Application and Prospect of Superconducting High Gradient Magnetic Separation in Disposal of Micro-fine Tailings

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Abstract: Magnetic separation technology is playing an increasingly important role in the field of environmental protection such as waste gas, waste water and solid waste treatment. As a new type of solid waste treatment technology, superconducting high gradient magnetic separation (HGMS) is mainly applied in the separation of micro-fine weakly magnetic particles because of the advantages of high separation efficiency, energy saving, simple equipment and easy automation. In this paper, the basic principle of superconducting HGMS was firstly introduced, then the research status of scholars at home and aboard on the disposal of micro-fine tailings were summarized. Finally, the direction of development for HGMS was put forward.

1. Introduction
Mineral resources are the important material foundation for the survival and development of human society. About 85% of the raw materials come from mineral resources in the process of rapid development of modern industry, and the demand for mineral resources is increasing rapidly[1]. Due to the complicated mineral composition and the backward mining technology, the resource loss is very serious in the exploitation of mineral resources, and a large amount of tailings are come out. In China, the average grade of iron ore is only 30%, 70% of the mineral resources will become tailings; mineral separation of copper, zinc and other mineral will produce more than 90% tailings; the tailings of gold, tungsten and other precious metals can be as high as 99%[2]. According to statistics, by 2015, China's iron tailings has reached more than 8 billion tons, and showed an increasing trend year by year[3]. The stockpiled tailings not only take up a lot of cultivated land, pollute water body, destroy the ecological environment, but also induce serious security risks. In order to maintain the safety of the tailings dam and reduce the environmental damage caused by tailings, miners enterprise and government every year put a lot of money and manpower, but still difficult to avoid disaster accidents. For example, on September 8, 2008, a particularly significant dam break accident had been happened in New Tower Mining Co., Ltd which located in Xiangfen, Shanxi Province. Accident discharged capacity of 268000 m³, mud area of 0.3 km², affecting the lower reaches of the mining area of about 500 m of office buildings, markets and some houses, the death toll was 277, the injured was 33 and 4 persons were missing, the direct economic losses of 96.192 million yuan. On November 23, 2015, Longxing Antimony Mining Co., Ltd which located in Xihe County, Longnan City, Gansu Province, occurred tailings leakage, and resulted in an abrupt environmental events across Gansu, Shaanxi, Sichuan three provinces. It serious impacted on people's production and living water. After assessment, the event caused a total economic loss of 6120.79 million Yuan. According to statistics, since 2000, the national...
total of more than 70 cases of tailings accidents had occurred. It brought a great harm to the survival of the people. According to the United States Clark University of Public Health Assessment Group research results show that the hazards of tailings accident was ranked 18th in the 93 kinds of accidents hazards\[4\]. Therefore, how to effective comprehensive utilization the tailings has become a hotspot in the field of scientific research workers under the severe situation of the shortage of mineral resources and the double pressure of the safety and damage of ecological environment caused by tailings.

From the point of view of resource utilization and law of conservation of mass, there is no "waste" in the world, and all substances can be participated in the next material cycle \[5,6\]. At present, it is generally believed that the tailings are a kind of resource that is put in the wrong place, and the tailings can be reclaimed by scientific separation and recycle technology. Comprehensive utilization of tailings can not only alleviate the increasingly scarce resources, but also can reduce the ecological and environmental pollution problems, to bring huge economic benefits, also is the mining enterprises take the direction of sustainable development\[7\].

Micro-fine particles easily lead to mineral particles on the surface of hydration film, due to minimal particle size, and have an important effect on its dispersion and aggregation in aqueous solution\[8,9\]. At the same time, it is extremely easy to slime. The traditional processing such as gravity separation, magnetic separation and flotation to deal with these micro-fine minerals are difficult to achieve satisfactory results. When used to treat such ore, it could not be effectively recovered, and caused a large number of useful mineral loss \[10\]. The superconducting high gradient magnetic separation (HGMS) technology has become one of the most promising new tailings recycling technology with unique separation principle and many advantages. With the continuous development of technology theory and equipment, it has been expanded and successfully applied in industrial solid waste and mine tailings. It has unique advantages in dealing with micro-fine weakly magnetic particles and non-magnetic particles in solid waste. In this paper, the development of superconducting HGMS was firstly introduced and the research status was summarized, then the direction of development for HGMS was analyzed.

