

# Separation of Flame and Nonflame-retardant Plastics Utilizing Magneto-Archimedes Method

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**Abstract.** In physical recycling process, the quality of recycled plastics becomes usually poor in case various kinds of plastic materials are mixed. In order to solve the problem, we tried to separate flame and nonflame-retardant plastics used for toner cartridges as one example of mixed plastics by using magneto-Archimedes method. By using this method, we can control levitation and settlement of the particles in the medium by controlling the density and magnetic susceptibility of the medium and the magnetic field. In this study, we introduced the separation system of plastics by the combination of wet type specific gravity separation and magneto-Archimedes separation. In addition, we examined continuous and massive separation by introducing the system which can separate the plastics continuously in the flowing fluid.

## 1. Introduction

### 1.1. Background

Plastics are used for various purposes in our daily life and industries. Due to the mass production and consumption of plastics, we face the exhaustion of natural resources and the environmental problems.

In order to solve the problems, physical recycling has been paid particular attention for sustainable use of natural resources and CO<sub>2</sub> reduction. However, in physical recycling process, the quality of recycled plastics becomes poor when the various kinds of plastic materials are mixed together.

To solve the problem, we focused on magneto-Archimedes method where the difference of densities and magnetic susceptibilities of mixed plastics are utilized. If we can separate the mixed plastics accurately and massively by using the method, physical recycling which is superior to chemical recycling in the sense of environmental load, can be promoted furthermore. In this study, we conducted the separation experiments using magneto-Archimedes method as a fundamental experiment. Based on the results, we examined the possibility of the continuous separation system by using a superconducting solenoidal magnet.

### 1.2. Separation objects

The materials suitable for the physical recycling are those satisfy the following conditions, that is, 1) industrial waste having large amount and 2) including small amount of contaminant or foreign










substances. Thus, we separated flame-retardant plastics (black) and nonflame-retardant plastics (black, translucent, blue, orange, gray, white) used for toner cartridges as one example of mixed plastics. Flame-retardant plastics are hardly combustible because they contain flame retarders such as aromatic brominate compounds. Once flame and nonflame-retardant plastics are mixed, the flame-retardant effect is reduced. In this study, we separated flame-retardant plastics (black) selectively from the mixture of flame and nonflame-retardant plastics by using magneto-Archimedes method.

### 1.3. Purpose

We tried to separate flame and nonflame-retardant plastics accurately and massively. The target purity and processing speed were set to 90 % and 200 kg/h, respectively. By employing 10 magnetic separation apparatuses developed in this study, the processing speed of 2000 kg/h will be realized, which corresponds to the annual amount of waste plastics of toner cartridges in Japan[1].

First, we examined separation process based on the density and magnetic susceptibility of each plastic. Table 1 shows the density and magnetic susceptibility of each plastic. The density of the flame-retardant plastic is larger than those of some nonflame-retardant plastics, whereas is smaller than those of residual nonflame-retardant plastics. Therefore, in order to separate flame-retardant plastics only by wet type specific gravity separation, two-stage wet type specific gravity separation by using two different mediums is required. In addition, in case the difference in densities is small, separation accuracy becomes lower. Thus, we conducted magnet-Archimedes method which can separate each object accurately, focusing on the difference in magnetic susceptibilities among the plastics.

**Table 1.** Densities and magnetic susceptibilities of plastics used for toner cartridges.

Color		Type	Density (gcm <sup>-3</sup> )	Magnetic susceptibility (-)
Flame-retardant black		HIPS (High Impact Polystyrene)	1.085	$1.06 \times 10^{-5}$
Nonflame-retardant translucent		POM (PolyOxyMethylene)	1.412	$-3.85 \times 10^{-6}$
Nonflame-retardant black		HIPS	1.250	$2.90 \times 10^{-6}$
Nonflame-retardant blue		ABS (Acrylonitrile Butadiene Styrene Resin)	1.050	$-5.39 \times 10^{-6}$
Nonflame-retardant orange		HIPS	1.044	$-5.39 \times 10^{-6}$
Nonflame-retardant gray		HIPS	1.042	$-6.41 \times 10^{-6}$
Nonflame-retardant white		HIPS	1.040	$-4.36 \times 10^{-6}$

