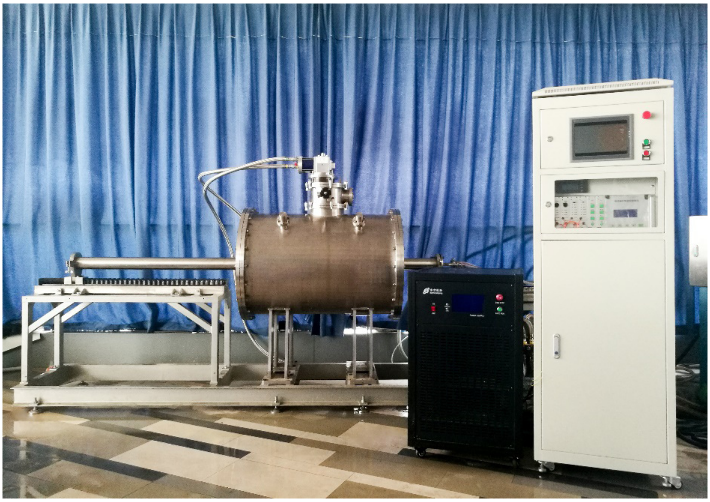

Fig. 1. The oscillating superconducting magnetic separator.

3. A Brief Description of an Oscillating Superconducting Magnetic Separator

No matter what kind of superconducting materials — high- or low-temperature superconductors (HTS or LTS) — are adopted for superconducting magnetic separators, the main structure is basically the same. It consists of a three segments: magnet, separation and control.

3.1. *Magnet*

The core part of a oscillating superconducting magnetic separator is its magnet. An LTS magnet mainly consists of a solenoid, liquid helium and cryogenic Dewar, aluminum shielding case and cooling head as well a yoke, among which the superconducting solenoid is made of NiTai alloys that is at the superconducting state at 4.2 K. Liquid helium and the collecting tower of the liquid helium and Dewar together provide 4.2 K cryogenic working environment. There is no aluminum case outside and the iron yoke plays a shielding role and partitions the separating area in order to ensure that the leaking magnetic field meets the national standard (Fig. 2).

With improvement in superconducting properties and the decline of its manufacturing costs as well as the decrease of costs and sale price of cryogenic coolers, it has gone into the practice to directly cool down a superconducting magnet. An HTS separator consists of a superconducting solenoid, the cooling head of a cryogenic cooler and shielding case and yoke, etc. Its structure is relatively simple in comparison with an LTS magnet. The superconducting magnet manufactured by CCSST is made of HTS $YBa_2Cu_3O_{7-x}$ (YBCO) tapes with width of 4.8 mm by means of layering doubly wound coils. The space between two coils is filled by insulators and

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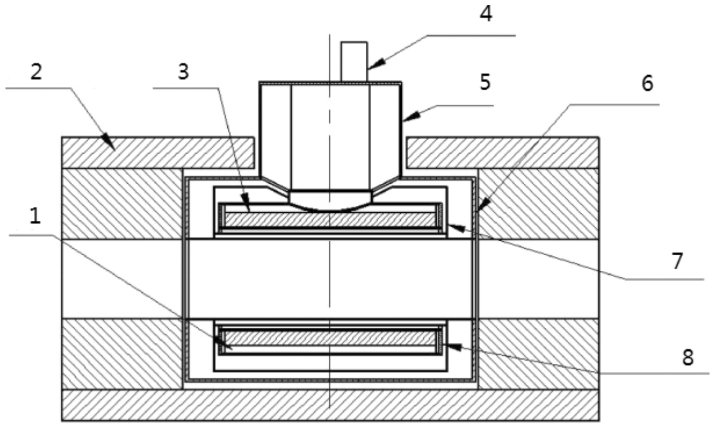

Fig. 2. Structural sketch of cryogenic superconducting magnet system. (1) Liquid helium zone, (2) iron yoke (magnetic shielding), (3) LTS solenoid, (4) cooling head of a cooler, (5) in and out lines and collecting tower of liquid helium, (6) Dewar's exterior cylinder (300 K), (7) cryogenic shielding (aluminum shielding case (60 K)) and (8) Dewar's interior cylinder (4 K).

a high conducting copper layer. A cryogenic cooler ensures a working environment of 10–30 K. There is a semi-closed adiabatic case made of high-conducting Cu, which is cooled down by the cooling head of first degree of a cryogenic cooler. All the parts maintain the same low temperature of 60 K. The iron yoke is placed in the interior of the outside shell, reducing the distance from the magnet and thus leading a more uniform magnetic field in the room temperature aperture (Fig. 3), while ensuring no leak of the magnetic field.

