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Magnetic separation technique for groundwater by five HTS melt-processed bulk magnets arranged in a line

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ABSTRACT

A magnetic separation study for groundwater purification has been practically conducted by using the multi-pole magnet system. The magnetic pole was composed of 10 open magnetic spaces by arranging five HTS melt-processed bulk magnets in a line in a vacuum sheath. The individual bulk magnets were activated by feeding intense pulsed magnetic fields up to 6 T. The magnetic field distribution was estimated with respect to various pole arrangements. The actual groundwater samples of Sanjo City were processed so as to form large precipitates by adding the coagulant and pH controlling. The maximum separation ratio of the iron-bearing precipitates has exceeded over 70% when slurry water was exposed to 10 magnetic poles of up to 2.5 T at a flowing rate of less than 4.8 l/min. An obvious attraction of flocks to the magnetic poles was observed even when the water contains no magnetite powder at the flow rate of 1.01 l/min. This implies the validity of the multi-pole magnet system with respect to the actual application to water purification.

1. Introduction

In Sanjo city in Japan, the groundwater has been used for incinerator furnace coolant in the waste material disposal works. Fig. 1 shows a schematic illustration of the conventional disposal furnace (a) and the water purification process (b), respectively. Exhaust gas of 1200 K which is generated from burning waste materials is cooled to 600 K by gushing water before emitting it out of furnace. The groundwater in this district contains Fe element with high concentration of around 14 ppm, as shown in the figure. As the furnace would have been seriously damaged if the water nozzles would be stopped up by accumulating rust, the water must be kept clearer than usual to reduce the number of times of maintenance. As the purification processes requires the additives and coagulants, it has been needed to propose more efficient and cheaper ways than those at present. In the study, a magnetic separation technique using high temperature superconductingbulk magnets (hereafter abbreviated as HTS bulk magnets or bulk magnets) has been investigated to adapt them to the groundwater purification process.

The melt-processed HTS bulk magnet systems in cooperation with small-sized refrigerators are characterized as intense magnetic field generators [1–3]. An intense magnetic field generator which contains five bulk magnets in a line was prepared for this study. As Fujiwara et al. [4] reported in 2006, it emitted an intense field of 1 T in the open space outside the vacuum chamber.

Since it is difficult to activate the multi-pole bulk magnets by means of the field cooling method, the pulsed field magnetization technique (PFM) are conducted in this experiment. PFM technique is well known to be easy and compact way to activate bulk magnets in comparison with the field cooling method which requires large scale superconducting solenoid magnets [5]. In the past, various PFM techniques have been investigated to let the bulk magnets trap intense magnetic fields. Fujiyama et al. [6] discussed on the field trapping property of inhomogeneous bulk materials. Fujishiro et al. [7] reported that the performance of trapped magnetic field reached 5.2 T by applying multi-pulse fields in the process of stepwise temperature falls. Ida et al. [8] attempted to activate the bulk magnets by the method in which the bulk magnets were sandwiched by vortex-type pulse coils settled face-to-face, and showed that the vortex type coil was effective to obtain the conical trapped field distribution. Hiyama et al. [9] reported that five-aligned Gd-based bulk magnets were successfully activated by pulsed fields with use of sprit-type pulse coils. Fujishiro

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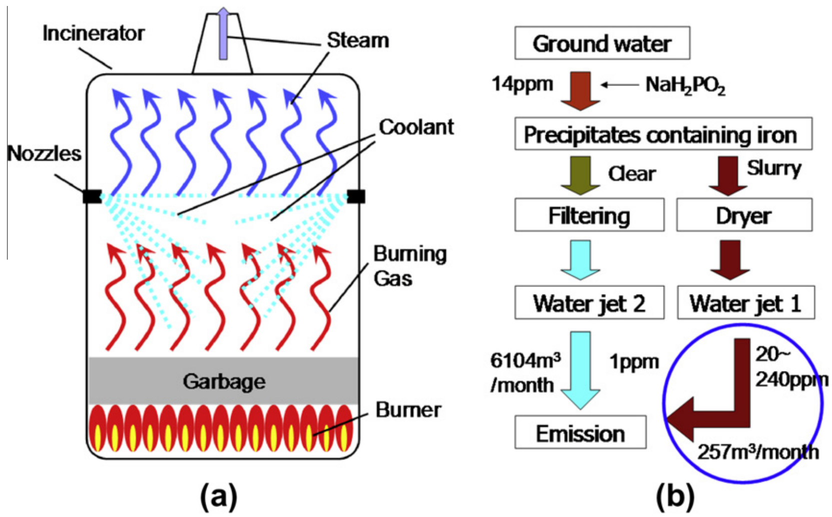

Fig. 1. Schematic illustration of waste material disposal furnace (a) and water purification process of groundwater (b).

et al. [10] attempted to apply this magnet system to the magnetic separation technique. In this experiment, we have adopted this equipment to purify the groundwater and to show the effectiveness in the practical environmental issue.