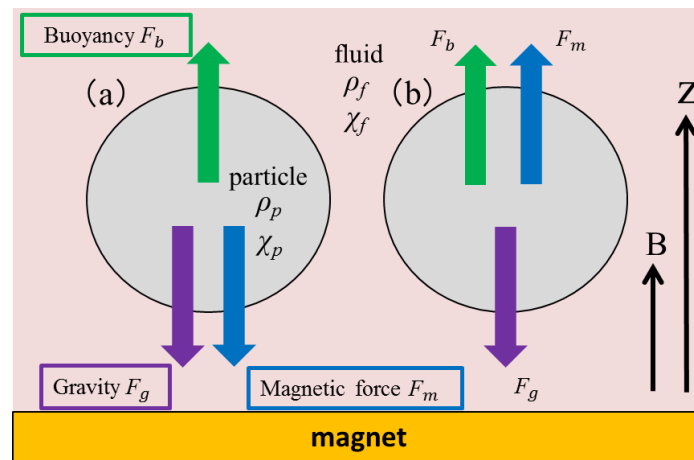
## 2. Magneto-Archimedes method[2]

Archimedes' principle is that a particle in a fluid is subjected to buoyancy which equals to the weight of the fluid replaced by the particle. This means that it is possible to increase buoyancy by increasing the weight of the fluid apparently. When we use a paramagnetic medium as the fluid, the weight of the fluid

becomes apparently heavier due to the magnetic force. In this way, we can increase the buoyancy acting on the particle in the fluid.

In addition to buoyancy, gravity and magnetic force act on the particle. Due to the resultant force, the particle levitates depending on its density and magnetic susceptibility. Magneto-Archimedes separation can be performed by utilizing the difference in levitating position of particles. Figure 1 shows the conceptual illustration of the magnetic Archimedes effect (one-dimensional representation). Figure 1(a) shows the forces acting on a paramagnetic particle in a paramagnetic medium. The z-axis is oriented vertically upward and the magnetic field is applied in the positive direction of z-axis.

Buoyancy  $F_b$  acts on the paramagnetic particle in the positive direction of z-axis, whereas gravity  $F_g$  and magnetic force  $F_m$  acts in the negative direction. Figure 1(b) shows the forces acting on a diamagnetic particle. Buoyancy  $F_b$  and magnetic force  $F_m$  act on the diamagnetic particle in the positive direction of z-axis and gravity  $F_g$  acts in the negative direction.



**Figure 1.** Conceptual illustration of magneto-Archimedes effect (one-dimensional representation).

(a) paramagnetic particle (b) diamagnetic particle  $\rho_p$ : Density of particle,  $\rho_f$ : Density of medium  
 $\chi_p$ : Magnetic susceptibility of particle,  $\chi_f$ : Magnetic susceptibility of medium

Firstly, we examined the resultant force of the paramagnetic particle ( $\chi_p > 0$ ) in the paramagnetic medium. The resultant force  $F_z$ , which is sum of gravity  $F_g$ , magnetic force  $F_m$  and buoyancy  $F_b$  acting on the paramagnetic particle is expressed as (1).

$$F_z = F_b - F_m - F_g \quad (1)$$

Both gravity  $F_g$  and magnetic force  $F_m$  acting on the paramagnetic particle are in the negative direction of z-axis as shown in figure 1(a), and hence these signs are negative. Regarding the term of gravity, when we define  $g$  as gravitational acceleration, gravity per unit volume acting on the particle is in the negative direction of z-axis and expressed as (2).

$$-F_g = -\rho_p g \quad (2)$$

Regarding the term of magnetic force  $F_m$ , magnetic force per unit volume acting on the particle is denoted one-dimensionally as (3), where  $B$  is magnetic flux density and  $\mu_0$  is space permeability.

