Development and Application Characteristics of High Gradient Magnetic Separator

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Abstract. As one of the most effective techniques for fine particle processing, high gradient magnetic separation is mainly used in the separation and enrichment of fine and weak magnetic particles and other important industrial fields. High gradient magnetic separator is a new type of high intensity magnetic separator, which has strong ability to capture fine and weak magnetic particles, developed on the basis of ordinary high intensity magnetic separator. Based on the early periodic - high -gradient magnetic separators, the optimization development direction of high gradient magnetic separators and their application characteristics of various high gradient magnetic separators in these decades were summarized, and the future development directions of high gradient magnetic separator were presented.

1. Introduction

High gradient magnetic separator is a new type of high intensity magnetic separator developed on the basis of ordinary high intensity magnetic separator. Its basic principle is that when ferromagnetic filaments are magnetized to saturation in a uniform magnetic field, the high magnetic field gradient generated can produce strong capture ability for fine and weak magnetic particles [1]. As one of the most effective technologies for fine particle processing, HGMS is mainly used for the separation and enrichment of fine and weak magnetic particles (hematite, limonite, ilmenite, wolscheite, etc.), coal desulfurization, kaolin purification, wastewater treatment, etc. [1].

As for the typical physical separation technology of high gradient magnetic separation, equipment is the key factor to drive its development. In 1969, in a Kaolin company in the United States, the world's first industrial grade periodic high gradient magnetic separator was applied to kaolin purification [2], which marked the fine particle magnetic separation recovery technology into a new stage of development. In recent decades, with the accelerating progress of mineral resources exploitation and the increasing difficulty of resource processing and utilization, the research on magnetic separation equipment has made great progress. At present, a variety of types of high gradient magnetic separators have been developed at home and abroad. In terms of feeding mode, it can be divided into periodic and continuous type; In terms of material sorting state, it can be divided into dry and wet; In terms of sorting ring placement, it can be divided into flat ring and vertical ring; In terms of magnetic system type, it can be divided into electromagnetic and permanent magnet type (electromagnetic and can be divided into conventional electromagnetic and superconducting electromagnetic).

On the basis of the early periodic high gradient magnetic separators, the optimization development direction of high gradient magnetic separators and the application characteristics of various high gradient magnetic separators emerged in these decades were summarized in this paper.
2. Early Cycle Type High Gradient Magnetic Separator

In 1968, the Former Magnetic Engineering- joint company of the United States developed the world's first high gradient magnetic separator, that is, the early cycle type electromagnetic high gradient magnetic separator. Its main characteristics are: using stainless steel magnetic steel wool as separation medium, its ferromagnetic steel wool medium in the background magnetic field higher than 0.75 T will reach magnetization saturation and produce high magnetic field gradient level of 10^5 T/m of magnitudes, and the force course is short. The application effect showed that the high gradient magnetic separator has a strong ability to collect fine weak magnetic particles. It is suitable for kaolin purification, wastewater treatment and separation of various fine and weakly magnetic minerals [3]. Later, in the early 1970s, the United States and Sweden also developed PEM and SALA periodic electromagnetic high gradient magnetic separator, which were respectively applied to kaolin purification and steel plant wastewater treatment [4].

In China, the research and development of high gradient magnetic separation equipment lags behind foreign countries for more than 10 years. In the mid and late 1970s, Shenyang Mining Machinery Factory and other units in China developed periodic electromagnetic magnetic filter and magnetic separator [5], and carried out tests in fine iron ore dressing, iron removal from non-metallic ore and wastewater treatment.

The early periodic type electromagnetic high gradient magnetic separator has a good separation and treatment effect on the magnetic content of fine particle materials. In industrial application, this type of equipment is mainly suitable for kaolin and other non-metallic ore iron enhancement and wastewater treatment. In addition, this equipment is often widely used in the form of test equipment in fine mineral processing experimental research.

The main advantages of early periodic electromagnetic high gradient magnetic separator are [1]: less magnetic leakage, low medium filling rate (only 4% ~ 14%), Equipment with analogue amplification, low equipment production costs (the investment of unit magnetization volume is about half of the continuous type). The main disadvantages of early periodic electromagnetic high gradient magnetic separator are: (1) equipment load cycle rate is low, can only work intermittently, (2) processing magnetic material with high content, will lead to greatly reduced productivity of equipment (industrial applications are not suitable for processing magnetic material with high content). (3) It is easy to lead to medium (mechanical) blockage and magnetic inclusion, which is not conducive to improving the grade and recovery of magnetic products; (4) the use of electromagnetic materials as magnetic system is not conducive to energy consumption.