Fig. 1b shows a conventional groundwater purification process. The precipitates containing Fe element are condensed and filtered in the process. The clear water with Fe concentration of 1 ppm is directly showered in the furnace through the flush nozzle "water jet 2" in Fig. 1b. Beside this main process, the disposed slurry which still includes water with high concentration is filtered again and led in the furnace through "water jet 1". The Fe concentration of the filtered water through this sub process is estimated to 20–240 ppm. The experiment was operated to purify the water indicated as "water jet 1".

We know a couple of magnetic separation systems. One is the high gradient magnetic separation (HGMS, Okada et al. [11]) and the other is open gradient magnetic separation (OGMS, Fukui et al. [12]). It has been reported by Oka et al. that the Fe in the groundwater was effectively removed by HGMS technique with use of face-to-face HTS bulk magnets, in which the iron balls of 3 mm in diameter were installed in a water channel between the magnetic poles emitting magnetic field over 2 T [13].

As mentioned above, Fujishiro et al. [10] reported that the Fe oxide powder mixed beforehand in the water has been effectively removed by passing it through the multi-pole magnet which contains five activated bulk magnets. On the other, Oka et al. [13] clarified that HGMS technique with use of the bulk magnets is effective to purify the groundwater. As we know there are a lot of application candidates of magnetic separation techniques and we must confirm the validity of the technique on the view point of each practical application, we attempted to adopt the multi-pole magnet system to the groundwater purification to verify if the technique is practical or not.

In this discussion, we deal with the performances on the separation ratio of Fe against the flowing rate of groundwater which contains the magnetized flocks which are formed by adding the fine Fe oxide powder after the former magnetic separation experiment which was performed with use of five-aligned bulk magnets system [10].

2. Experimental

Fig. 2 shows a photo of experimental setup of the bulk magnet system used in this study [4,9,10]. Five HTS bulk magnets were installed in the vacuum sheath with keeping thermally insulated condition from outside. They were cooled by Gifford McMahon refrigerator (AISIN SEIKI Co. Ltd., type GD-251) and then activated by the PFM technique using a split-type pulse coil. The pulse coil was settled on the both sides of the sheath to sandwich it, as shown on the right hand side in Fig. 2.

As shown in Fig. 3, the *c*-axis oriented Gd–Ba–Cu–O bulk magnets of rectangular-shape ($34 \times 34 \times 15$ mm^3, Nippon Steel Co., Ltd.) were embedded in the thermal conduction bar of copper, which tightly fixed the bulk samples from their side faces which were perpendicular to the *a*–*b* plane of the crystal. A distance between each bulk magnet was designed to be 25 mm. The conduction bar was connected to the cold head of GM refrigerator and cooled to 30 K.

The sheath-type magnetic pole is activated by PFM. The activation was performed by applying pulsed fields of 5.5–5.8 T with a rise time of 12 ms from the 60 mF condenser bank by using a split-type copper coil, which is dipped in liquid nitrogen. The pulsed magnetic field was applied just once for every bulk magnet in the following order, applied magnetic flux densities and discharging voltages; #1(5.8 T, 700 V), #5(5.2 T, 600 V), #4(5.5 T, 650 V), #2(5.8 T, 700 V), and #3(5.8 T, 700 V) [9]. After each magnetizing for a bulk magnet, the magnetizing coil was shifted sideward along the sheath, and next bulk was activated in turn in the same manner. In addition, the direction of field application was chosen in two cases. Five bulk magnets were magnetized in the