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

Magnetic force field (the product of magnetic flux density and magnetic field gradient) always negative, because  $\frac{dB}{dz} < 0$  is held. The magnetic force per unit volume acting on the paramagnetic particle is expressed as (4).

$$-F_m = \frac{\chi_p}{\mu_0} B \frac{dB}{dz} \quad (4)$$

Buoyancy  $F_b$  is the inverse resultant force of gravity and magnetic force acting on the displaced medium by the paramagnetic particle. Consequently, buoyancy  $F_b$  per unit volume acting on the paramagnetic particle is expressed as (5)

$$F_b = \rho_f g - \frac{\chi_f}{\mu_0} B \frac{dB}{dz} \quad (5)$$

Therefore, the resultant force  $F_z$  per unit volume acting on the paramagnetic particle in the paramagnetic medium is expressed as (6), which is derived from (1)(2)(4)(5).

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

Next, we examined the resultant force of the diamagnetic particle ( $\chi_p < 0$ ) in the paramagnetic medium. The resultant force  $F_z$  is expressed as (7).

$$F_z = F_b + F_m - F_g \quad (7)$$

In addition, magnetic force is expressed as (3). Therefore, (6) is provided by (2)(3)(5)(7). After all, the resultant force  $F_z$  per unit volume acting on the paramagnetic or diamagnetic particle in the paramagnetic medium is expressed in the same formula as shown in (6). When the resultant force  $F_z > 0$ , the particle levitates, whereas the resultant force  $F_z < 0$ , the particle settles. Just when the resultant force  $F_z = 0$ , the levitating position of particle is defined. When the resultant force  $F_z = 0$ , magnetic force field  $B \frac{dB}{dz}$  is expressed as (8), derived from (6)

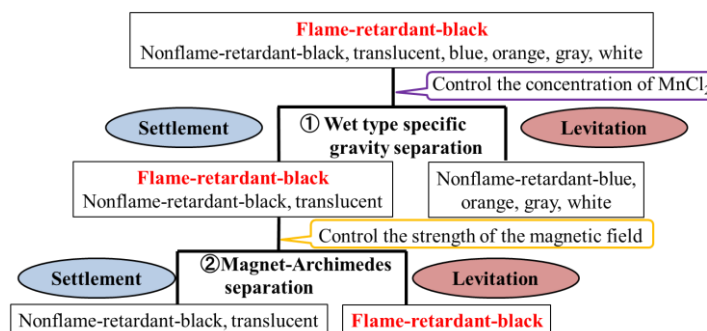
$$B \frac{dB}{dz} = \frac{\rho_p - \rho_f}{\chi_p - \chi_f} \mu_0 g \quad (8)$$

The density and magnetic susceptibility of materials are fixed and hence the levitating heights of particles are uniquely defined. In magneto-Archimedes method, the objects are separated depending on the difference in levitating heights.

### 3. Examination of separation conditions

#### 3.1. Examination of separation process

Although we can separate each object accurately by using magneto-Archimedes method, there is a problem of processing speed. To solve the problem, we introduced wet type specific gravity separation, which can separate each object massively before the magneto-Archimedes separation. In addition, in order to realize continuous separation, we used a common medium in wet type specific gravity separation and magneto-Archimedes separation. In this study, we used manganese chloride aqueous solution (hereinafter referred as  $\text{MnCl}_2\text{aq.}$ ), because it shows paramagnetism and soluble in water. The separation process is shown in figure 2. First, we settled flame and nonflame-retardant plastics whose densities are larger than the medium. Next, we separated flame-retardant plastics selectively from the mixture of the settled plastics by utilizing magneto-Archimedes levitation. In this way, we can control levitation and settlement of the plastics by controlling the concentration of the medium and the strength of magnetic field.

