

Study on separation of nonferrous metal utilizing magneto-Archimedes method

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(Received 16 January 2019; revised or reviewed 20 June 2019; accepted 21 June 2019)

Abstract

In order to improve resource value, separation of nonferrous metals obtained from crushed materials of home appliances is required. In this study, we aimed to develop a continuous separation system by magneto-Archimedes method using magnetic fluid as a medium and the permanent magnet as a magnetic field source. Firstly, the separation conditions were examined in which only copper is settled and the difference in levitation positions between aluminum and other metals are over 1 cm. Based on the results, levitation experiment of each metal and separation experiment from the mixture of nonferrous metals were confirmed. The separation experiment showed that the continuous separation of copper and aluminum from a mixture of nonferrous metals is possible.

Keywords: nonferrous metals, magneto-Archimedes method, magnetic fluid

1. INTRODUCTION

In recent years, recycling of waste home electrical appliances has been promoted in order to reduce the amount of waste and utilize effectively as resources. Fig. 1 shows the processing flow of the waste home appliances being performed [1]. First of all, waste home appliances are recovered from each household or office, and they are manually disassembled to recover home appliance parts (Compressor, heat exchanger, etc.). Next, the remaining parts are shredded and separated by three processes. Firstly, ferrous metals are recovered by magnetic separation. Secondly, nonferrous metals are recovered by eddy current separation. Lastly, plastics are recovered by specific gravity separation. Those recovered by eddy current separation include several kinds of nonferrous metals. It is necessary to separate into single nonferrous metals with high purity to improve resource value.

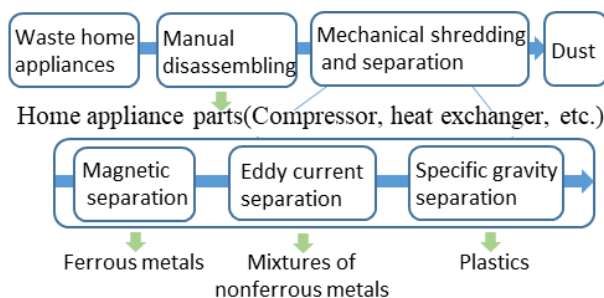


Fig. 1. The processing flow of the waste home appliances.

Heavy liquid separation and color sorting are performed as conventional sorting methods. However, in general,

heavy liquid separation, the specific gravity of the liquid is limited to 3 g/cm³ or less. Also, in color sorting, it is difficult to select metals with similar colors and plated metals.

Among copper, aluminum, zinc and brass, which are nonferrous metals contained in crushed materials of household appliances, separating copper and aluminum are particularly required. Thus, this study focused on the magneto-Archimedes method aiming at separation of copper and aluminum with high accuracy from the mixture of nonferrous metals.

In our previous studies, the possibility of precise separation by the magneto-Archimedes method was demonstrated using MnCl₂ solution and an internal magnetic field of a superconducting solenoidal magnet [2-4]. Other researches also show the possibility of separation of various materials [5-6]. However, the separation method in the bore has limitations on the separation mechanism, which results in the difficulty of continuous mass processing. In this research, we focused on the magnetic fluid of superparamagnetic substance showing strong magnetism even under low magnetic field, aiming at developing a continuous separating system by magneto-Archimedes method using the permanent magnet.

2. THEORY OF MAGNETO-ARCHIMEDES METHOD USING MAGNETIC FLUID

2.1. Magneto-Archimedes method

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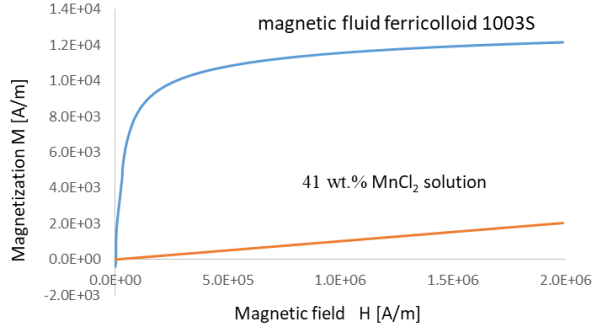


Fig. 2. Magnetization curves of the magnetic fluid (ferricolloid 1003S) and MnCl_2 aqueous solution (41 wt. %).