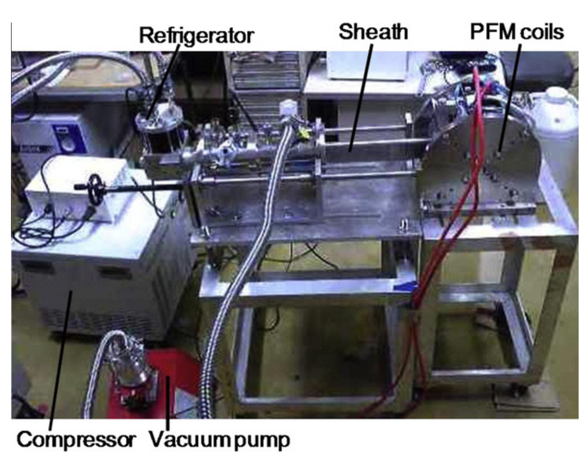

Fig. 2. Strong field generator containing five-aligned bulk magnets in the sheath and magnetizing coil to activate them.

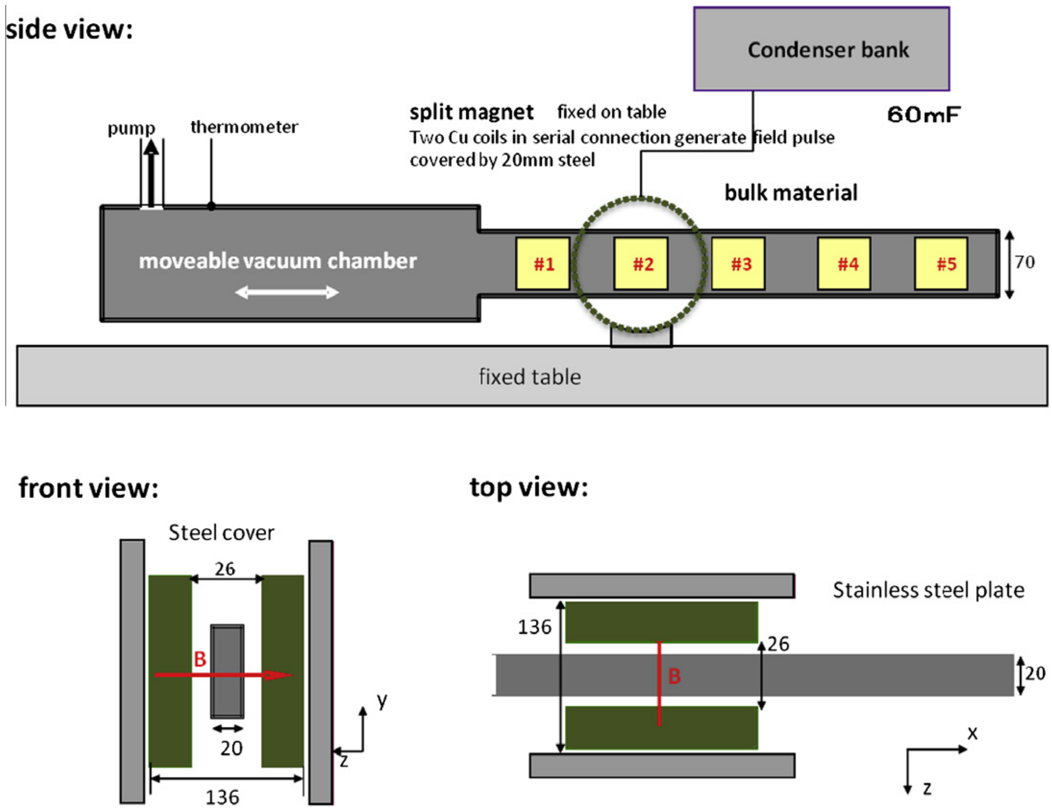

Fig. 3. Schematic illustrations of bulk magnet system and magnetizing apparatus to apply pulsed fields.

same magnetic poles and alternating poles by changing current directions on their magnetizing processes. The strength of the trapped magnetic fields and their distributions were precisely measured by scanning a Hall sensor (F.W. Bell, BHT921) at the surface of the vacuum sheath for the direction normal to the sheath surface, and analyzed by three dimensional and line scan profiles.

The magnetic flocks were formed by adding poly-aluminum chloride (PAC) and coagulants to the groundwater with the concentrations of 700 ppm and 0.5–1%, respectively. The magnetite fine powder of 50 ppm was added to the water and flocks to give them ferromagnetic property. The performance of magnetic separation ratio was compared to the cases with and without magnetite addition.