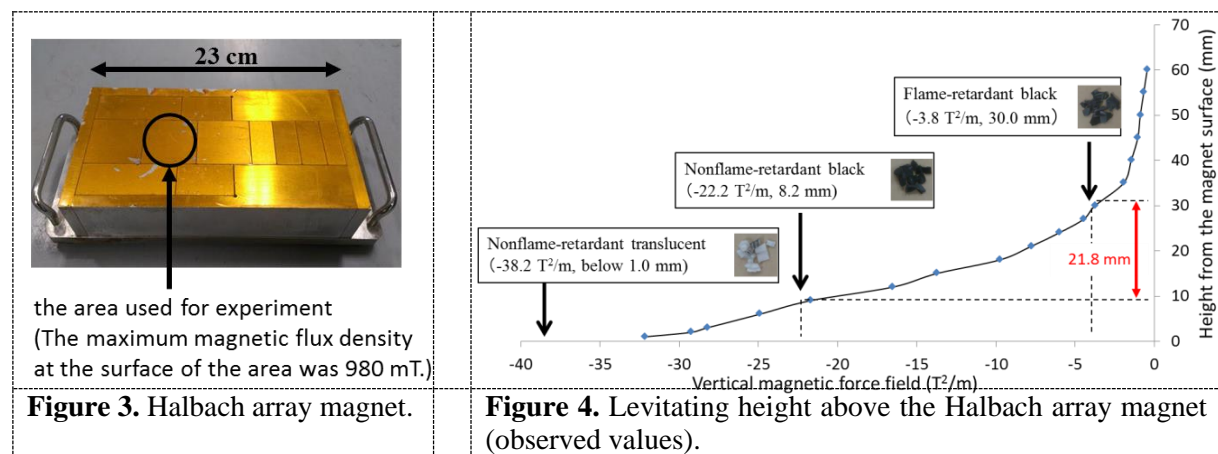


**Figure 2.** Separation process of separating Flame and non-flame-retardant plastics.

### 3.2. Batch type separation using a Halbach array magnet

We conducted batch type separation experiment according to the separation process of figure 2. In wet type specific gravity separation process, the result of calculation showed that flame-retardant (black), nonflame-retardant (black and translucent) settled in 7 wt.%  $\text{MnCl}_2\text{aq.}$

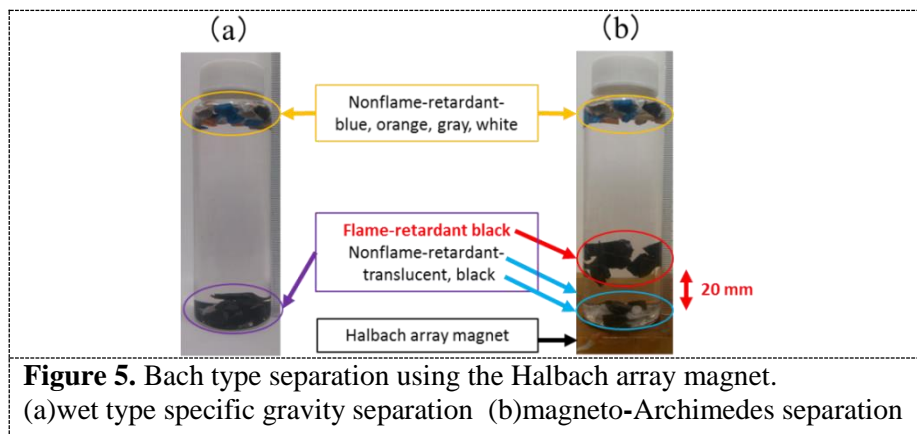
Next, we examined the concentration of  $\text{MnCl}_2\text{aq.}$  suitable for the magneto-Archimedes separation. Here, we used a Halbach array magnet as fundamental experiment before introducing a superconducting solenoidal magnet. The appearance of the Halbach array magnet and its specifications are shown in figure 3 and table 2, respectively. Figure 4 shows the levitating height of each plastic when the maximum magnetic flux density at the bottom of the separation vessel was 980 mT and the concentration of  $\text{MnCl}_2\text{aq.}$  was 6.7 wt.%. The levitating heights were obtained by the graph showing the vertical distribution of the magnetic force field of the Halbach array magnet and calculation of the magnetic force field at the levitating height. Figure 4 indicates that the difference in heights between flame-retardant (black) and nonflame-retardant (black) was 21.8 mm.