The principle of Archimedes is that a particle in a fluid is subjected to the buoyancy which has the same magnitude and opposite direction of gravity acting on the same volume of fluid. Hence, the buoyancy increases in a fluid having a larger specific gravity. The magneto-Archimedes phenomenon is based on this. For example, when attracting a medium downwards with a magnet, the apparent weight of the fluid increases, that makes the object being levitated.

In magneto-Archimedes method, the buoyancy acting on the particles in the medium is controlled, and the materials are separated by the difference in levitation heights.

2.2. About magnetic fluid

Here, the magnetic fluid used as a medium in this study is explained. The magnetic fluid consists of the slurry of colloidal particles, stably dispersed by surface treatment of ferromagnetic fine particles such as magnetite with a particle size of about 10 nm. The magnetization per unit weight of the magnetic fluid can be regarded as the sum of the magnetization of the dispersed particles and is expressed by the following formula [2].

$$\sigma = \rho_2 \left(\frac{\sigma_s}{\rho} \right) \frac{(\rho - \rho_1)}{(\rho_2 - \rho_1)} \quad (1)$$

σ_s is magnetization of dispersed particles, ρ is density of magnetic fluid, ρ_1 is density of solvent, and ρ_2 is density of dispersed particles.

Fig. 2 shows the magnetization curves of the magnetic fluid (ferricolloid 1003S ichinen chemicals Co.,LTD., Japan) used in this study and the saturated aqueous solution of MnCl_2 which is a paramagnetic medium. By comparing the two magnetization curves, it is found that the magnetic fluid shows a strong magnetization even in a low magnetic field. Therefore, the magnetic fluid as the medium enables the magneto-Archimedes separation of the nonferrous metals with large specific gravity, using the leakage magnetic field of the superconducting solenoidal magnet or the permanent magnet.

2.3. Theory of magneto-Archimedes method [3]

Here, the theory of magneto-Archimedes method with magnetic fluid as the medium is explained. As an example, the conceptual diagram of the magneto-Archimedes phenomenon is shown in Fig. 3. Fig. 3 (a) shows the forces acting on the diamagnetic particles in the magnetic fluid, and Fig. 3 (b) shows the force acting on the magnetic fluid

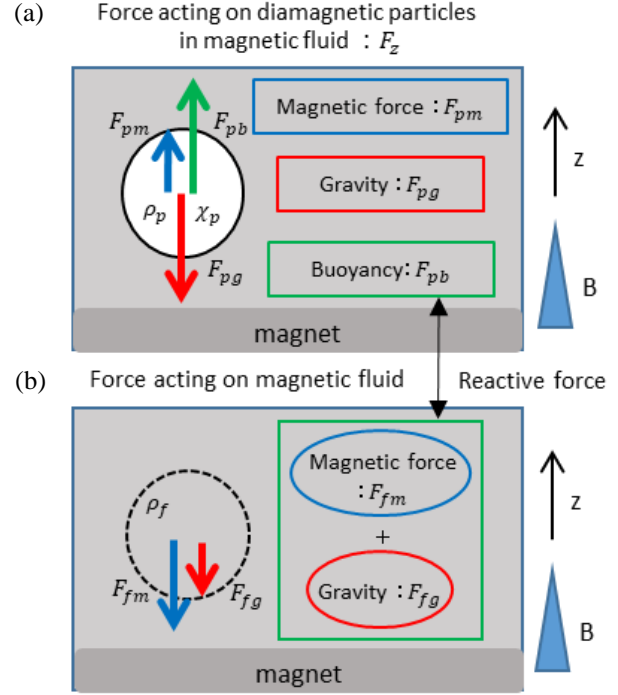


Fig. 3. Conceptual illustrations of magneto-Archimedes effect; (a) the force acting on the diamagnetic particles in the magnetic fluid (b) The force acting on the magnetic fluid.