From the comparison of Fig. 2 with Fig. 3, it is seen that the HTS magnetic separator does not have a liquid helium zone. It only needs to get an evacuated space between the magnet and the shell. It is unnecessary to seal the interior. While there exists a liquid helium zone in the LTS magnet, it needs sealing the interior and resisting the high pressure from the liquid helium. Because the working zone of an HTS magnet is much greater than that in an LTS one, the designing requirements for heat leak of the Dewar is degraded.

Magnetization of every superconducting magnet is excited by a small exciting electric source. Once the magnetic field reaches its desired intensity, the magnetic field automatically enters the stable and permanent state. Under such a mode, the magnetic field remains forever without any external electric source. The compensation of the energy consumption is extremely low. For instance, the magnet manufactured by CCSST only needs about 0.22 kw. Only for maintenance of the separating area, the cooling head and/or filling in helium needs demagnetization.[7]

3.2. *Separating system*

An oscillating superconducting magnetic separator is alternately composed of three ineffective and two effective separation chambers. The effective separation chambers

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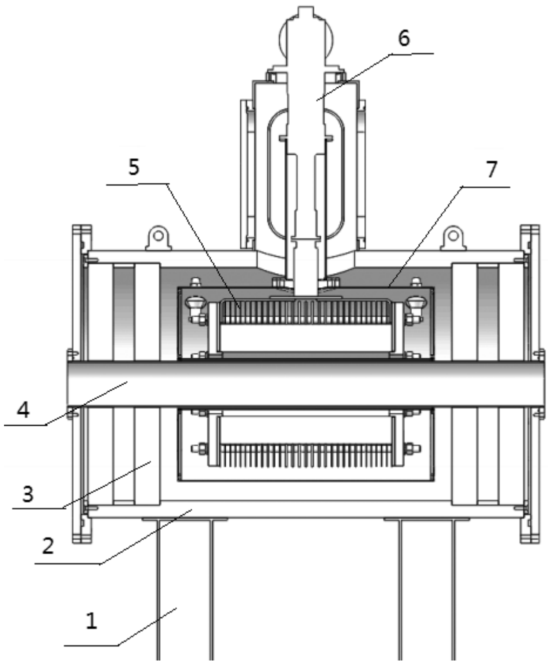

Fig. 3. Sketch of an HTS magnet. (1) Support, (2) shell, (3) yoke (magnetic shielding), (4) room temperature aperture, (5) magnet (10–30 K), (6) cryogenic shielding (aluminum shielding case (60 K)) and (7) cooling head.

are located in the magnetic field and affected by a uniform magnetic force and resisted in motion by the Lorentz force, whereas the ineffective separation chambers are used to balance the effective separation chambers for the magnetic balance and thus their designs and dimensions mainly depend on the design of equipment magnet in order to ensure the oscillating displacements of the group of the separation chambers in the magnetic field without needing large external forces. Moreover, the group of the separation chambers make horizontal oscillating displacements in preset time intervals under the accentuation of an electric motor. When ores are in the process of separation, the separation chambers in the magnet perform separations while the separation chambers outside the magnet are being washed and cleaned. Both are carried out alternatively, greatly increasing the separating efficiency.

4. The Newest Applications of Oscillating Superconducting Separators in China

4.1. *Chemical whitenization replaced by impurity-removal whitenization for Kaolin*

At present, Chinese industry of Kaolin widely adopts chemical whitenization to remove impurity and whiten soils. The chemical sensitization technology may result

Table 1. Main indexes of techniques of superconducting separation (%).

