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In-situ observation of particles deposition process on a ferromagnetic filter during high-gradient magnetic separation process

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ABSTRACTS

In-situ observations of particles deposition process on a ferromagnetic filter in high gradient magnetic separation were carried out under high magnetic fields to obtain information for the optimization of separation condition. The spike-like deposition structure was observed on the upper stream of the magnetic filter, different from the conventional deposition image obtained for paramagnetic particles. The length of the spike structure tends to be long with lower flow velocity and lower applied magnetic field. It was also observed that the chain structure or the bundle of such chaines were formed on the way to the filter under the condition of the low applied magnetic field and low flow rates. Results obtained here indicate that the effect of deposited particles on the spatial distribution of the magnetic field and the hydrodynamics, they are often ignored in the simulation so far, should be considered appropriately.

1. Introduction

In high gradient magnetic separation (HGMS), magnetic particles suspended in fluids can be separated efficiently. When a filter consisted of magnetic wires is placed in a magnetic fields, the steep magnetic field gradient will be formed in the vicinity of filter wires. Particles pass through this region attracted on the magnetic filter wires due to the magnetic force acting on particles. Fig. 1 schematically shows spatial distribution of the magnetic force acting on magnetic particles in the vicinity of a magnetic filter wire and Fig. 2 illustrates the image of HGMS process. Different from usual filtration techniques, as seen in Fig. 2, the opening of filters can be much larger than the size of particles because magnetic particles are attracted to magnetic wires due to the magnetic force. Therefore, efficient material separation is realized due to its low pressure loss. Even though the particles accumulated on the filter, the filter can be reused because stacked particles can be removed and collected by removing the magnetic field. This feature seems good for environment. Even if magnetic properties of objective materials are too small they can be separated by attaching or adsorbing on to the surface of magnetic particles. Therefore, wide range of materials can be separated by HGMS. Nowadays, HGMS is applied to the separation of precious materials [1–4], the environmental preservation [5,6], or the treatment of waste water [7], and so on. Efficiency of separation depends on the size and the magnetization of particles, the viscosity and the velocity of fluids, the magnetization and the diameter of the filter wire, the distance of filter wires, *etc.* To attain efficient separation process, the optimization of separation conditions was carried out through the computer simulation, however, the effect of particles deposited on the surface of filter wires was often ignored when considering the hydrodynamics of fluid and the spatial distribution of magnetic fields around the wire to simplify the calculation [8–11]. Conventionally, the deposition of particles on the filter wire considered only for paramagnetic particles and thought to be occurred in upper stream side of the wire widely piled up manner [12,13] and caused clogging of the filter while in many practical cases ferromagnetic particles separated in HGMS. The possible continuous duration of time of the separation process is affected by the clogging of the filter. This is important factor to consider the efficiency of process when HGMS is applied to some industrial processes. Appropriate consideration of deposited particles seems to be required in the simulation. Therefore, in this study, to obtain information for the optimization of separation condition, *in-situ* observations of particles deposition process on a ferromagnetic filter in HGMS were carried out under high magnetic fields.

2. Experimental

In this study, the cryocooler operated type of superconducting magnet, Model JMTD13C100 manufactured by JASTEC Co. Ltd., was used to apply high magnetic fields. This superconducting magnet can

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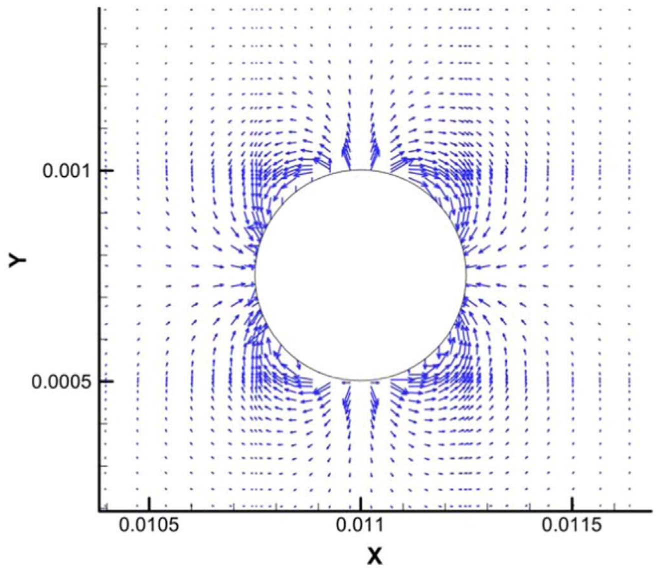