Fig. 4 shows the structure of magnetic separation channels in which the groundwater flows. A couple of separation channels made of acrylic resin were settled face-to-face on the both sides of the vacuum sheath which emits magnetic fields on its surface. The magnetic separation was performed by an open gradient method, as shown in Fig. 4. The dimensions of the water channels were 80 mm in height and 30 mm in thickness. In order to let the water flow near the magnetic poles, the partitions were settled in the channels. The water and flocks were thoroughly stirred and led to the water channels. The flow rates were controlled up to 4.8 l/min by the valves of B1 and B2. The purified water passing the front water channel was derived from the valve B3 after undergoing five magnetic poles and the finally purified water was drained from the back channel after passing 10 magnetic poles.

The purified water was precisely examined in terms of the concentration of Fe ions by the inductively coupled plasma (ICP) analysis. The separation ratios S were estimated against the flow rates of water, where S was defined as $S = (c_0 - c)/ c_0$. c_0 was iron concentration in the sample water with flocks just before the experiment and c was that at each flow rate.

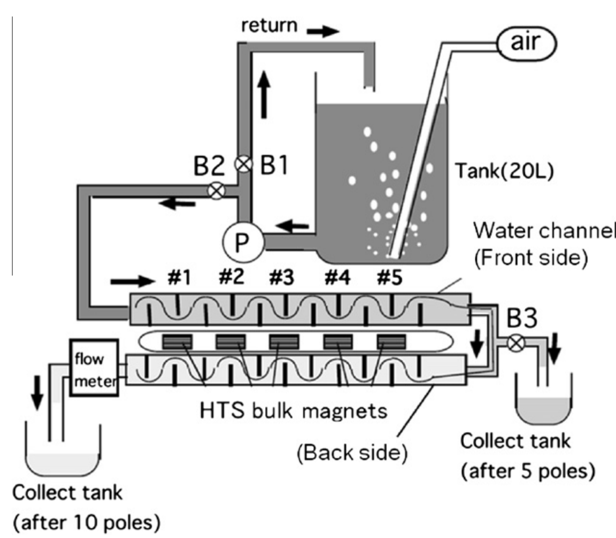

Fig. 4. Schematic structure of magnetic separation experiment with use of a couple of water channels which are attached beside the multi-pole magnetic sheath.

3. Results and discussion

Fig. 5a shows the three-dimensional magnetic field distribution when five bulk magnets were activated to the same magnetic poles in the sheath. The profile of the field distribution shows cone-shapes and the maximum magnetic fields were located at each center of the bulk surfaces. The maximum value of them was 2.2 T at the surface out of #4 bulk magnet, shown in the figure. The shape of trapped field strongly reflects the rectangular shape of the bulk magnets. A couple of two-dimensional line distribution profiles are shown in

