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Removal of iron oxide scale from boiler feed-water in thermal power plant by high gradient magnetic separation: field experiment

Yoko Akiyama[*, a], Suqin Li[b], Koshiro Akiyama[a], Tatsuya Mori[a], Hidehiko Okada[c], Noriyuki Hirota[c], Tsuyoshi Yamaji[d], Hideki Matsuura[d], Seitoku Namba[d], Tomokazu Sekine[e], Fumihito Mishima[f], and Shigehiro Nishijima[f]

[a] *Osaka University, Osaka, Japan*
[b] *University of Science and Technology Beijing, Beijing, China*
[c] *National Institute for Materials Science, Tsukuba, Japan*
[d] *Shikoku Research Institute Inc., Kagawa, Japan*
[e] *Ebara Industrial Cleaning Co., Ltd., Kanagawa, Japan*
[f] *Fukui University of Technology, Fukui, Japan*

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Abstract

The reduction of carbon dioxide emissions becomes a global issue, the main source of carbon dioxide emissions in the Asian region is the energy conversion sector, especially coal-fired power plants. We are working to develop technologies that will at least limit the increase in carbon dioxide emissions from the thermal power plants as one way to reduce carbon dioxide emissions. Our research aims to reduce carbon dioxide emissions by removing iron oxide scale from the feedwater system of thermal power plants using a superconducting high-gradient magnetic separation (HGMS) system, thereby reducing the loss of power generation efficiency. In this paper, the background of thermal power plants in Asia is outlined, followed by a case study of the introduction of a chemical cleaning line at an actual thermal power plant in Japan, and the possibility of introducing it into the thermal power plants in China based on the results.

Keywords: Thermal power plant, Low-carbon society, Boiler feed-water, High gradient magnetic separation, Iron scale

1. INTRODUCTION

In recent years, the emission of greenhouse gases, especially carbon dioxide (CO_2), has been regarded as a problem, and its suppression has become an urgent issue. Considering the amount of carbon dioxide emitted, the amount released from the energy conversion sector is the largest, especially from thermal power plants. For this reason, there is a need to shift to renewable energy, whereas the use of thermal power plants, especially coal-fired power plants, is still considered to be an important energy source in Southeast Asia [1]. This is because coal can be mined for a long time and the areas where it exists are dispersed and hence it is less expensive and a stable supply can be expected.

As mentioned above, though the emission of CO_2 from coal-fired power generation is large, it is predicted that the subcritical pressure coal-fired thermal power generation (SUB-C), which is thought to emit a large amount of CO_2, will increase especially in Southeast Asia.

On the other hand, in Japan, according to the 5th Strategic Energy Plan issued by Agency for Natural Resources and Energy, supercritical pressure coal-fired thermal power generation (SC) and SUB-C, which are relatively inefficient (relatively emit a large amount of CO_2), will be gradually decreased. The plan is to reduce CO_2 emissions by introducing efficient ultra-supercritical pressure thermal power generation (USC), integrated coal gasification combined cycle (IGCC), and integrated coal gasification fuel cell cycle (IGFC) [2]. Consequently, it is considered realistic and effective to control the amount of CO_2 emitted from thermal power plants that are now existing or will be constructed in the near future in Asia.

Here, we will discuss the reason why we pay attention to thermal power plants considering the current situation in Japan as an example. Fig. 1 shows the amount of CO_2 emitted by each sector in Japan in 2017 [3]. The total amount of CO_2 discharged this year was 1.19 billion tons, with the largest sector being the energy conversion sector of 41.3%, followed by the industrial sector of 24.9% and the transportation sector of 17.2%. What we can see here is that the energy conversion sector is the most emitted one and then it is important to deal with it here.

Most of the CO_2 emissions from the energy conversion sector corresponds to those from power plants. Fig. 2 shows the proportion of CO_2 generated by each power generation method in Japan in 2017 [4].

