Application to River Water Purification of Superconducting Magnetic Separation with Magnetic Particles as Seeding Agents

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Abstract

This study presents a newly developed superconducting magnetic separation system capable of continuous operation without interruption of feed-water owing to its unique structure, consisting of a continuously rotating disk-type magnetic filter and solenoid-type superconducting magnet. The continuously rotating disk-type magnetic filter, which is installed outwardly from the center axis of the magnet bore, is mounted on the cryostat and the superconducting magnet is energized using a permanent current switch, which consumes less electric power. This structure enables provision of a continuous operation system with high-speed and energy-saving separation treatment. We carried out a field test for two years including continuous operation for 1,000 hours. The test plant constructed had a capacity of 500 m³/day in order to study the possibility of applying the system for the purification of polluted lake and river water. The results show that the system has good performance, evidenced by a phosphorous removal rate of more than 85% and a suspended solid removal rate of less than 5 mg/L at a separation speed of 0.1 m/s. This system was found to be capable of being used practically for water pollution purification.

Key Words: Ferromagnetic particles, Magnetic separation, Multi-phase flow, Environmental engineering

I. INTRODUCTION

The coagulation, and magnetic separation method is one of the magnetic separation methods for purifying polluted water at high processing rate \(^1\) \(^2\). In the coagulation, and magnetic separation method, triiron tetra oxide particles (ferromagnetic particles) and coagulants are added to the raw water to form about 1 to 2 mm in diameter, containing triiron tetraoxide particles, SS (Suspended Solids), phosphorus, and other objects. Thus the flocs can be attracted and separated by magnetic force and the separation speed is higher than other conventional water purification methods with coagulation technique, such as chemical precipitation and dissolved-air flotation methods, which uses difference of density between a floc and water specific gravity. This developed method is capable of removing not only SS but also phosphorus in raw water due to the coagulants. Besides, the employment of superconducting magnet is effective to generate high magnetic field in a large space at relatively low electric power. Therefore the magnetic separation using superconducting magnet is effective as a water treatment method with large processing rate in which large magnetic separation area is employed. This paper describes the results gained in the field test, which was conducted on Ohori River in Chiba prefecture, on a continuous operation of 1,000 hours of a superconducting magnetic separator with coagulation techniques.

II. PRINCIPLE OF PURIFICATION SYSTEM

The purpose of the study on coagulation and magnetic separation system is to provide a compact yet large-capacity high-speed (0.1m/s or higher) water purification system capable of removing SS and phosphorus in lakes, river and wastewater as efficiently as possible. In particular, high gradient magnetic separation, which uses strong magnetic force generated by high magnetic field gradient, is an ideal high-speed purification among magnetic separation methods. High gradient magnetic separation was used in the field verification test. In the high gradient magnetic separation method, a magnetic filter consisting of ferromagnetic wires is installed in space to which magnetic field is applied in order to generate high magnetic field gradient and strong magnetic force near the ferromagnetic wire surface (see Figure.1).

Figure 2 is the process diagram of the coagulation magnetic separation system used. This continuously processing system consists of a coagulator for producing ferromagnetic flocs, a magnetic separator for separating ferromagnetic flocs from the water after coagulator, and an after-treatment unit for thickening and dehydrating the effluent sludge from the...
magnetic separator.

Fig. 1 Principle of high gradient magnetic separation. Fig. 2 Diagram of the purification system.

The coagulator consists of two types of mechanical reactors: a flash mixer and a flocculation reactor. The triiron tetraoxide and coagulants injected from the chemical injectors are uniformly mixed in the flash mixer at high agitation speed. In the process of sending the water from the flash mixer to the flocculation reactor, high polymer flocculants is injected. The agitation speed is milder in the flocculation reactor than in the flash mixer. In this agitation process, floc containing triiron tetraoxide and aggregated particles (SS, phosphorus, etc.) are formed in the flocculation reactor. Since the floc contains triiron tetraoxide, it is magnetically attractive at the next process, magnetic separator.

Fig. 3 Schematic figure of continuously rotating disk-type filter. Fig. 4 Schematic figure of filter cleaning process.

The continuously rotating disk-type magnetic filter, which is eccentrically mounted on the central axis at the upper part of magnet, keeps rotating between high magnetic field area created above the magnet and the low magnetic field area that is horizontally away from the high magnetic field (see Fig.3). The ferromagnetic flocs are separated by the continuously rotating disk-type magnetic filter in the high magnetic field, while the continuously rotating disk-type magnetic filter is cleaned in the low magnetic field. Figure 4 shows a study and an evaluation on cleaning of continuously rotating magnetic filter. Simulation with computational fluid dynamics is effectively applied for mechanical design study on the continuously rotating filter to provide appropriate fluid flow field in magnetic separation, and cleaning domain. As is shown in the figure, the flow fields in both domains are found to be appropriate at the stage of mechanical design using computational fluid dynamics. The residue containing the flocs from filter washing is discharged into the thickener. Since
high magnetic field and high magnetic field gradient are employed, the coarse magnetic filter can be employed. Pressure loss of the magnetic filter is thus low. The structure enables the magnetic filter washing and revitalizing with less energy. In the coagulation magnetic separation system, ferromagnetic flocs separated is collected as sludge, and thickened in the thickener and dehydrated by centrifugal dehydration to be collected as dehydrated sludge. The supernatant water in the thickener and the water separated from the centrifugal dehydrator are returned to the raw water feed pipe before the injection point of triiron tetraoxide and is purified along with the magnetic separator. The system is thus closed.