2. Development of Superconducting HGMS

Magnetic separation is physical separation method based on the difference in magnetic properties of various ore minerals or materials \[11\]. The schematic diagram of the separator is shown in Figure 1\[12\]. Application of magnetic separation technology began in 1792, the British scholars used magnetic separation technology for iron ore selection. They got a good mineral processing indicator, and subsequently declared the relevant patents. In 1845, the United States invented the industrial magnetic separator, by the 1920s, various types of magnetic separators successive came out, magnetic separation technology in the field of mineral processing continue to get development and improvement. But at this time the magnetic separation technology can only be separated from large and strong magnetic particles, while the separation of paramagnetic and weakly magnetic particles was powerless, magnetic separation technology was greatly limited\[13\].

![Figure 1. Schematic diagram of magnetic separation](image-url)
In the design of the magnetic separator, the magnetic field strength and the magnetic field gradient are the two most important variables that affect the separation effect. Magnetic field gradient refers to the magnetic field strength in the direction of the magnetic field rate of change. Figure 2 illustrates two different magnetic field morphologies. Case A represents a uniform magnetic flux pattern without a magnetic field gradient, and the field strengths at any point are substantially the same. Hence, the magnetic particles entering the magnetic field will be attracted to the magnetic flux line and then remain fixed. Case B represents a high gradient magnetic field pattern in which the flux is converged. When such a magnetic flux passes through a smaller area, the magnetic field strength will increase significantly. The magnetic particles entering the magnetic field will not only be attracted to the magnetic flux line, but will also move to the region with the largest magnetic flux density, usually at the top of the bottom pole piece. In short, the magnetic field absorbs the particles while the magnetic field gradient moves the particles [14].

![Figure 2. The illustration of two kinds of magnetic field gradient](image)

In the early 1970s, the American scholars raised up the HGMS technology research, they used the interaction of different magnetic particles and magnetic matrix (usually ferromagnetic metal wire) which are in magnetic field. Ferromagnetic metal wire in the magnetic field produces a high gradient magnetic field with uneven distribution of magnetic field intensity. Magnetic particles are subjected to magnetic forces and they are easily separated from non-magnetic particles. As the HGMS device can be large-scale, rapid separation of magnetic particles, so the application scope of HGMS technology has gone beyond the traditional magnetic mineral processing, now into the waste gas, waste water and other environmental protection areas. However, because of magnetic field intensity constraints, the slurry flow velocity is low, processing capacity is small, non-magnetic and weakly magnetic particles are difficult to separate [15].

Usually the main magnetic material (ferromagnetic material) of magnetic separator has magnetic saturation limit (2 T), so the magnetic flux density of conventional magnetic separator has no more than 2 T. To break this limitation, need to change the magnetic material from the ferromagnetic to superconductor. When the material in the superconducting state, the resistance is zero, so in a fine superconducting wire, can pass a lot of current, no heat loss, which can be get more than 2 T super magnetic field[16]. After a long period of exploration, superconducting technology came into being, the use of superconducting coil instead of the conventional copper coil, can be up over to 10 T high gradient magnetic field [17], so that the scope of application greatly expanded, not only can handle magnetic particles, weakly magnetic or even non-magnetic particles can also be adsorbed and separated.

The development of superconducting HGMS technology makes it possible for magnetic separation to be used for separation and recycle of valuable materials from micro-fine tailings. As the superconducting operation of zero resistance, low power consumption, less area demanded and high degree of automation. At the same time, it is the most potential new technology under the energy saving emission reduction situation, and has the advantages of environmentally friendly. Hence, superconducting HGMS technology will have a good prospect of industrial application.
3. Application Status of Superconducting HGMS in Micro-Fine Tailings

At present, cryogenic superconductivity high gradient magnetic separator is widely used. According to the presence of magnetic matrix, they can be divided into superconducting high gradient magnetic separator (with magnetic matrix) and superconducting open gradient magnetic separator (without magnetic matrix). While the former accounted for the majority. According to the transmission medium they can be divided into dry and wet superconducting high gradient magnetic separator.[18]

3.1. The Application Instance of Dry Superconducting High Gradient Magnetic Separator

The United States Auburn University and Oak Ridge National Laboratory (ORNL) conducted dry HGMS of coal desulfurization experiment and achieved success in 1976. Then they started to make dry high gradient magnetic separator research work. The main processes are: 1, low speed airflow--gravity feed dry HGMS process[19]; 2, airflow feed dry HGMS process[20]; 3, circulating air fluidized bed feed dry HGMS process[21].