**Table 2.** Specifications of the Halbach array magnet.

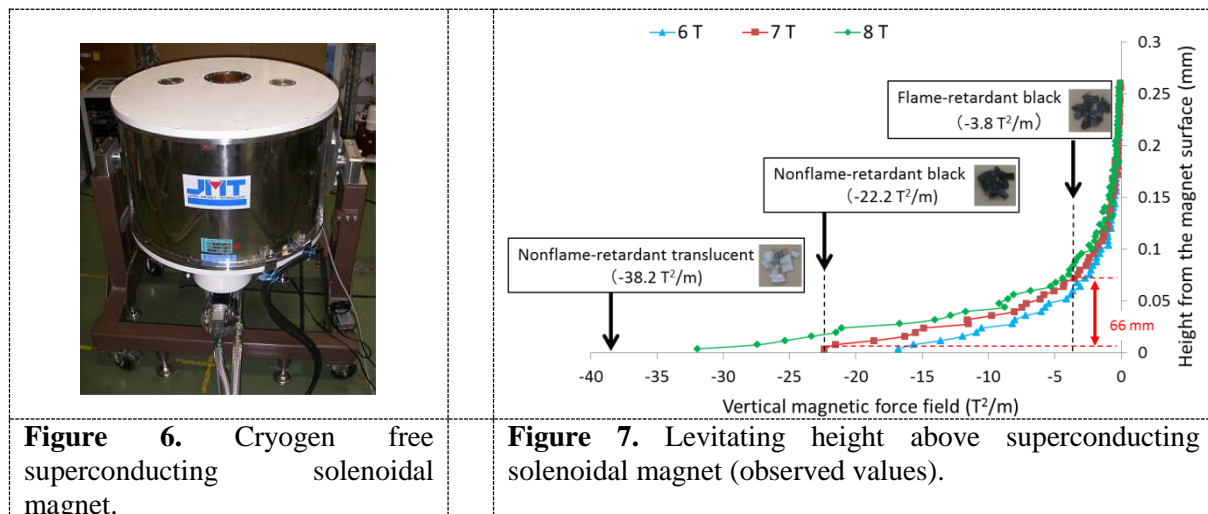
Drawing number	Width (m)	Depth (m)	Maximum magnetic field (T)	Maximum magnetic field product ( $\text{T}^2\text{m}^{-1}$ )
12E136-A (NEOMAX ENGINEERING Co.,Ltd.)	0.23	0.13	1.4	-140

Figure 5 (a) and (b) show the results of wet type specific gravity separation and magneto-Archimedes separation conducted under the conditions mentioned above, respectively. Magnetic field is applied vertically upward by placing the separation vessel on the Halbach array magnets after wet type specific gravity separation. The results showed that flame-retardant plastics (black), nonflame-retardant plastics (black, translucent) were settled by wet type specific gravity separation, and then only flame-retardant plastics (black) were levitated among the three settled plastics by magneto-Archimedes separation. The results of this experiment showed the possibility of separation for any kinds of plastics.



### 3.3. Batch type separation using a superconducting solenoidal magnet

In order to introduce the continuous separation apparatus, it is important to improve separation speed and accuracy. We used a superconducting solenoidal magnet that has a wide range of magnetic field and can increase the magnetic force field gradient. The appearance of the superconducting solenoidal magnet and its specifications are shown in figure 6 and table 3, respectively.



**Table 3.** Specifications of the superconducting solenoidal magnet.

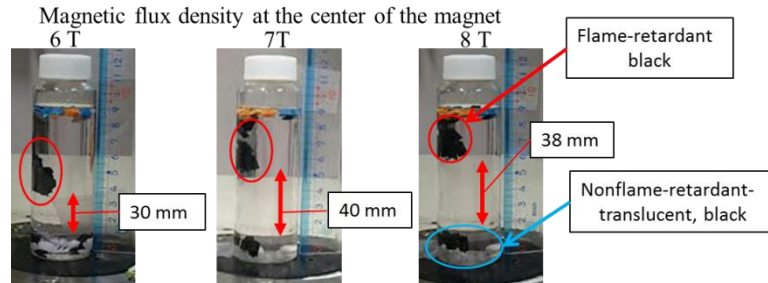
Model number	Bore diameter (m)	Length of bore (m)	Maximum magnetic field (T)	Maximum magnetic field product ( $T^2m^{-1}$ )
JMTD-10T100E3	0.10	0.46	10	-350