Fig. 1. Schematic drawing of the spatial distribution of the magnetic force acting on magnetic particles in the vicinity of a magnetic filter wire in magnetic fields. White large circle represents the cross section of the magnetic wire. The magnetic field applied in a horizontal direction. The direction and the length of arrows correspond to the direction and the intensity of the magnetic force.

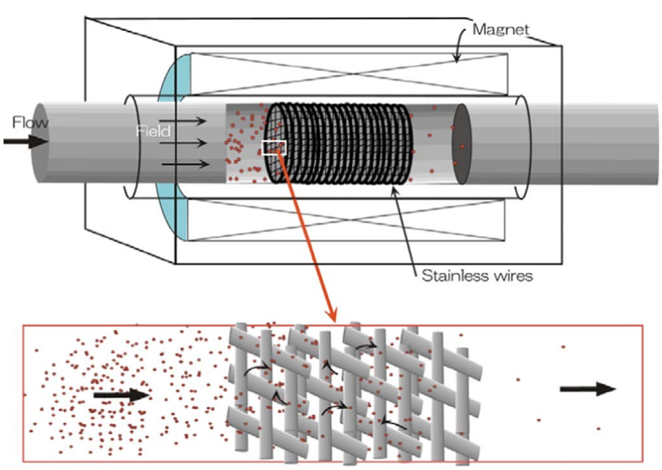

Fig. 2. Schematic figure of high gradient magnetic separation process.

generate high magnetic fields up to 13 T and has a room-temperature bore of 100 mm in diameter. The schematic drawing of experimental setup and the appearance of the filter housing are shown in Fig. 3(a) and (b), respectively. Magnetic filters used in this study were made of SUS430. The openings of filters used here were 16 meshes and 30 meshes. Whole diameter of these filters was 25 mm and diameters of the filter wires are 0.5 mm and 0.22 mm for 16 meshes and 30 meshes, respectively. The side wall of filter housing was made of acryl to see the inside. A piece of magnetic filter was fixed in this housing and introduced into the bore of the superconducting magnet. The position of the filter was fixed at the magnetic field center. The magnetic particles used here were zirconia ferrite particles manufactured by Japan Metal & Chemical Co., Ltd. The size of this particle was larger than 0.6 μm. The suspension of 0.5 g zirconia ferrite particles in 1 L of distilled water was used as the sample. In the experiment, whole flow channel was filled with distilled water at first, then, the sample suspension was flowed from the sample reservoir placed on the top of the superconducting magnet into the filter housing. The velocity of the sample suspension was controlled using the valve placed at the downstream. Behavior of suspension was observed from the side of the filter using a CCD camera, model UN43H of Elmo Co., Ltd., inserted into the bore of superconducting magnet. Observations were carried out with changing the flow rates and the applied magnetic fields up to 10T.

3. Results and discussion

Without magnetic fields, it was confirmed that Zirconia ferrite particles pass through the filter except small amount of particles physically adsorbed on the surface of the filter wires.

Fig. 4 shows the results of particle deposition process when the sample suspension was flowed with the speed of 8.4 ml/s using 16 meshes filter under 0.50 T. Different from the conventional deposition model for paramagnetic particles, the spike-like deposition structure was formed on the upper stream of the filter. It was also observed that the length of the spike was grown up more than 10 mm. In the experiment, the flow rate of the sample suspension was controlled, however, once the sample suspension was introduced into the superconducting magnet bore, particles move much faster than the fluid due to the distribution of background magnetic fields given by the superconducting magnet. The actual meaning of the flow rate control is to control the amount of particles introduced into the filter housing per unit time.