LNG-fired power generation is 40%, coal-fired power generation is 32%, oil-fired power generation is 9%, and hydraulic power generation, geothermal power generation and renewable energy generation are 8% each. Therefore

* Corresponding author: yoko-ak@see.eng.osaka-u.ac.jp

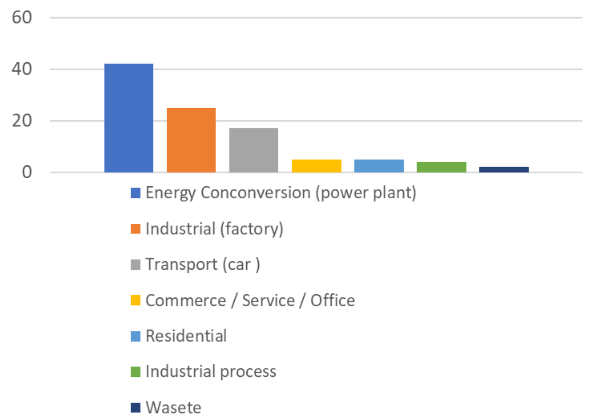

Fig. 1. CO_2 emissions by sector in Japan in 2017.

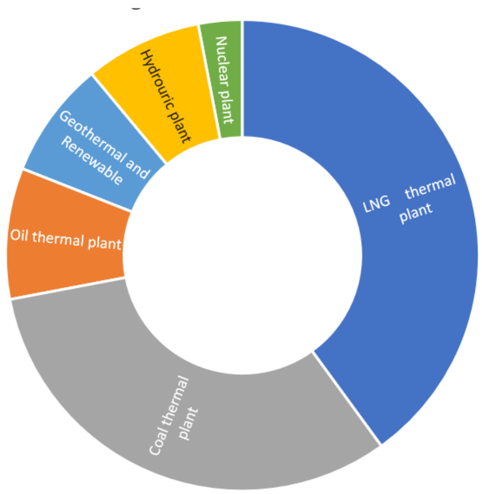

Fig. 2. The proportion of CO_2 emission by each power generation system in 2017.

LNG-fired power generation is 40%, coal-fired power generation is 32%, oil-fired power generation is 9%, and hydraulic power generation, geothermal power generation and renewable energy generation are 8% each. Therefore the CO_2 emitted from thermal power plants accounts for 81% of the total energy conversion sector. In other words, it can be said that the main cause of CO_2 emissions in Japan is thermal power generation. For this reason, we decided to focus on the CO_2 emitted by thermal power plants. In China, coal-fired power generation accounted for 70% of power generation in 2016 [5], and the amount of CO_2 emitted from thermal power plants is the same as in Japan. It is also deduced that the same situation is taken place in Southeast Asian countries.

Therefore, in this study, we focused on the emission of CO_2 from thermal power plants and decided to develop the technology to suppress the increase in emission. Specifically, we will develop a superconducting high-gradient magnetic separation system that removes iron oxide scale in the water supply system of thermal power plants and suppress the decrease in power generation efficiency results in reduction of CO_2 emissions.

We calculated how much CO_2 could be reduced by the removal of iron oxide scale. Accumulation of iron oxide scale leads to a decrease in heat exchange efficiency and pressure losses in pipework resulting in an increase in CO_2 generation. The increase in CO_2 emissions due to the adhesion of iron oxide scale is estimated to be an increase of 1.6 million tons of CO_2 emission per year in Japan. Conversely, if iron oxide scale adhesion prevention is realized, it will lead to a reduction of the same amount of CO_2 emission. In this work, we will develop the superconducting magnetic separation system to remove the iron scale from water supply system and to prevent the increase of CO_2 emissions from thermal power plants.

2. OVERVIEW OF FEEDWATER TREATMENT METHODS FOR THERMAL POWER PLANTS

It was mentioned above that the generation and accumulation of iron oxide scale in the feedwater system of thermal power plants reduce their thermal efficiency, increases pressure loss, and contributes to the generation of CO_2. In the worst case, iron oxide scale can cause accidents such as boiler tube failure, so it has always been important to prevent generation and accumulation iron oxide scale. The history of boilers can be said to be the history of the fight against iron oxide scale, and many methods to prevent generation of iron oxide scale have been studied in order to prevent accidents.

There are two main types of water treatment methods in use today: total volatile material treatment (AVT) and oxygenated treatment (OT). AVT is used in subcritical and supercritical thermal power plants, whereas OT is used in ultra-supercritical thermal power plants. AVT is also applied to combined-cycle power generation. Therefore, it is safe to assume that AVT treatment is the mainstream for thermal power plants in Southeast Asia, while in Japan, given the fact that the style of thermal power plants is changing, it is safe to say that it is time for a transition from AVT to OT. Even under such water treatment, iron oxide scale is still generated. Therefore, our study aims at removing the iron oxide scale generated even under such water treatment.