As is described previously, the separation speed of coagulation magnetic separation system can be over ten times higher than conventional methods with coagulation. Thereby, separation area needs less space. Furthermore, since the magnetic separator is capable of separating small flocs approximately 1 to 2 mm in diameter at high speed, utilizing high gradient magnetic field, floc generation and growth requires less time in coagulator (0.5 minutes for flash mixing, 2 minutes for flocculation). The coagulator can be thus compact. The flocs captured on the magnetic separator are magnetically compressed and the porosity of floc is reduced. Consequently, the floc density collected by the magnetic separator increases to achieve high settling velocity in the thickener. Thereby, the thickener can be downsized. By making these systems operate as a continuous system, each element device can also be downsized. Overall system downsizing is thus realized, and the footprint can be decreased to one-tenth of the chemical precipitation system.

III. PURIFICATION PERFORMANCE IN THE FIELD TEST

This section shows some results gained in the field verification test using actual river water at the pilot setup of coagulation magnetic separation system (Fig. 5, 6).

In the experiment, iron sulfate as coagulant, triiron tetraoxide as magnetic seeding agent, anionic high polymer flocculants, and sodium hydroxide as pH adjuster were used. Sampling raw water and purified water was conducted every 0.5 or 1 hour during the operation, and the averaged values of those data were employed to describe and evaluate the purification performance in this test. The T-P (total phosphorus) concentration of purified water and raw water during the test period is shown in Figure 5. The T-P concentration of purified water was kept stable between 0.02 to 0.13 mg/L. And the SS (Suspended Solids) concentration of purified water and raw water during the test period is shown in Figure 6. The SS concentration of purified water was kept stable 0.05 mg/L or less, while the SS concentration of the influent fluctuated widely.

Figure 7 shows the chart on the effect of the magnetic filter filling ratio on the magnetic separation performance. As filling ration of magnetic filter increases, the removal performance either increases up to 8% in volume, since filtration wire length also increases. However the removal performance decreases under the condition of the ration of 10% or over. It is supposed that filter cleaning does not work effectively in case of 10% due to high porosity and it causes the decrease of removal performance.
A study to evaluate magnetic field strength in magnetic separation area was conducted as well. Under the condition of magnetic flux of 0.5T or higher, the magnetization of magnetic powder reaches the saturation value and that of magnetic filter achieves 90% of the saturation value. Therefore, it is considered that magnetic separation performance is constant in the condition of magnetic flux of 0.5T or higher. Indeed, as shown in this chart, removal performance of flocs is virtually almost unchanged at magnetic flux of 0.5T or higher in magnetic separation area (see Fig.8).

An evaluation on magnetic force operating on the disk-type filter using computational magnetic field simulation is important from the view point of its strength design. However, the direct definition of magnetic filter matrix structure in computational magnetic field simulation is not practical to calculate magnetic force on the magnetic filter. And it increases computation load substantially, since number of mesh is greatly increased. Therefore, magnetic filter matrix is defined as a porous media substance in the calculation of the design study. The formula of the magnetic force operating on the filter matrix is expressed as formula 1, using the volume ratio of magnetic filter wire in the matrix.

$$\vec{F}_M = V_F \cdot \gamma \cdot \text{grad}(\vec{M}_F \cdot \vec{H})$$

(1)

$\vec{F}_M$ : Magnetic force operating on magnetic filter (N), $V_F$ : Volume of magnetic filter matrix (m³), $\gamma$ : Filling ratio in volume of magnetic filter in magnetic filter matrix (-), $\vec{M}_F$ : Magnetization of magnetic filter substance (Wb/m²), $\vec{H}$ : Applied magnetic field (A/m)

Figure 9 shows an evaluation result of the calculation formula 9 using the idea of porous media to estimate magnetic force on magnetic filter matrix. Estimation result calculated with the formula 9 is approximately close to experimental results. On the other hand, the difference between calculation results and experimental results are found in the region near the magnet. Therefore, assessment factor of about 1.5 is practically necessary for strength design of disk-type filter.

The flocs captured in the magnetic separator are magnetically compressed and the porosity of floc is reduced.
Consequently, the floc density collected by the magnetic separator increases to achieve high settling velocity in the thickener. Thereby, the thickener can be down sized. Figure 10 shows the thickening performance of sludge from the magnetic filter washing and revitalizing. The concentration of sludge reached at more than 10000 mg/L within an hour showing the good thickening performance. Accordingly, the whole space can be down sized in the coagulation magnetic separation system.

**IV. CONCLUSION**

The coagulation magnetic separation system has been proven as an effective technique for removing phosphorus, thus purifying lakes and rivers and the hybrid water purification with the coagulation magnetic separation system and ecological water purification using aquatic plants has also been proven to work effectively to remove phosphorus and nitrogen. The group conducted field verification tests for a year and half, and also conducted long-term continuous operation of the system to check whether it is possible to maintain desired treatment performance against the fluctuation of water quality due to seasonal change, and thus perform comprehensive evaluations of the system.

**REFERENCES**