3. Optimization Development of High Gradient Magnetic Separator

In order to overcome the above many shortcomings of early high gradient magnetic separators and better serve industrial production, researchers at home and abroad have constantly optimized and developed high gradient magnetic separators from the following aspects: improving the load cycle rate of magnetic separation equipment; preventing medium (mechanical) blockage; reducing magnetic inclusion and blockage; improving (magnetic) capture power and separation accuracy; increasing the background magnetic field intensity of separators, promoting separators to scale up; energy saving and consumption reduction, and other aspects.

3.1. Research and Application of Improving Separator Load Periodic Rate

In order to improve the load periodic rate of magnetic separator and improve the processing capacity of fine particle separation, Sala Company in Sweden developed Mark type and SALA-HGMS1 type flat ring high gradient magnetic separator in the 1970s on the basis of periodic electromagnetic high gradient magnetic separator [6]. Later, some domestic scientific research units also developed laboratory and production SHP type flat ring type high gradient magnetic separator, but which has not yet formed series. In the late 1970s, SALA-HGMS480 continuous flat ring high gradient magnetic separator was used stern Lhasa Iron Mine in Sweden. Tailings with -19 μm fine particle content of 55.30%, main iron minerals are hematite and iron grade of 11.50% are used as feeders. After one-time high gradient magnetic separation, iron concentrate with iron grade of 42.61% and tailings with iron grade of 7.05% were obtained [7].
The main advantages of the continuous flat ring high gradient magnetic separator are: the equipment load periodic rate is greatly improved. The main disadvantages are: the sorting ring (rotating ring) is placed horizontally; the main use of toothed plate type or mesh type media to capture magnetic particles, in the process of material sorting, this will produce frequent mechanical blockage and magnetic blockage and seriously affect the effect of material sorting.

3.2. Research and Application of Preventing Medium Clogging
Poor selectivity and easy to cause medium (mechanical) blockage and other reasons greatly limit the application of flat ring high gradient magnetic separators. In order to effectively alleviate this problem, in the 1980s, the United States and other countries developed a variety of types of vertical ring high gradient magnetic separators represented by iron wheel magnetic separator.

The main advantages of vertical ring high gradient magnetic separators are: the use of reverse water to wash magnetic particles, so that the coarse particles in the pulp could not pass through the magnetic medium but washed out by reversed water, which effectively alleviate the mechanical blockage of the magnetic medium pile. The main disadvantages are as follows: when dealing with materials with high magnetic content, especially when strong magnetic minerals are not removed in low intensity magnetic separation operation, it is easy to lead to magnetic inclusion, which makes the selectivity of the separation process worse, and even occurs magnetic blockage and interferes with the separation process in serious cases.

3.3. Research and Application of Reducing Magnetic Inclusion and Blockage
In order to reduce the magnetic inclusion and plugging phenomenon caused by early high gradient magnetic separator processing materials with high magnetic content, relevant scholars organically combined magnetic force and mechanical vibration force or pulsating fluid force, and successively developed vibrating high gradient magnetic separator, pulsating high gradient magnetic separator and vibrating-pulsating high gradient magnetic separator.

3.3.1 Vibrating High Gradient Magnetic Separator. In 1974, the United States invented the vibrating high gradient magnetic separator, and its main advantage is conducive to remove the non-magnetic components from the magnetic material. So far, Scholars at home and abroad have developed the following three types of vibration high gradient magnetic separators: Solenoid electromagnetic vibration high gradient magnetic separators, transverse magnetic field electromagnetic vibration high gradient magnetic separators, and solenoid mechanical vibrating high gradient magnetic separators.

The solenoid electromagnetic vibration high gradient magnetic separator arranges an AC coil below each section of medium, and uses the coil and strong background magnetic field to drive the medium to vibrate, so as to reduce magnetic inclusion and blockage in the separation process. The transverse magnetic field electromagnetic vibrating high gradient magnetic separator [8] is a kind of small testing machine, successfully developed in 1982. This kind of equipment uses the gap between ac coil and iron core magnetic system as the background magnetic field. Due to the close position relationship between coil and magnetic pole, the coil and magnetic pole will vibrate when they are subjected to the non-uniform magnetic field force at the edge of magnetic pole, thus driving the vibration of the sorting box, so as to reduce the magnetic inclusion and blockage in the sorting process.

The solenoid mechanical vibration high gradient magnetic separator [9] adds an additional set of mechanical vibration mechanism, and fixes the separation medium on the vibration part to make it vibrate up and down with the vibration part, so as to reduce the magnetic inclusion and blockage in the separation process.