(one-dimensional notation). The z -axis is oriented vertically upward and the magnetic field is applied in the positive direction of z -axis.

At this time, magnetic force F_{fm} and gravity F_{fg} act on the magnetic fluid in the negative direction of z -axis. On the other hand, buoyancy F_{pb} and magnetic force F_{pm} act on the diamagnetic particles in the magnetic fluid positive direction of z -axis, and gravity F_{pg} acts in the z -axis negative direction.

Therefore, the force F_z per unit volume acting on the diamagnetic particles in the magnetic fluid is given as the resultant force of the three forces.

$$F_z = F_{pm} + F_{pg} + F_{pb} \quad (2)$$

We focus on each term of formula (2), when the density of the particles, the density of the medium, and the volume susceptibility of the particles is respectively represented by ρ_p , ρ_f and χ_f .

First, when we define the magnetic flux density as B and the space permeability as μ_0 , the magnetic force F_{pm} per unit volume acting on the particles is expressed as (3).

$$F_{pm} = \frac{\chi_p}{\mu_0} B \frac{dB}{dz} \quad (3)$$

Next, when we define the gravitational acceleration as g , the gravity F_{pg} per unit volume acting on the particle is expressed as (4)

$$F_{pg} = -\rho_p g \quad (4)$$

Finally, when we define the magnetization of the magnetic fluid as M , the buoyancy F_{pb} per unit volume acting on the particles is calculated as the reaction force of the force acting on the magnetic fluid as follows.

$$F_{pb} = -(F_{fm} + F_{fg}) = -(M \frac{dB}{dz} - \rho_f g) \quad (5)$$

Consequently, according to (2)-(5), the resultant force per unit volume acting on the diamagnetic particle in the magnetic fluid is shown as (6).

$$F_z = \frac{\chi_p}{\mu_0} B \frac{dB}{dz} - \rho_p g - M \frac{dB}{dz} + \rho_f g \quad (6)$$

Formula (6) shows the force acting on diamagnetic particles, but one acting on paramagnetic is also represented by the same formula.

F_{fm} is four orders of magnitude smaller than F_{pm} . Thus the first term of formula (6) can be ignored, and F_z is expressed by formula (7).

$$F_z \approx -\rho_p g - M \frac{dB}{dz} + \rho_f g \quad (7)$$

In this equation, when F_z is positive, particles are levitated and the position is defined when F_z is equal to 0. By substituting zero into F_z (7), the levitating condition of the particles in the magnetic fluid is expressed as (8).

$$(\rho_p - \rho_f)g \leq -M \frac{dB}{dz} \quad (8)$$

The right side of this equation shows the reaction force of the magnetic force acting on the magnetic fluid, which is equal to the apparent buoyancy acting on the particle. The left one shows the difference between the gravity and the normal buoyancy acting on the particle, which corresponds to the magnitude of the force required for levitating. Hence the equation (8) shows that the levitation and sedimentation of the particles and the levitating height can be controlled by changing the magnetic force acting on the magnetic fluid.

3. EXAMINATION OF SEPARATING CONDITION

3.1. Examination of magnetic field

TABLE I shows the physical properties of aluminum, zinc, brass and copper, which are the nonferrous metals included in the crushed home electrical appliances waste. Since the difference in density between copper and its alloy brass is small, it is considered that the difference in levitating heights by the magneto-Archimedes method becomes small. Thus we aimed to separate pure copper by sedimentation, whereas aluminum and other metals are separated by the difference in levitation heights. At first, to settle only copper, the permanent magnets were made to face each other so that the magnetic force acting on the magnetic fluid has a maximum value at a certain vertical height. Next, to increase the difference in levitation heights between aluminum and other metals, the magnets were inclined in the direction so that the distance between the upper parts of the magnets being wider.

In this study, two neodymium magnets (NEOMAX 44H, $5 \times 5 \times 1$ cm) with a surface maximum magnetic flux density of 0.4 T were used. From the magnetization curve of the magnetic fluid and the result of magnetic field analysis, the distance between the center of magnets and the inclination angle were adjusted so that only copper was settled and levitating difference between aluminum and other metals is more 1 cm. As a result of the examination, separating conditions were determined at the distance

TABLE I
THE DENSITY AND THE VOLUME MAGNETIC SUSCEPTIBILITY OF NONFERROUS METALS INCLUDED IN THE HOME ELECTRICAL APPLIANCES WASTE.

