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High-gradient magnetic separation for wastewater treatment based on direct-conduction cooling superconducting magnets with large diameter, room temperature aperture

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Abstract. The development of cryogenic technology has greatly reduced the cost of large-diameter superconducting magnets and the difficulty of operation, making it possible for industrial fields. Our team has developed a large-diameter (room temperature aperture of more than 400 mm) superconducting magnet with direct-conduction cooling by a single GM refrigerator, combined with the designs of the transmission device, we have developed a superconducting magnetic separation water treatment system that can operate continuously. In order to apply this system to practical engineering projects, it is necessary to optimize its operating parameters to improve the equipment's treatment capacity and ensure the treatment effect. Through experimentation, we obtained relatively reasonable parameters for water flow rate and chain drive speed, which have been verified in actual engineering projects.

1. Introduction

Multiple countries around the world are facing water scarcity issues[1]. Water pollution is one of the main causes of water scarcity. Currently, traditional water treatment technologies such as chemical treatment, biochemical treatment, and membrane filtration are commonly use. However, these traditional methods often have low treatment efficiency, require large land area, and have long processing time. Some methods also involve the use of a large amount of chemicals, leading to secondary pollution and high treatment costs. Therefore, there is an urgent need for the development of new wastewater treatment technologies with efficient, energy-saving, and cost-effective.

Superconducting magnetic separation water treatment technology utilizes superconducting magnets to generate a strong magnetic field. It uses paramagnetic screen to create a wide-range high-gradient magnetic field. When magnetic substances in the water flow through the high-gradient magnetic field, they are attracted by the magnetic force and adhere to the screen.

Based on this principle, a superconducting magnetic separation water treatment technology has been developed, and has attracted attention from various countries[2-4]. This technology is considered a new application of superconducting magnets in the industrial field, following their use in medical magnetic resonance imaging and mineral magnetic impurity separation[5].

Japanese scientists have found that after being treated with superconducting magnetic separation with a magnetic field strength of 3T, the COD content in wastewater decreased from 1000 mg/L to 20 mg/L[6, 7].

In above works, the high efficiency of superconducting magnetic separation water treatment technology was demonstrated. However, in the actual working conditions of industrial - scale water treatment projects, there are characteristics such as large water flow, significant water quality fluctuations, and continuous operation, et. al. Therefore, we conducted research on the superconducting magnetic separation water treatment technology under the actual working conditions of water treatment to accumulate experience for the engineering application of this technology.

2. Process Flow and Structural Design

Due to the large daily processing volume required for water treatment projects, large-caliber superconducting magnets are needed. We developed a large-diameter superconducting magnet, as shown in Figure 1. The superconducting coil is wound using niobium-titanium (NbTi) wire and manufactured using the VPI (Vacuum Pressure Impregnation) process. The room-temperature aperture diameter of the magnet is 400 mm, with a central field strength of 2 T. The operating temperature is 4K, and it is cooled by a single Gifford-McMahon (GM) refrigerator (Model: RDK415) with a power of 8 kW(Cooling Power: 1.5W @ 4.2K) through direct conduction cooling. The time required for the magnet to cool from room temperature to its operating temperature is approximately 48 hours.

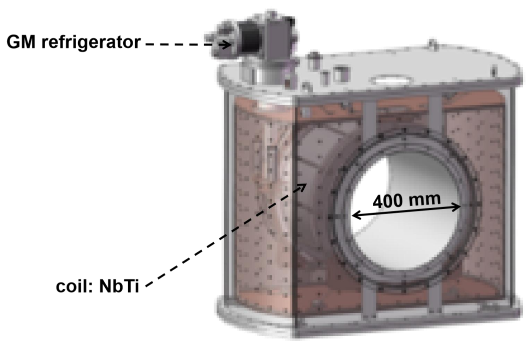

Figure 1. Superconducting magnet (400 mm).