In AVT, ammonia (NH_3) is added as a pH adjuster and hydrazine (N_2H_4) as a reducing agent to reduce the amount of dissolved oxygen in the feedwater. In OT, on the other hand, ammonia is added as a pH adjuster and the appropriate amount of oxygen is added as oxidizing agent. These scale components are ferromagnetic or paramagnetic, and magnetic force separation is considered to be superior to other methods such as membrane separation with high pressure loss. In particular, the superconducting high-gradient magnetic separation method (HGMS), which is capable of high-speed mass processing, is expected to be applied.

Under these conditions, scales composed mainly of magnetite (Fe_3O_4) and hematite (Fe_2O_3) are formed in AVT and OT, respectively. In this paper, the application of HGMS to thermal power plants employing AVT is described.

3. FIELD EXPERIMENT IN THERMAL POWER PLANT EMPLOYING AVT IN JAPAN

3.1. On-line and Off-line HGMS System

The ultimate goal of our research is to develop a practical HGMS system that can continuously remove the scale generated in the boiler feedwater using superconducting magnets while the thermal power plant is in operation. As a preliminary step, we conducted a field experiment in which superconducting magnets were installed in the boiler chemical cleaning line of an actual thermal power plant. Here, HGMS introduction into the feedwater system of the thermal power plant is defined as "on-line", and the introduction into the boiler chemical cleaning line of the thermal power plant is defined as "off-line".

Chemical cleaning (off-line), which is the subject of this study, is a method of removing scale deposited on boiler pipes by circulating acidic cleaning solution while the thermal power plant is shut down. In the chemical cleaning system, the scale in the cleaning solution is generally removed by a cyclone separator (centrifugal separator). We tried to recover the scale in the circulating washing solution by HGMS system as an alternative to the cyclone separator. The target amount of scale to be captured in the final on-line system is to 120 kg, which corresponds to the generation amount of the scale in two years of operation of a thermal power plant. The target amount of scale to be captured in the chemical cleaning line is also 120 kg. If the target capture amount can be achieved in this off-line experiment, it will indicate the possibility of introducing the technology into the on-line system. In order to verify the feasibility of introducing a magnetic separation system, we conducted the magnetic separation experiment on-site by installing a system 1/16 size of the actual system in the chemical cleaning line of a boiler at a thermal power plant in Fukushima Prefecture.

3.2. Experimental Conditions and Methods

As mentioned above, the main components of the boiler scales are magnetite (Fe_3O_4) in AVT and hematite (Fe_2O_3) in OT. This field test was conducted in the thermal power plant that employs AVT.

The schematic diagram of the experimental system and experimental conditions are shown in Fig. 3 and in Table 1, respectively. The circulation line of the chemical washing solution (6% organic mixed acid, pH 2-3, 85℃) was bypassed and 1/210 of the flow amount was passed through the HGMS magnetic separator. The applied magnetic field was set to 0.3 T based on the value of a previous study [6], which showed that the AVT scale could be uniformly captured on the magnetic filter. A superconducting magnet with a room temperature bore diameter of 100 mm shown in Fig. 4 was used for the field experiments. 15 ferromagnetic Magnestain® flat-woven filters with a filter diameter of 50 mm, a wire diameter of 1 mm, and a mesh opening of 3.2 mm were placed in a superconducting magnet for magnetic separation. During the magnetic separation, the tubes were winded around the outside of the magnetic separation chamber containing magnetic filter and was constantly cooled with tap water to prevent inside of the magnet bore from becoming high temperature. The scale concentration in the cleaning solution was measured by collecting the solution from the sampling valves installed before and after the magnetic separation chamber, and the separation ratio was calculated using (1). Sampling of the solution before and after separation was performed after 5, 10, 20, 30, and 40 minutes from the start of water flow to the magnetic separator.

After the experiment, the magnetic filter was removed and the trapped scale weight was measured at room temperature. The results obtained in the field experiment at the thermal power plant were compared with the results of a laboratory experiment using the same superconducting magnetic separation system used in this study, and with the results of a large-scale experiment using a magnetic filter with a diameter of 300 mm, which is one-seventh that of the actual scale, to evaluate the scale removal capacity of the separation system.