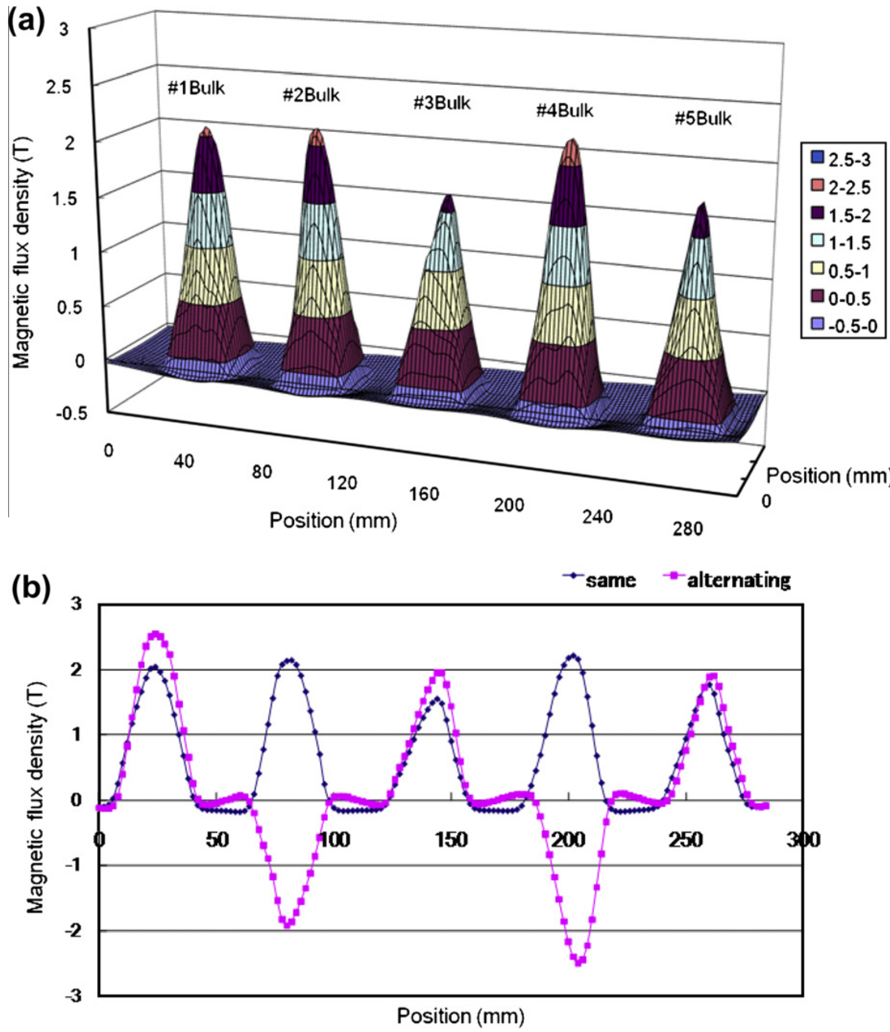

Fig. 5. Three dimensional distribution of trapped magnetic field on the sheath surface (a), and cross sectional distribution with same and alternating magnetic pole arrangement (b).

Fig. 5b. In the figure, plotted are the data obtained in both cases of same and alternating magnetic poles, respectively. One can see that excellent trapped fields in absolute values were obtained by alternating magnetic pole arrangement. The maximum value was 2.5 T at #1 bulk magnet. It is inferred that the distance between the bulk magnets, which was designed as 25 mm, was not enough to eliminate the returning path of the flux lines. Therefore the trapped field for alternating pole arrangement was slightly enhanced in comparison with same magnetic pole arrangement. For alternating poles, the trapped flux along the *c*-axis increases with decreasing the distance between the magnets located side by side. In contrast, the same magnetic poles arranged in a line must be placed apart to avoid their mutual interferences. Furthermore, the distribution of parallel direction to the sheath surface must be estimated to discuss on the performance of the total separation system.

A photograph of the experiment is shown in Fig. 6. The groundwater and flocks were poured to the water channel from the right hand side of the picture, and flew out after passing through the spaces in front of five magnetic poles. When another water channel was attached on the back side of the sheath, the water undergoes the magnetic field spaces for 10 times. One can easily see that the flocks were attracted to the magnetic poles, reflecting their rectangular shape. It is obvious that the dark-colored water shown at the beginning changed clearer and clearer as the water undergoes the magnetic field spaces in the channel.

Fig. 7 shows the separation ratios of Fe element against the flow rates of the water and flocks as functions of the magnetite concentration and the number of the times of magnetic poles the water passes. A couple of cases were examined with respect to the same and alternating pole arrangements, respectively, as shown in Fig. 7a and b. The data measured after passing five-poles at the front and back sides of the sheath were also plotted in Fig. 7b,

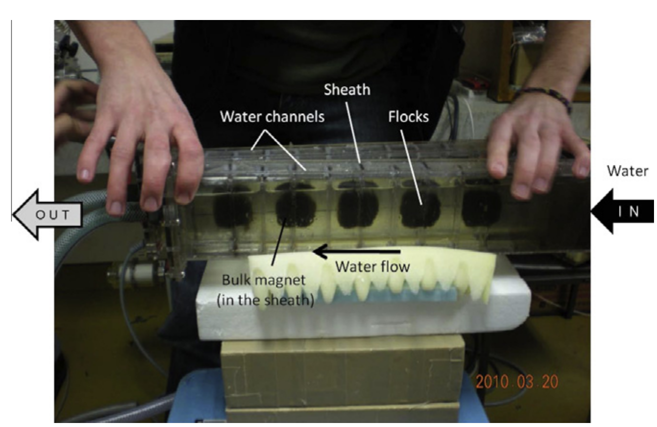

Fig. 6. Photo of the experiment by open gradient magnetic separation technique.