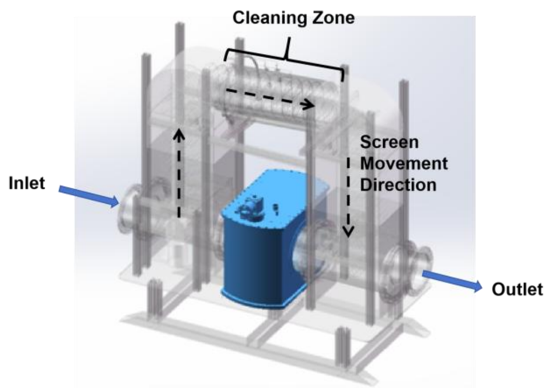

Figure 2. Automated separation system

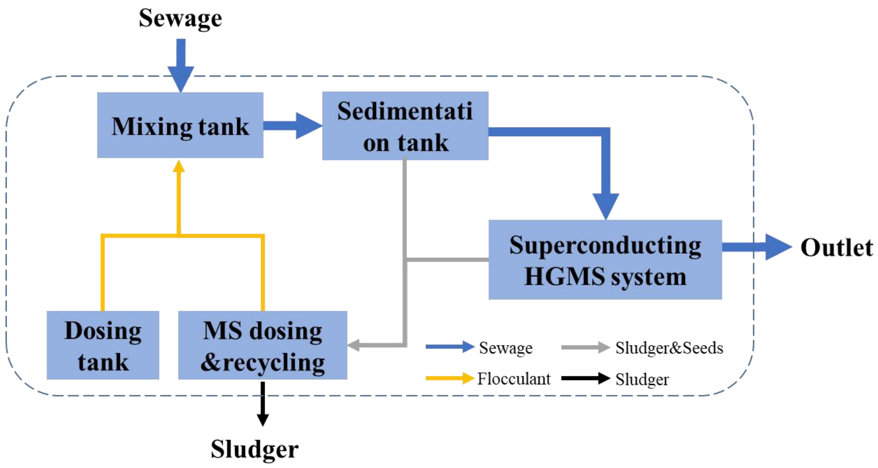

Figure 3. Process flow chart of superconducting magnetic separation water treatment.

Based on the aforementioned superconducting magnet, an automated separation system with a matching structure has been designed for the continuous extraction of pollutants from wastewater. This system features a chain-type circulation design equipped with a cleaning system. The screen on the chain serves to create a high-gradient magnetic field that adsorbs pollutants. Once adsorption is completed, the chain transports the screen to a non-magnetic area (cleaning zone) for re-washing, after which it returns to the magnetic field area for further operation, as illustrated in Figure 2.

The industrial process of superconducting magnetic separation for water treatment involves adding flocculants and magnetic seeds to the wastewater. After a period of reaction, pollutants form magnetic flocs, which are then separated and removed by magnetic force after the fluid flows through the superconducting magnet. The separated magnetic flocs are concentrated and collected into the magnetic seed recovery device. They are treated in a high-speed shearing machine, allowing the flocs to separate from the magnetic particles, which are then recycled back into the system. The flocs are dehydrated to form sludge that enters the related treatment process, as shown in Figure 3.

In the above system, the transmission speed of the screen and the water flow rate in the pipeline are two key factors affecting the performance of the equipment.Since the transmission direction of the screen is opposite to the direction of water flow, when the velocity difference is large, due to the impact force of the water flow, magnetic particles cannot be adsorbed by the screen, and this also causes the flocs to break. Therefore, to improve the processing capacity of the equipment, efforts should be made to ensure the water flow velocity while reducing the moving speed of the screen. However, a slow - moving screen can lead to two adverse effects. Firstly, it will cause the accumulation of pollutants on the screen, and may even result in the shedding and overflow of pollutants. In addition, the moving speed of the screen also affects the time it moves in the cleaning zone, thus influencing the cleaning effect. Both of these adverse effects can cause the processing effect of the equipment to fail to meet the standards. Ideal equipment operating parameters should ensure both processing efficiency and treatment effect.

During engineering applications, water quality varies significantly and fluctuates, making it impossible to theoretically optimize all parameters individually. Therefore, we adopt a commissioning experiment approach. By using characteristic water samples, we adjust the system's operating parameters to determine its treatment capacity.

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3. Results and discussion

The test water sample is septic tank water. Due to the high content of pollutants in this sample, under the same flow rate, the treatment load on the system is heavier. Therefore, it can verify the maximum treatment capacity and treatment effect under the state of high pollutant load. The COD of the water sample is 142 mg/L, and the SS is 21 mg/L.