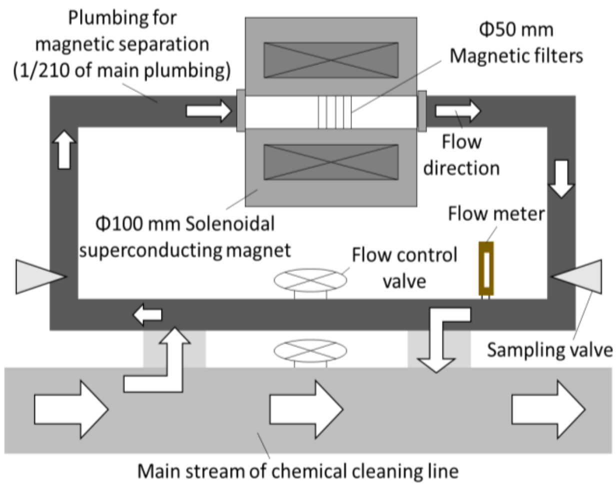

Fig. 3. Schematic diagram of the field experiment.

TABLE 1
CONDITIONS OF THE FIELD EXPERIMENT.

Filter material	Magnestain®
Filter diameter [mm]	50
Wire diameter [mm]	1.0
Shape	Plain weave
Mesh opening [mm]	3.2
Interval between the filters [mm]	2.0
Number of filters	15
Flow velocity [m/s]	0.3
Applied magnetic field at the center [T]	0.3
Amount of scale [g]	(266.7)
Experimental time [min]	42
Scale concentration [ppm]	150-220
Cleaning liquid properties	Organic mixed acid (pH = 2-3)
Cleaning liquid temperature [℃]	80-85

$$\text{Separation rate (\%)} = \frac{\text{Inlet Conc. (ppm) - Outlet Conc. (ppm)}}{\text{Inlet Conc. (ppm)}} \times 100 \quad (1)$$

Fig. 4. Solenoidal superconducting magnet in the field experiment.

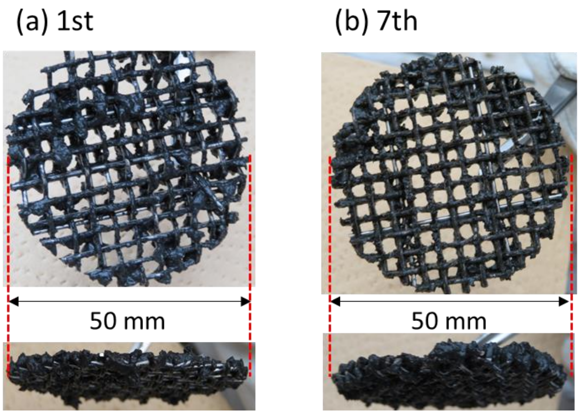

Fig. 5. The scale captured in the field experiment, (a) 1st filter (b) 7th filter.

3.3. Results and Discussions

What we confirmed through this field experiment is that the scale is captured uniformly on the magnetic filter and that the separation ratio and total capture amount have achieved each target value.

Firstly, we discuss the uniformity of capture. Fig. 5 shows the front and side views of the scale captured by the 1st and 7th filters from the inlet side of the 15 installed filters.

These figures indicate that the scale is trapped above and below the filter wire, i.e., in the direction of the flow of the fluid, as shown in the schematic diagram in Fig. 6 [7].

If the filters are aligned alternately, it is easier to capture the particles that are not captured by the filters in upstream, but the filters and the captured particles will increase the flow resistance and pressure loss. On the other hand, the filter structure proposed in this study can hold a large amount of scale without increasing the pressure loss, because the filters are aligned in phase and particles can be captured in a wall-like structure between the two filters, as shown in Fig. 6.

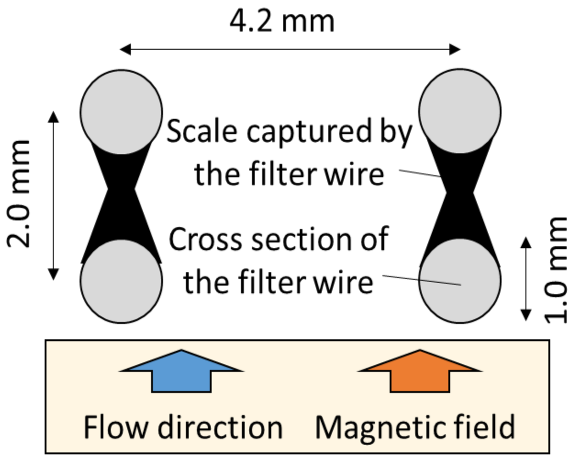

Fig. 6. Schematic diagram of the scale captured between the filter wires.