In the Iron and steel industry, the number of iron particles in the dust, which produced by the top bloom oxygen converter and electric arc furnace steelmaking, is particularly large. Take Guangzhou Iron & Steel Company as an example, converter steelmaking dust is strong magnetic substance, the specific magnetic susceptibility of dust is greater than $38 \times 10^{-6} \text{m}^3/\text{kg}$. But the particle size of the dust is very small, $-74 \mu\text{m}$ particles size accounted for 96.85%. The separation efficiency is not satisfactory using traditional magnetic separation technology. As the high magnetic field intensity and high magnetic field gradient advantages, the HGMS technology can make the magnetic particles in the dust be subjected to great magnetic force and easily overcome the viscous force of the airflow, thus effectively capturing the micro-fine magnetic particles in the dust. Wu Xiuwen et al.[22] took the dust which from Guangzhou Iron & Steel Company as the research object. They carried out dust removal experiments to investigate the use of dry HGMS technology. The experimental results determine the optimum process parameters i.e., magnetic flux density of 0.52 T, magnetic matrix filling ratio of 2%, gas flow of 12 m$^3$/h. The total dust removal efficiency can reach 94.7%.

The grain size of a potassium feldspar ore in Lianzhou City Guangdong Province is $-45 \mu\text{m}$, the content of Fe$_2$O$_3$ is 0.41%, and mechanical iron is 0.1%. It mainly composed of ferrous manganese ore which is weakly magnetic mineral. Feng Dingwu et al.[23] employed a dry superconducting high gradient magnetic separator to remove metal impurity from feldspar. The potassium feldspar powder is dried and transported by wind to a separator. When the powder passes through the dispenser nozzle, the gas expands so that the particles are sufficiently dispersed. Dispersed magnetic particles are captured by magnetic matrix by vibrating superconducting high gradient magnetic separator. Under the condition of magnetic flux density of 1.0 T, particle flow velocity of 2.0 m/s, magnetic matrix filling ratio of 3.8% and magnetic matrix vibration frequency of 30 Hz. The content of Fe$_2$O$_3$ in magnetic concentrate decreased from 0.41% to 0.27%, the recovery rate of nonmagnetic material was 80.8%.

3.2. The Application Instance of Wet Superconducting High Gradient Magnetic Separator

Currently in the field of industrial production the superconducting high gradient magnetic separator is mainly wet type. The schematic diagram of common wet type separator is shown in Figure 3[24]. The advantage of wet HGMS is that it is easy to disperse for pulp and high separation efficiency. The shortcomings are: 1, dry materials need to add water into pulp; 2, magnetic concentrate need dehydration and drying, micro-fine particles are easy to loss during dehydration process; 3, some dry process does not allow the introduction of wet operation[25,26].
1-concentrate trough, 2-magnetic drum, 3-iron yoke, 4-separating cylinder, 5-the main magnetic system, 6-deputy magnetic, 7-feed device

**Figure 3** Schematic diagram of wet superconducting high gradient magnetic separator

Zhejiang Huangyan Lead Zinc Plant produces 100 tons of tailings per day, the tailings (without any treatment) are stacked directly in tailings impoundment, which seriously threaten the survival of downstream residents. Main components of tailings are silicate and containing aluminum minerals, such as quartz, sericite, illite, etc. Those can replace feldspar for ceramic energy-saving raw material and make the porcelain temperature reduced by about 100 °C. However, ceramic energy-saving material requests the content of Fe₂O₃+MnO less than 1.5%, while the content of Fe₂O₃+MnO in Huangyan tailings is 14.03%, which is far beyond the standard. The presence of Fe and Mn is mainly pyrite, hematite, rhodochrosite, manganese calcite, which can be easy to remove by superconducting HGMS. Peng Shiying[27] carried out a laboratory study on the tailings, the results confirm the optimal parameters i.e., magnetic flux density of 1.3 T, slurry flow velocity of 2.32 cm/s, slurry concentration of 10%, dispersant (sodium hexametaphosphate) of 2.5 kg/t, magnetic matrix filling ratio of 5%. The content of Fe₂O₃ in magnetic concentrate has decreased from 6.66% to 1.05% and MnO from 6.82% to 0.41%. Obviously, superconducting HGMS is a very effective way to remove Fe and Mn impurities from the tailings. The content of Fe₂O₃+MnO in magnetic concentrate is less than 1.5%, which meets the requirement of ceramic energy-saving raw materials.