First, through laboratory bench tests, determine the type and dosage of the flocculant, as well as the water quality after treatment. After experimental screening, polyaluminum chloride (PAC) is selected as the flocculant and polyacrylamide (PAM) is selected as the coagulant aid, with dosages of 100ppm and 2 ppm. The magnetic seeds used are 100-mesh magnetite(Fe_3O_4) particles, with a dosage of 100ppm. After treatment, the COD of the outlet is 39 mg/L, and the SS is 6mg/L. Carry out a pilot scale experiment using the chemicals at the above mentioned addition concentrations. After a 15 minute mixing reaction in a premix tank, the mixture flows through a superconducting magnet for magnetic separation treatment. Figure 4 shows the pilot scale experimental device.

Figure 4. The pilot scale experimental device.

Then, test the influence of different water flow velocities on the effluent effect. Set the chain drive speed as about 63 mm/s.When the water flow rate was less then 0.25 m/s, the COD and SS of the effluent were 40 mg/L and 6 mg/l, which was consistent with the results of the bench scale test. When the water flow rate was 0.5m/s, the COD and SS of the effluent were 48mg/L and 10 mg/L, slightly higher than the results of the bench scale test, but still in line with the requirements of COD(50 mg/L) and SS(10 mg/L) in water treatment standards. When the water flow rate was large then 0.5m/s, the COD and SS did not meet the requirements.

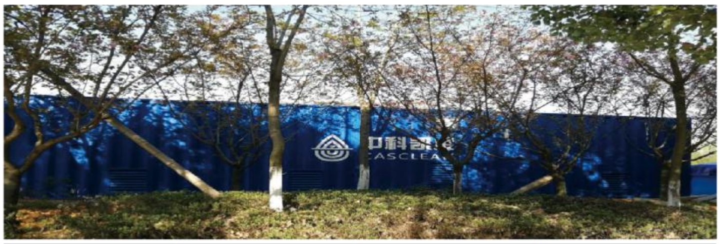
Calculate the daily treatment capacity of the equipment based on the above data. When the water flow velocity is 0.25 m/s, the daily treatment capacity of the equipment is 2717 tons, which is the daily treatment capacity capable of ensuring the separation effect. When the water flow velocity is 0.5 m/s, the daily treatment capacity is 5434 tons, for projects with relatively low effluent water quality, it can be determined through debugging whether to adopt this parameter. If the flow rate exceeds the effective range, there will be serious overflow of flocs and magnetic seeds, and the separation effect of the system will fail.

River water treatment
Taiyuan, China
Daily Capacity: 30000 t/d

	Original	After treatment	Reduction
COD_{Cr}	50-70 mg/L	40 mg/L	≥30%
TP	1 mg/L	0.4 mg/L	≥60%

Figure 5. Application case of superconducting magnetic separation water treatment technology in domestic wastewater treatment .

Domestic wastewater treatment
Tonglu, China
Daily Capacity: 5000 t/d



	Original	After treatment	Reduction
COD_{Cr}	≤150 mg/L	≤40 mg/L	≥73%
Turbidity	≤80 mg/L	≤5 mg/L	≥94%
TP	≤5 mg/L	≤0.5 mg/L	≥90%

Figure 6. Application case of superconducting magnetic separation water treatment technology in river wastewater treatment .

The above results have been verified in several practical engineering projects. As shown in Figure 5, the project is build to domestic wastewater treatment, daily capacity is 5000 t/d. After treatment, the COD is decreased from 50-70 mg/L to 40 mg/L. Figure 6 shows a river water treatment project, the total quantity of the project is 30,000 t/d, and the daily treatment capacity of a single device is 5,000 t/d. After treatment, the COD is decreased from 150 mg/L to 40 mg/L.

4. Conclusion

A superconducting magnetic separation water treatment equipment suitable for industrial applications has been developed. Through experimental trials and adjustments, we can obtain the maximum treatment capacity of the equipment that ensures the quality of the effluent. This parameter can guide the engineering design of water treatment projects. The daily treatment capacity designed through our experiments has also been verified by engineering projects. Within the designed range, the equipment exhibits excellent treatment effects on pollutants such as COD and SS.

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