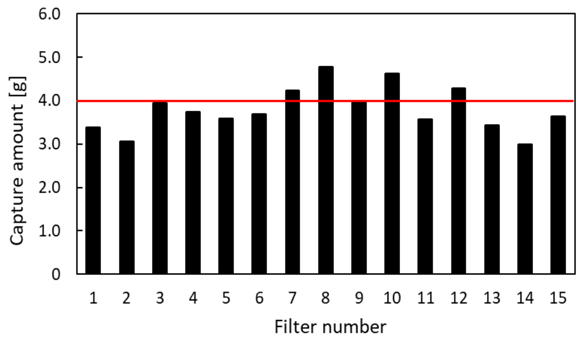

Fig. 7. The spatial distribution of captured scale in the flow direction in the field experiment.

In the alternating arrangement, the particles are captured only in the high magnetic field gradient area of on the wire surface, whereas in the phase-aligned filter, the particles are trapped in the form of chains of magnetite particles between the front and rear filters and finally make wall-like structure along the phase-aligned filter wires. It is therefore possible to capture more scale in the phase-aligned filter than when aligned alternately.

The weight of the scale trapped in each filter was shown in Fig. 7. The magnetic field at the center of the bore is larger than those at both ends, resulting in a little higher capture amount in the filters around the center of the bore.

The total amount of scale captured by the 15 filters was 59.9 g, and the average amount of scale captured per filter measured separately was about 4 g, indicating that the scale was captured almost evenly. This indicates that all filters function effectively and capture the scale almost uniformly with respect to the flow direction. This also indicates that a magnetic flux density of 0.3 T is appropriate for trapping magnetite scale efficiently. In addition, Fig. 5 shows that the scale is also uniformly captured in the radial direction of the filter, which is perpendicular to the flow direction.

Next, we discuss the separation rate and the total amount captured. The results of the separation rate of scale are shown in Fig. 8. The separation rate was over 80 % under the target capture amount of 50 g, which is sufficient value compared to the separation rate of 20-40 % in the actual cyclone. The decrease in the separation rate after 10 minutes after start of experiment was due to exceeding the saturated capacity of the magnetic filter used in this experiment, which can be solved by setting the number of filters considering the filter capacity.

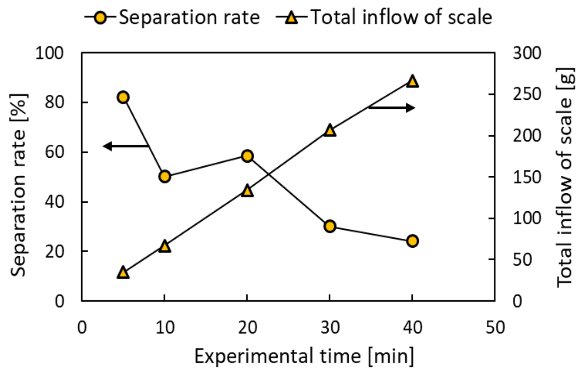

Fig. 8. Time dependency of separation rate and total inflow of scale in the field experiment.

Finally, we checked whether the total amount captured reached the target value or not. According to the proportional calculation based on the above results, the system used in this experiment would need to capture 47 g of scale in order to capture 120 kg of scale with an HGMS system for practical use. The results confirmed that 59.9 g of the scale was captured, which is about 27% larger than the target value. The results demonstrated that the same capture capacity can be obtained for chemical cleaning in a real thermal power plant as in laboratory and large-scale experiments.

Fig. 9 summarizes the experimental results of our previous studies and the field experiment this time, showing the fact that the amount of scale trapped is proportional to the area of the magnetic filter.

In a lab experiment using the same superconducting magnet as this field experiment, 59.4 g of the simulated scale was trapped in the filter. On the other hand, 20.9 kg of the simulated scale was captured in a large-scale experiment using filters 6 times larger in diameter than the filter used in this field experiment (300 mm outer diameter filter), which corresponds to about 36 times of this study. From these results, it was confirmed that the amount of scale captured was simply proportional to the area and number of filters [6, 8].