Index	Fe_2O_3	TiO_2	ISO whiteness	Recycling rate of concentrated ore
Raw ore	1.26	0.10	53	100
5.5 T concentrates	0.56	0.03	66	81
5.5 T tailings	2.31	0.22		19
1.0 T concentrates	0.79	0.05	56	92
1.0 T tailings	6.01	0.15		8

in severe environmental pollution and corrosion of equipment. Meanwhile, it may change the previous properties of raw Kaolin, reducing the applied fields of products, Taking the example of Kaolin with irons in Zhangzhou analyzed by China Kaolin Co. Ltd., under a variety of conditions of magnetic fields, it treats Kaolin by using steel hairs as a high gradient medium. The results are listed in Table 1. As can be seen, when the magnetic induction rises from 1.0 T to 5.5 T, the content of ferric oxides in the concentrates after magnetic separation decreases from 0.79 to 0.50, whereas the whiteness of the concentrates increases from 56% to 66%. This experiment shows that the increase of the magnetic induction from 1.0 T to 5.0 T obviously raises up the magnetic impurity-removing capability of the red soils in Zhangzhou. Similar hematite and goethite all present weak magnetization. This experiment is in accord with the theory that the separation efficiency of weak magnetization ores increases with the increase of magnetic induction. The highest magnetic induction of a regular electric magnet or permanent magnet is about 1.0 T. As seen from this experiment, the result of removing irons and whiteness of Kaolin in Zhangzhou in terms of a superconducting magnetic field is far more advanced than a conventional magnetic field. To reach 1.0 T of the magnetic induction, a conventional electric magnet needs water to cool the equipment, increasing the treatment costs. The superconducting magnetic separation is a better technology for iron removal and whiteness of Kaolin in Zhangzhou.[8]

4.2. *Reduction of the copper content in molybdenum concentrates after copper-molybdenum separations in a floatation*

The raw ores of this kind of mineral deposits are of low quality and its mosaic size is quite fine and the main recycled ores are copper pyrites and molybdenite that possess a layered structure and better natural floatability and generally exist with copper pyrites and iron pyrites in the form of commensalism, leading to a difficulty of separation.[9] At present, most of copper-molybdenum mining enterprises adopt the copper-floating and molybdenum-suppressing separation technique of flotation, resulting in the long process of techniques, high costs, severely contaminating environment and great overlimit of copper content in the molybdenum concentrates.[10,11] The average coefficient of magnetization of copper pyrites is 67.53×10^{-9} m^3/kg and weak magnetic, whereas the average coefficient of magnetization of copper-molybdenum is -0.098×10^{-9} m^3/kg and non-magnetic.

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Table 2. Grading of concentrated molybdenum ores — superconducting separation results.

		Grade %		Recycling ration %	
Name of products	Production ration/%	Cu	Mo	Cu	Mo
Concentrate 1	49.97	0.037	53.43	2.72	51.64
Concentrate 2	43.19	0.373	53.06	23.68	44.32
Concentrates	93.16	0.193	53.26	26.40	95.96
Tailings	6.84	7.32	30.52	73.60	4.04
On-site MC	100	0.680	51.70	100.00	100.00

Note: MC — molybdenum concentrates.

The Zhengzhou Institute for Comprehensive Utilization of Mineral Industry, affiliated to China's Academy of Geological Science, uses superconducting magnetic separation to carry out experimental investigations on fine copper pyrite. They carried out optimization of experiments mainly on pulse number, amount of dispersants and intensity of the background magnetic field and the diameter of magnetic matrices and finally found out that under the condition of the background magnetic field of 3.582 kA/m, the amount of sodium hexametaphosphate needed of 0.15%, and pulse number of 40 Hz, selecting a separating dielectric rod of 3 mm to perform grading and experiments of the superconducting magnetic copper-molybdenum separation for molybdenum concentrates, a good result of reduction of the copper content has been reached. The results are listed in Table 2.[12]

It can been seen from Table 2 that the molybdenum concentrates can reach as ideal target as the general recycling ration of molybdenum of 95.96% with Cu content of 0.193%, Mo content of 53.26% and production ration of 93.16% after superconducting magnetic separations. The Cu content in the molybdenum concentrates has been reduced to below 0.2%, which meets the requirement of the relevant industry and further raises the grade of Mo.

5. Prospect of Applications of Superconducting Magnetic Separator

With the progress of science and technology as well as the development of industrial practices, HTS magnetic separation technology has exhibited more and more advantages with respect to purification of Kaolin, ore separation, sulfur-removal of coals, treatment of contaminated water. On the other hand, the tendency of combining the superconducting magnetic technology with other technologies, such as bio-treatment technology of water, artificial wetland techniques, integration of the membrane separation technology and superconducting magnetic technology, etc., has become appreciable. Further developments and applications of the superconducting magnetic separation technology will lead to more and more economical and environmental benefits.

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Acknowledgment

The work was funded by the Grant of 2015DFR00120 from the Ministry of Science and Technology of China.

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