Fig. 5(a) shows a particle deposition observed when the sample suspension was flowed with the speed of 2.5 ml/s using 16 meshes

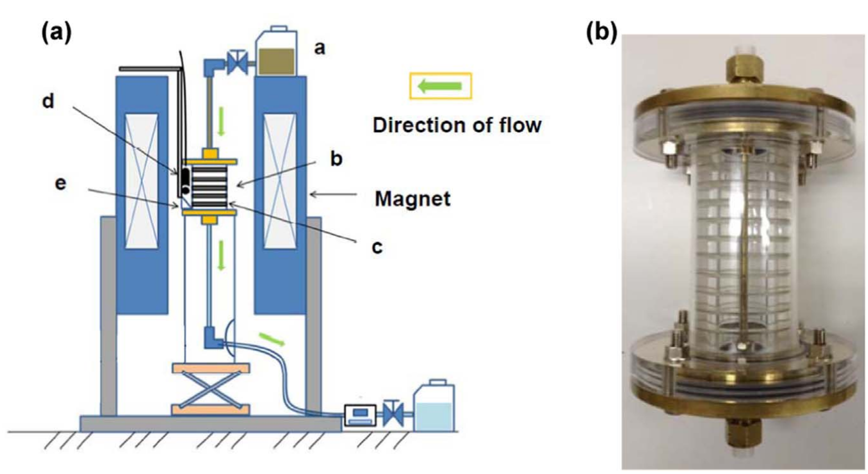

Fig. 3. The schematic drawing of experimental setup (a) and the appearance of the filter housing (b). a: sample reservoir, b: magnetic filter, c: filter housing, d: CCD camera, e: mirror.

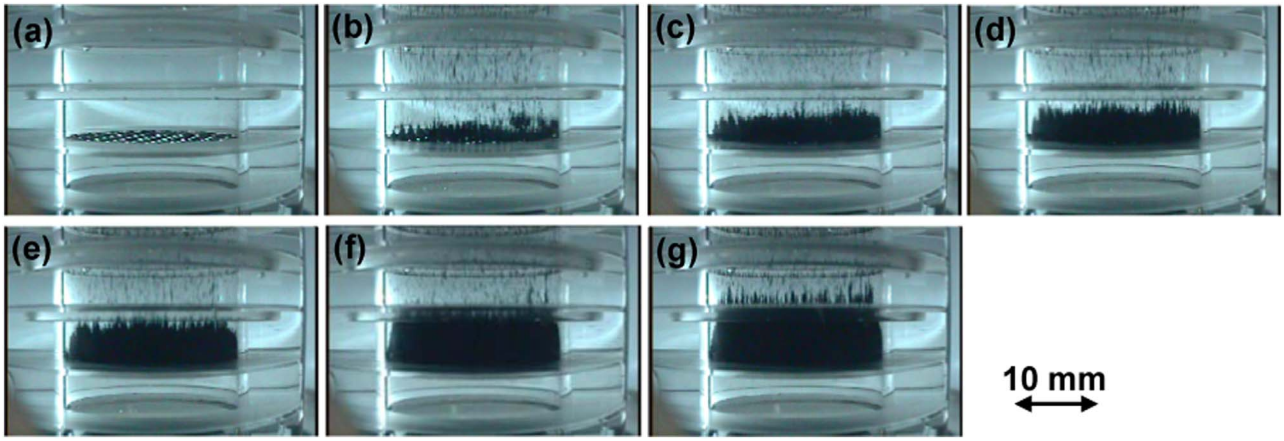

Fig. 4. Observed deposition process of magnetic particles. The sample suspension was flowed with the speed of 8.4 ml/s using a filter of 16 meshes under 0.50 T. beginning, (b) after 20 s, (c) 30 s, (d) 40 s, (e) 50 s, (f) 90 s, (g) 120 s.

