Material manipulation and separation using the horizontal magneto-Archimedes effect

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Abstract. We have studied the manipulation and the separation of substances using the horizontal magneto-Archimedes effect. By ingenerating a high magnetic field gradient in the horizontal direction, it is possible to move the target substance to a designated position in the horizontal direction. We attempted to separate several kinds of valuable metals by applying the horizontal magnetic force to the metals falling vertically into a paramagnetic medium. In order to enhance the magnetic force, we set up the ferromagnetic core array in magnetic fields. According to the trajectory analysis for the metal particles and the magnetic separation experiments, we succeeded in dynamically separating the metal mixture dropped to the vertical direction due to the strong horizontal magnetic force in relatively low magnetic fields. It is expected that this method creates a new device for the separation of substances.

1. Introduction
We have focused on the magneto-Archimedes effect as a means of separating and recovering variable substances such as metals and plastics from the mixture. The magneto-Archimedes effect in the vertical direction is a phenomenon in which the substance stably levitates at its specific position in the paramagnetic medium due to the balance between magnetic force and gravity under a vertical magnetic field gradient [1]-[3]. In our previous studies, a significant improvement in the power factor of the magnetic force $BdB/dz$ was achieved by inserting a ferromagnetic core array in the bore of the superconducting solenoidal magnet, and it resulted in levitating platinum with a very high density and a low magnetic susceptibility [4], [5]. However, it is difficult to separate and recovery substances with continuous processing in the bore of the superconducting magnet. Furthermore, the magneto-Archimedes effect in the vertical direction requires the large $BdB/dz$ because it is necessary to balance gravity and the magnetic force. Therefore, a high magnetic field becomes indispensable. Considering those issues, we put a spotlight on the horizontal magneto-Archimedes effect. Since there is no need for competition between the magnetic force and gravity in the horizontal direction, the relatively low magnetic fields can be used effectively. In this study we proposed a novel magnetic separation system utilizing the horizontal magnetic force and evaluated its performance by using the particle trajectory analysis and magnetic separation experiments. By using the combination of the horizontal magnetic force and gravity in open spaces, the substances were separated by falling to different positions.

2. Magnetic separation system using the horizontal magneto-Archimedes effect
Figure 1 shows a schematic diagram of the magnetic separation system using the horizontal magneto-Archimedes effect. The ferromagnetic core array composed of a lot of iron cylinders with 5
mm in diameter and 20 mm in length is set up in the uniform magnetic fields to generate a high magnetic field gradient in the horizontal direction. The vessel beside the array is filled with a paramagnetic medium of 40 wt% MnCl₂ solution. The various kinds of metal particles to be tested are dropped from the upper part of the vessel. The particle of the different material is expected to fall down to the different landing point due to the total force of both the horizontal magnetic force and gravity. The motion equation of the particles is expressed by equation (1).

\[
F_p = \frac{V^2}{\mu_0} B \cdot \nabla B + \left( \rho_f - \rho_p \right) V g - 6 \pi \eta r v
\]  (1)

Here, the first term on the right side indicates the magnetic force by the horizontal magneto-Archimedes effect, the second one shows the force by gravity and the third one is the drag force from the medium. In addition, \( V \) is the volume of the particle, \( \rho_p \) and \( \rho_f \) are the density of the material and the liquid medium, \( \chi_p \) and \( \chi_f \) are the magnetic susceptibility of the material and the liquid medium, \( \mu_0 \) is the vacuum magnetic permeability, \( B \) is the magnetic flux density, \( g \) is the gravity acceleration, \( \eta \) is the viscosity coefficient of the magnetic medium, \( r \) is the radius of the particle, and \( v \) is the relative velocity of the particle. Table 1 shows the physical properties of materials used in this study. Since the metal particles receive the different magnetic forces depending on their own magnetic susceptibility, it is hoped that they fall to the different landing points and are dynamically separated from the mixture in open spaces.

| material               | Density [g/cm³] | Magnetic susceptibility [-] | Viscosity coefficient [mPa s] |
|------------------------|-----------------|----------------------------|-------------------------------|
| Cu                     | 8.93            | -9.63x10⁻⁶                 |                               |
| Ag                     | 10.5            | -2.40x10⁻⁵                 |                               |
| Au                     | 19.32           | -3.40x10⁻⁵                 |                               |
| Pt                     | 21.45           | 2.64x10⁴                   |                               |
| Manganese chloride     | 1.36            | 6.99x10⁴                   | 6.698                         |
| aqueous solution (40 wt. %) |                |                             |                               |

**Figure 1.** Schematic diagram of the magnetic separation system proposed in this study.
3. Trajectory analysis of the particles

We carried out the trajectory calculation of the particles using equation (1) to investigate the magnetic separation performance by the finite element method using the COMSOL Multiphysics software. Figure 2a shows the magnetic field distribution in the open space at the uniform applied magnetic field of 2 T. By arranging the ferromagnetic core array an increase in the magnetic field and the appearance of the magnetic field gradient are remarkably observed. Figure 2b shows the magnetic field distributions in the x-axis direction from the center of the array. The maximum magnetic field and magnetic field gradient reached about 2.35 T and -16.7 T/m just above the ferromagnetic core array, respectively. Figure 2c indicates the magnetic field distribution in the z-axis direction with the various magnetic core spacing. Both the increase in the magnetic field and its uniformity above the array are clearly observed with reducing the core spacing.