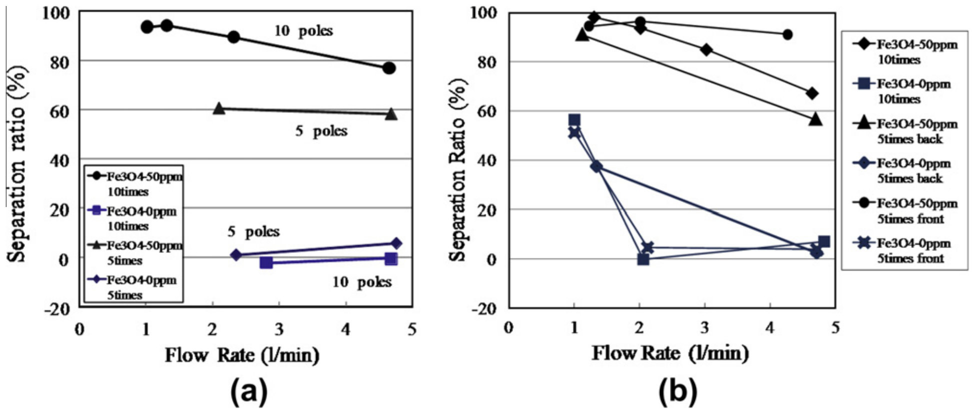

Fig. 7. Flow rate dependence of separation ratio for same (a) and alternating (b) magnetic pole arrangement.

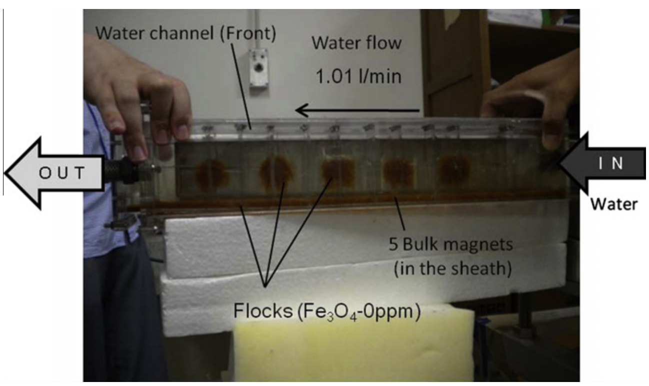

Fig. 8. View of the magnetic separation experiment for the flocks with no magnetite powder addition with a flowing rate of 1.01 l/min.

respectively. Although it is obvious that the separation ratios decrease with increasing flowing rates in every case, the performances are quite different between the cases whether the magnetite powder was added to the flocks or not. We must note that there are no substantial differences between the cases in which the bulk magnets are activated in the same and alternating pole arrangements. This may be attributed to the fact that the trapped fields did not show large differences enough to be reflected to the separation performance. However, when the distance between the magnets is designed to be closer and the magnets are alternately activated, the magnetic field would be highly improved.

Fig. 8 shows a view of separation experiment operated without magnetite addition. One can see apparent adhesion of the flocks on each magnetic pole when the flow rate is 1.01 l/min with use of 10 magnetic poles. This phenomenon corresponds to the separation ratio of 56.3%, as plotted in Fig. 7b. To observe sharply, we would see a precipitation of flocks on the bottom of the channel. This means that some improvements on the design of water channels would easily enhance the separation performances in near future. We believe that 10-time applications of such strong magnetic fields to the water enable us to develop a novel water purification technique with high efficiency.

4. Conclusions

The magnetic separation experiment was carried out with respect to the practical environmental issue with use of newly constructed multi-pole magnetic field generator containing five-aligned Gd-based bulk magnets. The PFM was operated by the split-type coils, and strong magnetic field of 2.5 T was generated at the sheath surface. Aligned bulk magnets arranged side by side mutually affected to each trapped field distribution even in the case that the distance between the bulk magnets was designed as 25 mm. This means that the trapped field must be improved when the distance is shortened and the magnets are alternately activated.

The separation ratios of the magnetic flocks which contain magnetite powder of 50 ppm have remained high performances of over 70% for under the flow rates less than 5 l/min. Although an addition of magnetite was dominant on the separation ratios rather than other parameters like flow rates or number of poles, we have observed an obvious attraction of flocks to the multi-pole magnets even when the water contains no magnetite powder at all. This implies that the further improvement on the water channel design must bring us the practical performance of water purification in actual environmental issues.

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