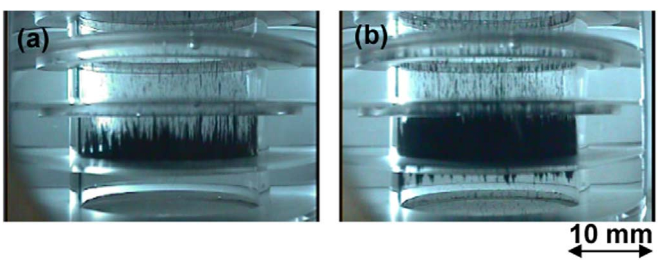

Fig. 5. Examples of particle deposition process. The sample suspension was flowed with the speed of 2.5 ml/s (a) and 19 ml/s (b), using a magnetic filter of 16 meshes under 0.1 T.

filter under 0.10 T. Under such a low field and a low flow rate conditions, particles form a chain structure or bundle structure of such chains due to the dipole-dipole interaction between particles on the way from the sample reservoir to the filter because of the magnetic fields given by the superconducting magnet. Fig. 5(b) shows a particle deposition observed with conditions 19 ml/s, 16 meshes filter and 0.1 T. Under such a low field and a high flow rate conditions, many of particles pass through the filter due to the weak magnetic force acting on particles, however, as seen in the figure, some of them were trapped at the downstream side of the filter, because the magnetic force still acts toward the filter wires even in the downstream side. This is one of the features of HGMS.

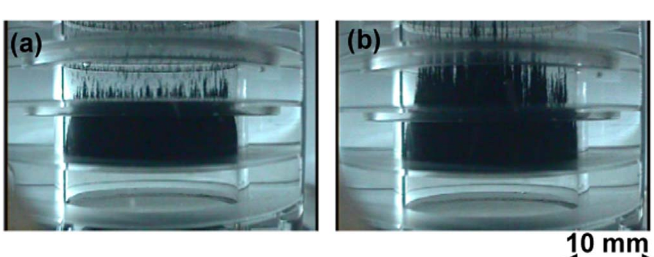

Fig. 6. Dependence of spike length on the flow rate. Both of them were observed under 0.50 T using a filter of 16 meshes. The flow rates of the sample suspension were 8.4 ml/s (a) and 2.9 ml/s (b), respectively.

Fig. 6(a) and (b) show results obtained when the sample suspension was flowed with the speed of 8.4 ml/s and 2.9 ml/s, respectively, with using 16 meshes filter under 0.50 T. These photographs were taken just before the end of the flow of the sample suspension. In both cases, almost no passing of particles through the filter was observed. As seen in figures, the length of the spike structure tends to be long with lower flow velocity.

Fig. 7(a) and (b) show results obtained using the filter of 30 meshes and 16 meshes, respectively, with changing the intensity of applied magnetic fields, 0.10 T, 0.50 T, 1.0 T, 3.0 T, and 10.0 T. These photographs were taken just before the end of the flow of the sample suspension. It was observed that the length of the spike structure tends to be long with lower applied magnetic fields. This means that the denser spike structure was formed with increasing magnetic fields. In addition, it was observed under the case of low applied magnetic fields that the length of spikes tends to be longer in the case of the filter of 30 meshes. In case of the filter of 30 meshes compared with the case of 16 meshes, the diameter of filter wires is smaller, therefore, the effect of the magnetization of wires on the spatial distribution of the magnetic field is much larger in the vicinity of the wire but limited in a short range. It may not necessarily appropriate to suggest because flow rates of the sample suspension were not always same, however, such a difference of the spike length may be observed due to the difference of the spatial wire density and the magnetic field distribution around the wire. Furthermore, in all experiments through this study, particle deposition occurred even in the place beyond the effect of wire magnetization on the spatial magnetic field distribution. From a qualitative perspective, it can be understood that the attractive force towards the spike itself acting on particles due to the gradient magnetic fields formed by the magnetization of deposited particles.