	Density [kg/m ³]	Volume magnetic susceptibility [-]
Aluminum	2700	2.07×10^{-5}
Zinc	7130	-1.56×10^{-5}
Brass (Cu+Zn)	8450	-1.20×10^{-5}
Copper	8960	-9.68×10^{-6}

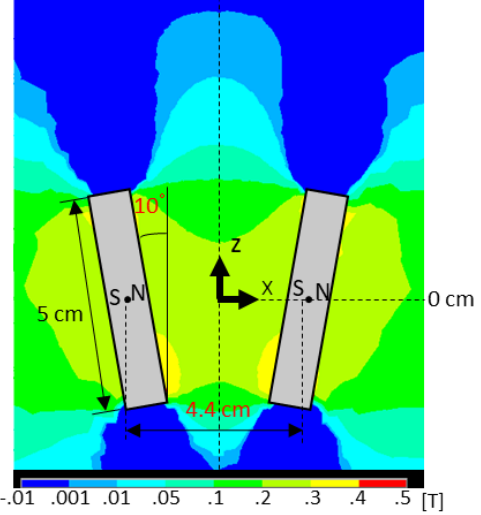


Fig. 4. The analysis result of magnetic field distribution with facing permanent magnets.

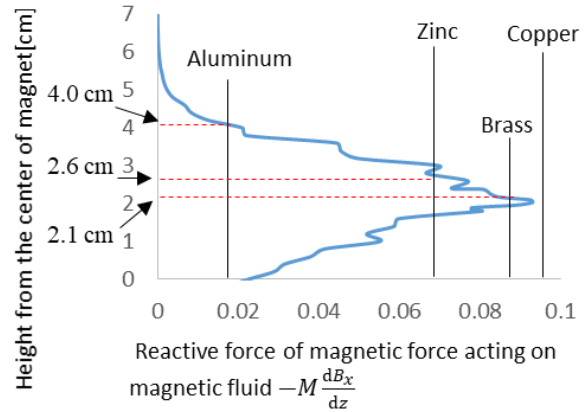


Fig. 5. The relationship between the distance in vertical direction and reaction force of magnetic force acting on the magnetic fluid.

between the center of magnets of 4.4 cm and inclination angle of 10 degrees. Fig. 4 shows the results of magnetic field analysis by FEM (Finite Element Method) using Ansys10.0. Fig 5 shows the reaction force of the magnetic force acting on the magnetic fluid as a function of the distance in the vertical direction from the magnet center.

3.2. Experiment of magneto-Archimedes levitation

Based on the conditions examined in the previous chapter, the levitating height of each metal was measured. In this experiment, metal pieces of copper, aluminum, zinc

TABLE II
THEORETICAL AND MEASURED VALUES OF LEVITATING HEIGHTS OF
NONFERROUS METALS.

	Theoretical value [cm]	Experimental value [cm]
Aluminum	4.0	3.9
Zinc	2.6	2.5
Brass	2.1	1.9
Copper	0 (Sedimentated)	0 (Sedimentated)

and brass screws were used as samples of nonferrous metals cut in several mm square. Firstly, the magnet position was adjusted so that the distance between the centers of the magnets is 4.4 cm and the angle of inclination is 10 degree. Secondly, the vessel containing the magnetic fluid was inserted in the center of the magnet. Thirdly, the stringed metal piece was slowly soaked into the magnetic fluid. Finally, the levitation height was calculated from the length of the string from the liquid surface.

TABLE II shows the theoretical and measured values of the levitating height from the magnet center in each metal. As a result of the magneto-Archimedes levitating experiment, it was confirmed that only copper is sedimented and other metals are levitated close to each theoretical positions.