![Magnetic field distribution](image)

**Figure 2.** The magnetic field distribution in (a) the open space at the applied magnetic field of 2 T, (b) the x-axis direction from the centre of the array and (c) the z-axis direction with the various core spacing of the magnetic core array.

In the trajectory calculation, the equation of motion due to the forces acting on the particles (gravity, magnetic force and drag force of fluid) in the three-dimensional space was solved by the time difference method. The magnetic force was obtained by calculating the magnetic field gradient from the calculation result of the magnetic field in space. Figures 3a and 3b show the results of the trajectory analysis for Cu, Ag, Au, and Pt particles with the size of 1 mm when the iron core spacing of the array...
was fixed at 0.1 mm and the applied magnetic fields changed from 2 T to 5 T and eighteen particles per each metal were dropped from the upper points within a width of 15 mm. The magnetic field lines spread three-dimensionally due to the generated magnetic field gradient by the ferromagnetic arrangement. Therefore, the particles also receive a magnetic force in the y direction \((B \, dB/dy)\), so the particles move in a form that spreads slightly in the y direction. It can be seen that the same metal particles fell to almost the same position. Since Cu which has the lightest density and the lowest diamagnetic susceptibility, it falls slowly and therefore it falls farthest. Ag is a little heavier than Cu, but its diamagnetic susceptibility is a little higher than Cu, so the horizontal magnetic force increases, and it goes to the second farthest. On the other hand, Au has almost the same magnetic susceptibility as Ag, but it does not fall too far because of its high density. In addition, Pt has a slightly higher density than Au, however, since its magnetic susceptibility is paramagnetic, its horizontal magnetic force is the weakest, so it falls to the front. When the magnetic field increases from 2T to 5T, the tendency does not change, and the landing point of each metal becomes far, as a result the resolution of separation improves accordingly. Figures 4a and 4b indicate the magnetic field dependence of the landing point for each metal with the particle size of 3 mm and 5 mm, respectively. As increasing the magnetic field, the landing point increases because the magnetic force is enhanced by increase in the power factor of \(dB/dx\). Figures 5a and 5b show the relationship between the landing point and the particle size for Cu and Au at the various magnetic fields. As the particle size increases, the landing point initially decreases slightly, but then tends to saturate. It is considered that this is because the volume \(V\) of the substance is included in both the magnetic force and gravity terms in the equation (1). As the gravity term increases, the fall time decreases, but the magnetic force term also increases, so it is considered that the distance moving in the horizontal direction does not change much.

![Diagram](image)

**Figure 3.** (a) Trajectory of each particle when the applied magnetic field changed and (b) Comparison of particle landing points when the applied magnetic field changed.
4. Experimental result

The magnetic separation experiments using a 2T split magnet were conducted to verify the behavior of particles in the simulation. The experimental equipment is shown in figure 6. The ferromagnetic core array was installed on the positive magnetic pole of the split magnet. The acrylic vessel was filled with a paramagnetic liquid medium of MnCl₂ 40 wt% aqueous solution, and the metal particles were dropped from the top of the vessel. We investigated the magnetic separation characteristics of precious metals such as gold, silver and copper. Table 2 summarizes the landing points of simulation and experimental for all metals. The tendency of landing points between the experimental and the simulation for all metals is almost the same. However, the experimental values are a little larger than the simulation ones. The absolute error is shown in Table 2. For example, Cu moved to 26 mm in the...
simulation, while it was 21 mm in the experiment. The relative error is about 23%. We believe that it comes from the repulsive force caused by the eddy current. The detailed examination is a future task.

![Figure 6](image)

**Figure 6.** Magnetic separation experiment with the split magnet.

| Materials | Landing position [mm] | Absolute error [mm] |
|-----------|------------------------|---------------------|
| Cu        | 21                     | 5                   |
| Ag        | 15.5                   | 2.5                 |
| Au        | 6.5                    | 5.5                 |
| Pt        | 2.5                    | 2.5                 |

**5. Conclusion**

We proposed a new magnetic separation system using the horizontal magneto-Archimedes effect. By setting up a ferromagnetic core array in magnetic fields, we succeeded in obtaining the large magnetic force in relatively low magnetic fields. The particle tracking simulation showed the possibility of the dynamic magnetic separation of substances, and the actual magnetic separation experiment using this system was demonstrated. It also revealed that the magnetic separation is possible with a lower magnetic field than the magneto-Archimedes effect in the vertical direction. In the near future, we plan to conduct the magnetic separation experiments in open spaces using a racetrack superconducting magnet with built-in the ferromagnetic core array.

**References**

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