Wen Haitao et al. [28] study on the utilization of low grade iron tailings by superconducting HGMS Technology. The samples are mainly weakly magnetic hematite and goethite with particle size of -45 μm. They carried out single factor experiment to investigate the effect of magnetic flux density, slurry concentration and slurry flow velocity on separation efficiency. Under the optimal parameters: magnetic flux density of 1.2 T, slurry concentration of 25 g/L and slurry flow velocity of 500 mL/min, the iron content of magnetic concentrate increased from 32% to 65%, which can meet the requirement of blast furnace iron making. The experiment result is satisfactory and has been provided an effective way to utilization of iron tailings.

Chen Luzheng et al.[29] analyzed the effect of parameters on separation efficiency in a laboratory scale with the micro-fine particle hematite (-74 μm). The results of investigation indicate that changes in the magnetic flux density and the rotation speed of matrix had the most significant influences on the performance. An increase in the rotation speed improved concentrate grade but reduced iron recovery, while the reverse was observed for changing the magnetic flux density. A too low feed flow rate resulted in an extremely high recovery but a lower concentrate grade. They obtained a magnetic concentrate, in which the iron content increased from 35.02% to 60.98%, and the concentrate recovery rate reached 84.28% under the optimum parameters of magnetic flux density of 0.7 T, ore feed rate of 50 g and slurry flow velocity of 9 L/min. It is proved that superconducting HGMS technology is feasible for recycle and enrichment of weakly magnetic iron tailings.
Dwari R.K. et al. [30] carried out the investigation on extraction iron from low grade siliceous iron ore by superconducting HGMS. The main components of the samples are magnetite, hematite, goethite, etc., and the gangue minerals are silicate and carbonate minerals, the particle size is -100 μm. Under the conditions of magnetic flux density of 0.2 T, slurry concentration of 20% and slurry flow velocity of 2 L/min, they obtained a good mineral processing indicator with concentrate iron grade of 66% and yield of 88%.

4. Future Prospects
With the continuous technological breakthrough and rapid development of industrial practice, superconducting HGMS technology shows more and more advantages in kaolin purification, mineral dressing, coal desulfurization, sewage treatment and other fields. In the field of mineral dressing, superconducting HGMS can capture effectively the micro-fine weakly magnetic particles and even separate the micro-fine particles which remaining in the tailings after conventional magnetic separation [31]. In the field of coal desulfurization, it can effectively reduce the soot of environmental pollution. In the field of sewage treatment, the superconducting HGMS technology has achieved remarkable results in the purification of industrial wastewater (such as papermaking, chemical manufacturing, textile, thermal power plant) and domestic sewage. It can be recycled sewage, reduce environmental pollution while also save water resources. Superconducting HGMS technology has a tendency to use in conjunction with other technologies, such as biological water treatment technology, membrane separation technology. It can recycle the valuable secondary resources and achieve the environmental benefits and social benefits of the harmonious unity. Superconducting HGMS technology after decades of research and development, has begun to go out of the laboratory and into the industrial production stage, it will gradually replace the existing standard industrial magnetic separator. Separator is expected to develop in the next few years as following aspects. 1, Low energy consumption, 2, High field strength and high gradient, 3, Equipment light weight, small size.

Although the superconducting HGMS technology has shown great advantages and broad application prospects, there are the limitations and technical difficulties such as the remanence of magnetic matrix. Hence, superconducting HGMS technology will be subject to certain restrictions in practice. In the future, the following three aspects will be the focus of research. 1, In order to improve the magnetic field gradient, must choose high magnetic saturation of the magnetic matrix. On the other hand, remanence of magnetic matrix, it is difficult to rinse the magnetic particles adsorbed by magnetic matrix and affect the efficiency of the next cycle. Research workers need to be considered how to solve this contradiction. 2, Due to the magnetic matrix selection had some technical difficulties, and it would increase operating costs, research workers should increase the intensity of magnetic matrix materials research and achieve lower costs. 3, Strengthen the exploration of scientific research such as the surface modification of magnetic seed, the interaction between magnetic seed and fine weakly magnetic particles, magnetic seed recovery process and the design and optimization of magnetic filter, etc.

5. References
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