4. SEPARATION EXPERIMENT OF NONFERROUS METALS UTILIZING MAGNETO-ARCHIMEDES METHOD

4.1 Examination of continuous separating system

The schematic diagram of the continuous separating system of each metal is shown in Fig. 6. Fig. 6(a) shows a stereographic view and Fig. 6(b) shows the side view. We

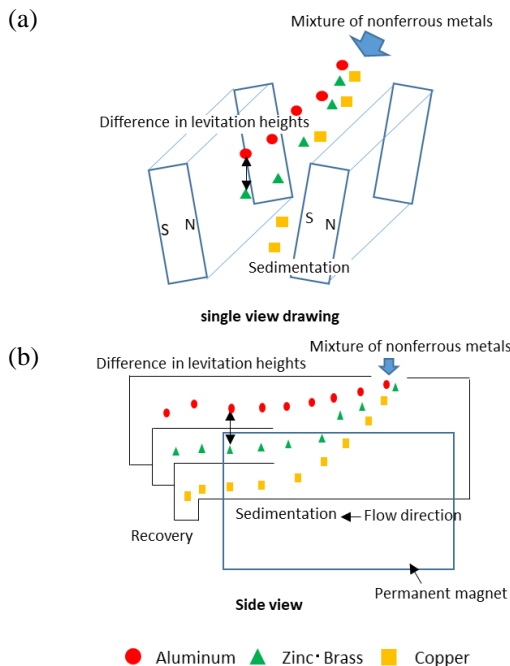


Fig. 6. Schematic diagram of a possible continuous separating system (a) Stereographic view (b) Side view.

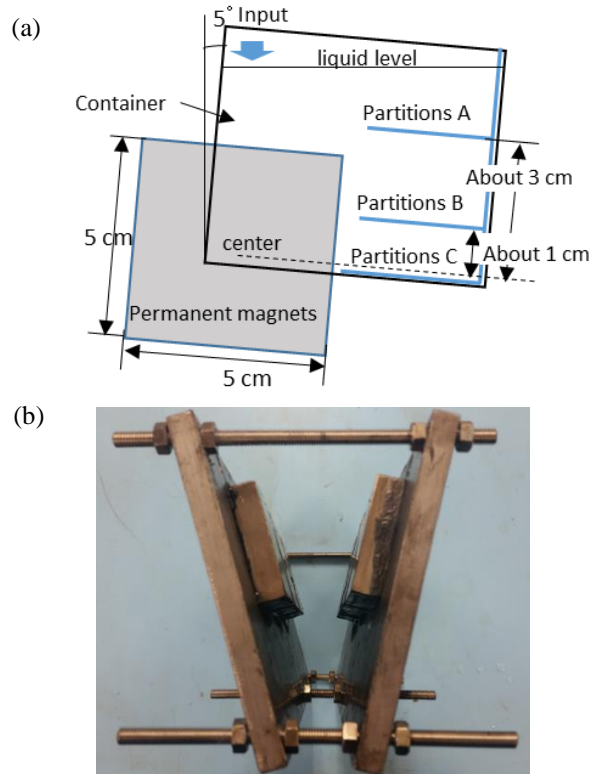


Fig. 7. (a) Schematic diagram of separating experiment and (b) a face-type magnets used in the separating experiment.

aimed to separate the metals continuously in the flow by the partitions between aluminum, copper and other metals.

As a fundamental experiment for that purpose, separating experiment was conducted with a system without flow.

4.2. Experimental method

The view of an experimental system is shown in Fig. 7. Firstly, the container (7 x 7 x 2 cm) was assembled, and a plastic basket with two partitions was set inside the container as shown in Fig.7 (a). Then the container was filled with the magnetic fluid. Secondly, the apparatus was installed between the face-type magnets shown in Fig. 7 (b), so that the positions of partitions are about 1 cm below the levitating height of each metal. Thirdly, a whole experimental system was inclined at 5 degrees so as to collect the separated samples at the end of the partitions, and five pieces at samples each for aluminum, zinc and copper and two pieces of brass screws were inputted. Finally, the nonferrous metals were recovered by pulling up the mesh partition.