In this field experiment, we were able to capture a scale that exceeded the target value, confirming the possibility of introducing superconducting magnets into the chemical cleaning line of boilers in thermal power plants employing AVT. This also suggests the possibility of applying the system to the on-line system for capturing scale in feedwater during boiler operation, which would be a similar size.

Here, we discuss the advantages of using superconducting magnets in this system. The most important advantage of a superconducting magnet against an electromagnet is that it can generate a large magnetic

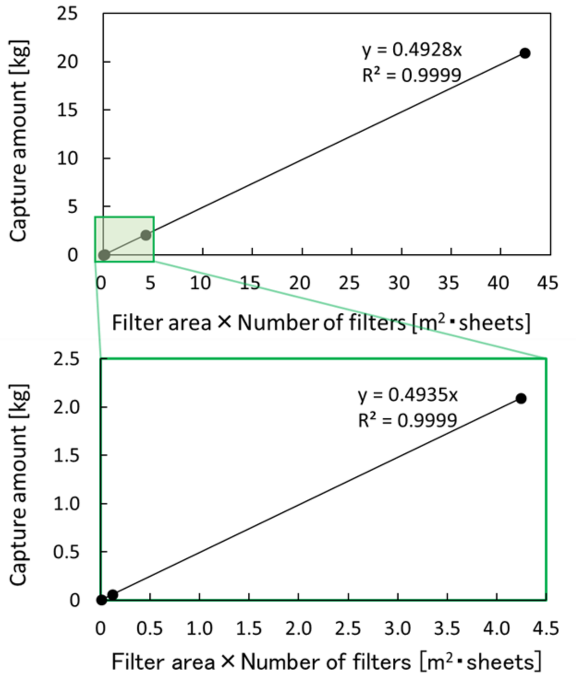

Fig. 9. Comparison of the capture amount of captured scale in the field and large-scale experiments.

field area. In practical use, a large amount of scale (120 kg) generated in the feed water in the thermal power plant during a two-years operation needs to be captured without any filter cleaning. In addition, the scale needs to be removed from the fluid at a high flow velocity of 0.3 m/s. These require a magnetic field of more than 0.3 T to be applied over a wide area.

The electromagnets have a narrow magnetic field area, so separation is possible if the flow path is narrowed at the separation area. But a drastic reduction of the flow path may increase in pressure drop, in addition to the difficulty of achieving the above capture capacity. For these reasons, the use of superconducting magnets is considered to be the most appropriate for this application. However, in order to use a superconducting magnet in the actual site, there are issues of cost and maintainability of the magnet itself, so we are examining the system design for practical use to solve these issues.

4. FEASIBILITY OF INTRODUCING HGMS SYSTEM TO THERMAL POWER PLANTS EMPLOYING AVT IN CHINA

There are many thermal power plants in China, and the problem of iron oxide scale also exists. At present, in the long-term use of the circulating cooling water system, there will be problems such as scaling and algae breeding, which will reduce the use efficiency and service life of the equipment. Scaling will seriously damage the heat transfer efficiency, greatly increase the energy consumption of the equipment, cause the water flow obstruction of the equipment circulation pipeline, cause the pipeline rupture due to pipeline corrosion, lead to unplanned shutdown, reduce the service life of the equipment, algae and microorganism breeding, will reduce the heat exchange efficiency, and increase the maintenance cost. With this superconducting high-gradient magnetic separation system, the iron oxide scale can be removed efficiently in the water supply system of thermal power plants, and it will result in reduction of CO_2 emissions.

The Chinese government proposes to achieve carbon peak by 2030 and carbon neutral by 2060. This separation system of iron oxide scale removal will provide a new idea for carbon emission reduction. As an indispensable heat exchange system in industrial production, circulating cooling water system has great potential for energy saving and emission reduction. So this technology would also have broad application prospects in China.

5. CONCLUSION

The reduction of CO_2 emissions from the thermal power plants in the Asian region is an urgent issue, and scale removal from boiler feed-water in the thermal power plant is one of the effective ways to suppress CO_2 emission. We conducted a field experiment using a HGMS system in the chemical cleaning line of a thermal power plant employing AVT, and found that the system can achieve the scale removal performance required in practical use. This indicates the possibility of introducing the HGMS system to AVT thermal power plants in Asian region.

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