3.3.2 Pulsating High Gradient Magnetic Separator. The pulsating high gradient magnetic separator is installed a spare part at the bottom of the traditional high gradient magnetic separator to create a way to make pulp do up and down motion, so in the process of sorting, magnetic particles will be extra competitiveness by a magnet force, for which makes the magnetic particles adsorbed by the assembled
magnetic medium surfaces loose, and reduce the magnetic inclusion and the blockage of the medium stack [10-11].

3.3.3 vibrating-pulsating High Gradient Magnetic Separator. Ganzhou Institute combined the principle of vibration and pulsation, and developed SLon vibrating-pulsating high gradient magnetic separator, which is currently being debugged.

3.3.4 Application characteristics of vibrating and pulsating high gradient magnetic separator. (1) Due to easy wear and electric leakage of coils, inconvenient maintenance and other reasons, solenoid electromagnetic vibrating high gradient magnetic separator failed to be applied in industry.

(2) The transverse magnetic field electromagnetic vibrating high gradient magnetic separator has been mainly used in the experimental study of the separation of refractory fine wolframite and cassiterite, and has achieved good application effect. However, the disadvantage of the magnetic pole gap should not be too large, resulting it in limited application scale.

(3) Because of the greatly reducing the blocking of separation medium, improving the separation effect, and shortening the time of washing magnetic products, the solenoid mechanical vibrating high gradient magnetic separator has a good prospect of industrial application. CL-φ 500, the first solenoid mechanical vibrating high-gradient magnetic separator in China, was developed around 1982, but the equipment was mainly suitable for kaolin magnetic filtration purification [12-13].

(4) The development of vibrating-pulsating high gradient magnetic separator is still in the debugging research, but it is predicted to achieve better application effect than a single vibrating or pulsating high gradient separator.

(5) In the recent 20 to 30 years, pulsating high gradient magnetic separation has developed into a common key technology for separation of weakly magnetic particles, which is widely used in separation of weakly magnetic metallic and non-metallic ores [14]. Slon type pulsating high gradient magnetic separator has formed many series of products and is widely used in industrial production. Salon type vertical ring pulsating magnetic separator is used for separation of red iron ore. Compared with flat ring high intensity magnetic separator, the iron recovery rate can be increased by 10% under the condition of constant iron concentrate grade, and the phenomenon of magnetic medium blockage can be greatly reduced [15]. However, long-term production practice shows that pulsating high gradient magnetic separation can obtain ideal recovery rate, but its selectivity is low. It is mainly confined to coarse operations at the front end of the production process, and a large number of low-grade tailings are discarded in advance to create favourable conditions for subsequent flotation, gravity separation and other cleaning operations [14].

3.4 Research and Application of Improving Capture Power and Sorting Accuracy

The multi-force field high gradient magnetic separator is based on improving (magnetic) capture force and the purpose of sorting accuracy, developed by utilization of magnetic and other fields. In recent years, the most successful representative multi-force field high gradient magnetic separator is centrifugal high gradient magnetic separator.

Centrifugal high-gradient magnetic separation is a new high-gradient magnetic separation method proposed by Professor Chen Luzheng of Kunming University of Science and Technology in 2010 [16]. At present, Professor Chen and his team workers have developed various types of centrifugal high-gradient magnetic separation equipment, and experimental studies of typical weak magnetic ores did by using the test equipment have achieved excellent separation indicators, fully confirmed the effectiveness and feasibility of the new centrifugal high gradient method and equipment [17-18].

Zheng Yongming et al. [16] used CenMag100 centrifugal high-gradient magnetic separator to separate a low-grade ilmenite ore from Yunnan. Through a rough separation, titanium coarse concentrate with TiO$_2$ grade and recovery of 36.67% and 49.70%, respectively, could be obtained, and the recovery of optional TiO$_2$ reached a good separation index of 79%. These indexes of the titanium coarse concentrate are obviously superior to the current practical process index of "pulsating high gradient magnetic separation roughing-shaker cleaning". The yield, TiO$_2$ grade and recovery of concentrate are respectively 4.00%, 4.17% and 24.83% higher than the latter, while the TiO$_2$ grade of
tailings is 1.63% lower. When the coarse titanium concentrate of centrifugal high gradient magnetic separation was concentrated by shaking table, it was found that TiO₂ grade of shaking table concentrate increased limited, but the recovery rate decreased significantly, indicating that centrifugal high gradient magnetic separation has high separation accuracy.

A large number of research results show that centrifugal high gradient magnetic separation process can replace or shorten the existing separation process for fine weakly magnetic minerals. Centrifugal high gradient magnetic separator compared with many pulsating high gradient magnetic separator has the advantage of powerful capture and high precision. However, the centrifugal high gradient magnetic separator research is still in the mid-term stage, and the successfully used equipment is mainly series of experimental scale.