4.3. Experimental result

The state of each metal recovered is shown in Fig. 8, and the number of recovered metals in each partition is shown in TABLE III. As a result of separating experiments, accurate recovery of aluminum, zinc and copper was confirmed, except for one copper collected in a partition B instead of targeting partition C, which is considered as just an experimental error depending on the deviation of injection position or speed. In contrast, brass was collected in partition C instead of the target partition B.

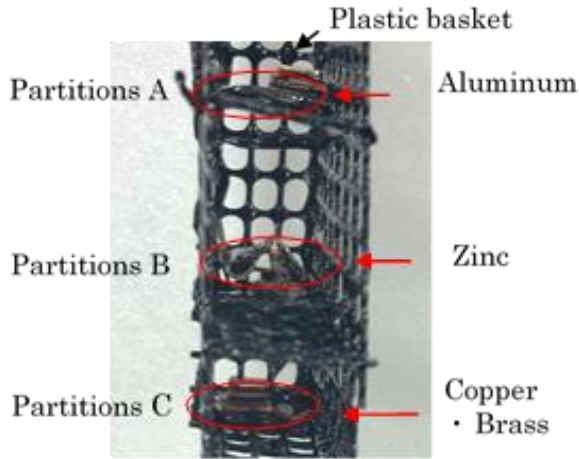


Fig. 8. The state of recovered nonferrous metals by partitions.

TABLE III
NUMBER OF NONFERROUS METALS RECOVERED IN EACH PARTITION.

	Inputted Sample	A	B	C
Aluminum	5	5		
Zinc	5		5	
Brass	2			2
Copper	5		1	4

○ The position of the partition to be collected

4.4. Discussion

Brass was settled and not recovered by partition B. The reason is considered that brass passed through the floating area due to the influence of acceleration because brass has a narrower floating area in the height direction in contrast with aluminum and zinc.

Based on the conditions of this experiment, we solved the motion equation of the particles by Runge-Kutta method with time development, and calculated the trajectory of metals. In the condition, the result of the three-dimensional magnetic field analysis by FEM shown in Fig. 4 was used as the magnetic field distribution, and the flow velocity was set to 0. The calculation range was set to 5 cm from the center of the magnet in vertical and horizontal directions. Fig. 9 shows the calculated particle trajectories. The results of the separating experiments and calculation of particle trajectories are almost agreed. It was confirmed that brass was levitated in the middle and captured by the partition B, when lowering the input position of brass by 0.5 cm than that in the experiment. From this result, it was confirmed that the brass passed through the floating area due to the influence of acceleration by falling. Therefore, we considered that accurate separation becomes possible by expanding the range that satisfies the brass levitating condition. For that purpose, it is necessary to examine the inclination angle of the magnets so that the magnetic force shown in Fig. 5 has a broad peak against the height from the magnet center.

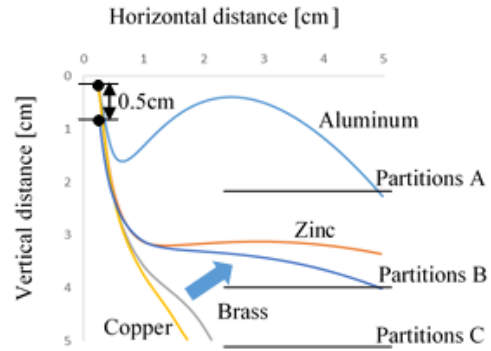


Fig. 9. Calculation of particle trajectories.

5. CONCLUSION

Aiming for the continuous mass processing for nonferrous metals, the magneto-Archimedes separation using magnetic fluid and the permanent magnet was examined.

As a result of the separation experiment, the possibility of the continuous separation of copper and aluminum from the mixture of nonferrous metals was shown, whereas the previous study showed only the batch separation in the small system in the magnet bore. In addition, it was shown that the use of magnetic fluid make the separation in low magnetic field possible, whereas previous study needed the magnetic field in several T that is only realized inside the bore of superconducting magnet. In the future study, we will quantify the separating accuracy in the flow and throughput by increasing the sorting amount using permanent magnets with the wider flow direction.

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