4. Conclusion

In this study, to obtain information for the optimization of separation condition, *in-situ* observations of magnetic particles deposition process on a ferromagnetic filter in HGMS were carried out under high magnetic fields. As a result, different from the conventional deposition model in case of paramagnetic particles, the spike-like deposition structure was formed on the upper stream of the filter. The length of the spike structure tends to be long with lower flow velocity and lower applied magnetic field. It was also observed that the chain structure or the bundle of such chaines

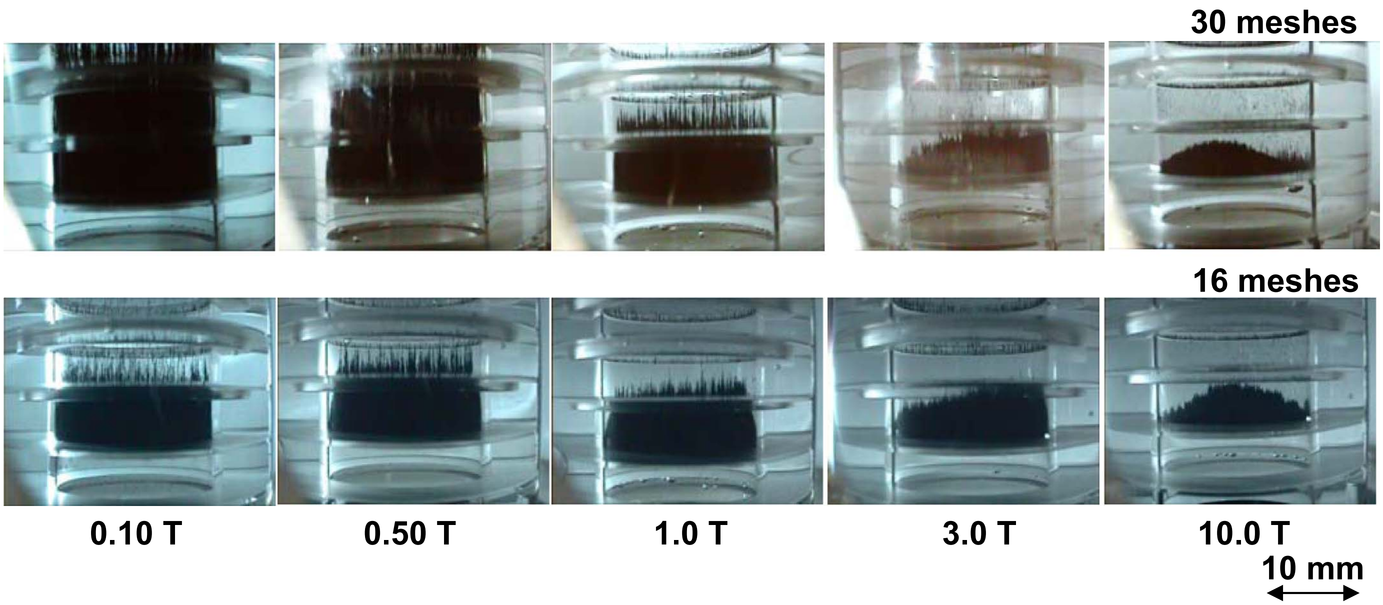

Fig. 7. Dependence of particle deposition on applied magnetic fields. Upper column: in case of the magnetic filter of 30 meshes, lower column: 16 meshes.

were formed on the way to the filter under the condition of the low applied magnetic field and low flow rates. In the computer simulation carried out to obtain optimal separation condition so far, the effect of particles deposited on the surface of filter wires was often ignored to simplify the calculation process, therefore, modification of the spatial distribution of the magnetic field and the hydrodynamic effect around the wire were not properly considered. From the observations in this study, however, it was confirmed that particles further deposit on the deposited particles and formed the spike structure due to the magnetization of already deposited particles. Therefore, it can be said that the effect of deposited particles on the spatial distribution of the magnetic field though their magnetization and the hydrodynamic effect cannot be ignored in the simulation. The knowledge obtained here seems to be important to consider the optimization of practical HGMS processes.

In this study, *in-situ* observation was carried out only from the direction perpendicular to the flow and only one filter was introduced into the housing. Further deepening of understandings of the deposition process of magnetic particles on magnetic filters will be expected through the detailed observation near the filter wire, observation from the direction parallel to the flow, and observations in the case of many filters with changing the distance of filters.

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