3.5 Research and Application of Other Performance Aspects of High Gradient Magnetic Separator

In recent years, from the aspect of increasing the background field strength of high gradient magnetic separator, promoting the large-scale equipment and energy saving, researchers at home and abroad have developed a variety of new high gradient magnetic separator with excellent performance. In terms of improving the background field strength of the equipment, DMG developed by Maanshan Mine Research Institute took the lead in lifting the background magnetic induction intensity of the electromagnetic vertical ring high gradient magnetic separator to 2T, which achieved outstanding effect in the application field of removal of iron from andalusite [19]. The disadvantage is that the diameter of the sorting ring of DMG is only 1.2m, and the processing capacity is small.

The reciprocating series tank type high gradient superconducting magnetic separator developed and produced by a certain department in the United States can realize the magnetic components from the magnetic medium surface under the condition of without demagnetization. The characteristics of this equipment are: magnetic field intensity could be up to 2-10T, could be used to separate micron weak magnetic materials with magnetic coefficient of 1×10⁻⁶cm³/g. Compared with similar periodic high gradient magnetic separator, its power consumption is reduced by 1/10, while the processing capacity is 9 times higher [8]. In recent years, Shandong Huate magneto electric co., LTD, and Chinese Academy of Sciences electrician institute jointly developed the domestic first 5.5 T non-volatile low temperature high gradient superconducting magnetic separator [20]. Because of the price advantage of this separator compared with the same products abroad, the type high gradient superconducting magnetic separator has been applied gradually in some related industries of china. Compared with conventional magnetic separator, the high gradient superconducting magnetic separator has high magnetic field intensity, and can greatly reduce energy consumption.

In terms of expanding equipment specification, shandong Huate magneto electric company of china has developed the largest evaporative cooling type vertical ring high gradient magnetic separator with sorting ring diameter of 3.6 m, the background of magnetic induction intensity of 1.8 T.Shenyang Longji electromagnetic technology co., LTD., etc. and several magneto electric equipment manufacturers in China also produced a 3 m models of large high gradient magnetic separator with diameter of the sorting chamber reached 0.5m,which showed a good practical application effect [21].

In terms of energy saving, scholars at home and abroad have carried out a lot of research on the development and application of permanent magnet high gradient magnetic separator for many years. In the 1980s, the "iron wheel" dry permanent magnet high gradient magnetic separator developed by American BATMAN Company was used to recover weak magnetic iron minerals from iron fusilier tailings. Lately the wet "iron wheel" permanent magnet high gradient magnetic separator was developed at home and abroad on the basis of the dry permanent magnet high gradient magnetic separator [22]. Scientific research bases of colleges and universities such as Central South University in China have also successfully developed various types of permanent magnet high gradient magnetic separation [23-26], and successfully applied in the separation of various materials and iron removal process of non-metallic ores at home and abroad. Compared with electromagnetic magnetic system, permanent magnetic system has the important advantage of saving energy consumption.

4. Conclusions

(1) After just a few decades of development, high gradient magnetic separator has been developed into
a variety of types and models of equipment. All kinds of high gradient magnetic separator s have been widely used at home and abroad, and obtained good technical application indicators, but in terms of all kinds of equipment, its magnetic circuit structure, magnetic field characteristics, suitable processing material characteristics and so on are relatively few. Therefore, it is necessary to carry out in-depth research in the above aspects in the future.

(2) The current magnetic system of high gradient magnetic separator is mainly electromagnetic, with high energy consumption, complex structure and other obvious disadvantages. On the contrary, permanent magnet, superconducting magnetic system can greatly reduce energy consumption, under these circumstances, new permanent magnet and superconducting high gradient magnetic separator will become a hot research and development i n the future.

(3) The separation principle and application results showed that vibrating - pulsating high gradient magnetic separator and the multi-force field high gradient magnetic separator has good application prospect in separation of weak magnetic minerals with characteristics of "poor, fine, complexity". As a result, it is necessary to speed up the development of these kinds of separators, and from the aspect of saving energy and reducing consumption, it is also necessary to develop large-scale and energy-saving separators.

(4) High gradient magnetic separators have many special unique advantages in processing fine weak magnetic materials. In china, some of these resources have the characteristics of "poor, fine, complexity" and most of the existing treatment processes have the disadvantage of complex and long technological process, and using a lot of processing equipment. Therefore, the multi-force field of high gradient magnetic separation technology research and the development of new equipment upon this idea should not be ignored.

5. References

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