In the same way as the separation experiment using the Halbach array magnets, we examined the concentration of  $MnCl_2aq.$  and the strength of magnetic field. Figure 7 shows the levitating heights of each plastic when the concentration of the  $MnCl_2aq.$  was 6.7 wt.%, and the maximum magnetic field was set to 6 T, 7 T and 8 T at the center of the magnet. When the maximum magnetic field was 7 T at the center of the magnet, it was found that the difference in heights between flame-retardant plastics (black) and nonflame-retardant plastics (black) was 66 mm, which showed the maximum.

Figure 8 shows the results of magneto-Archimedes separation under the conditions mentioned above. When the maximum magnetic field was 7 T at the center of the magnet, and the difference in heights of



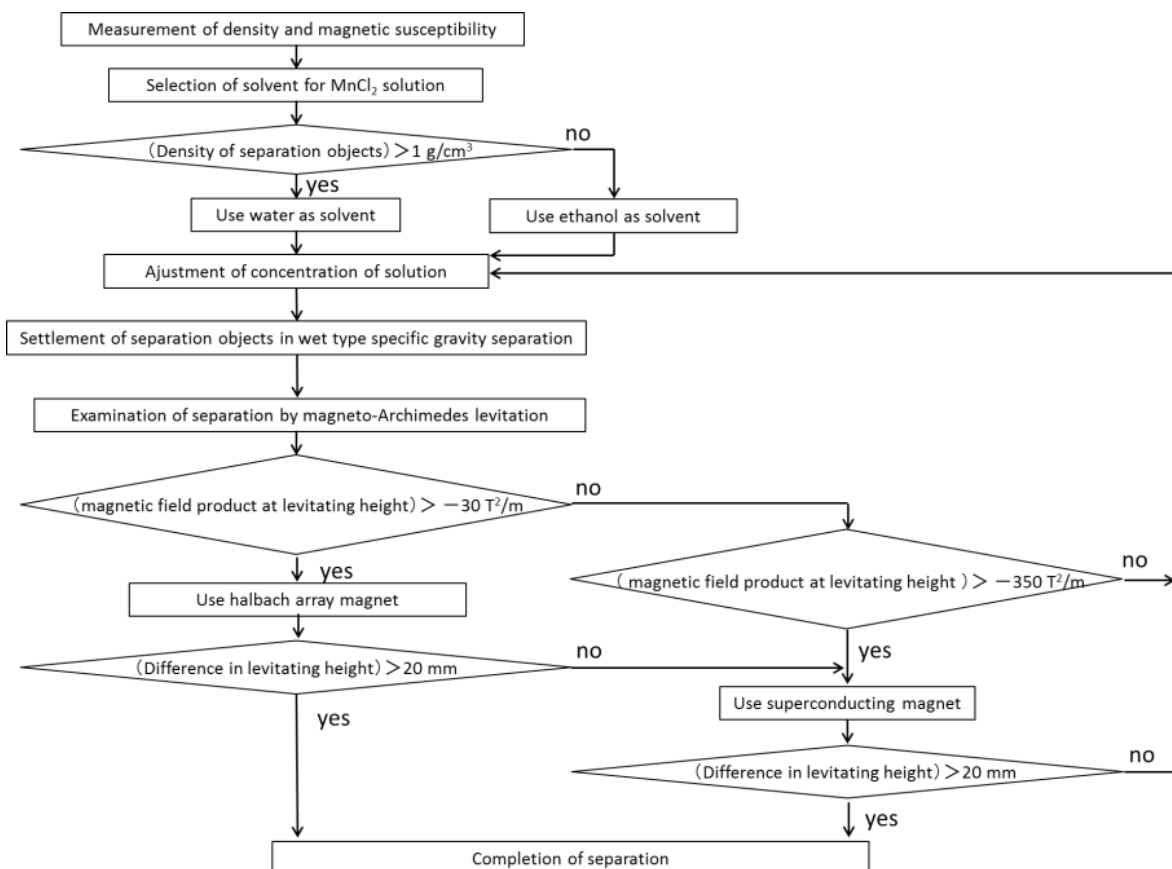
flame-retardant plastics (black) and nonflame-retardant plastics (black) was 40 mm. It was twice as large as that with the Halbach array magnet. The results showed the possibility of accurate separation by superconducting solenoidal magnets.



**Figure 8.** Batch type separation using the superconducting solenoidal magnet. (These samples were put outside the magnet)

### 3.4. General plastics separation method

Based on the results of batch type separation, we designed the process of flowchart for separating general plastics as shown in figure 9. In this flowchart, when the density of separation object is larger than  $1 \text{ gcm}^{-3}$ , we use water as the solvent of  $\text{MnCl}_2$ . When the density of separation object is less than  $1 \text{ gcm}^{-3}$ , we use ethanol as the solvent of  $\text{MnCl}_2$ . By selecting the solvent in this way, we can always settle separation objects. Furthermore, we can levitate the object selectively from the mixture of plastics by using magneto-Archimedes method.

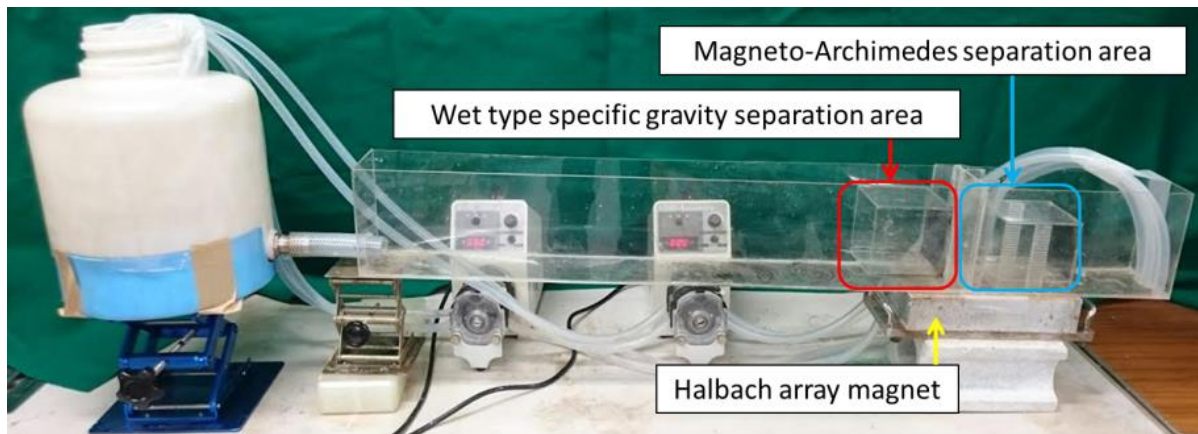


**Figure 9.** Flowchart of separation for any kinds of plastics.

#### 4. Examination of separation conditions

Finally, we examined massive separation by using continuous separation apparatus and the Halbach array magnet as shown in figure 10. In this system, plastics in the fluid flowed into the wet type specific gravity separation area and floated plastics were trapped with the filter.

Then, the settled plastics passed through the filter flowed into the magneto-Archimedes separation area. Here, they were separated by the partition depending on magneto-Archimedes levitation heights. In order to improve the separation speed and accuracy, we are trying to make a larger continuous separation apparatus using the superconducting solenoidal magnet.



**Figure 10.** Continuous separation apparatus using the Halbach array magnet.

#### 5. Conclusion

By utilizing the difference in density and magnetic susceptibility of plastics, we conducted wet type specific gravity separation and magneto-Archimedes separation using common medium in both separation processes. The result showed the possibilities to separate any kinds of plastics with high accuracy. In addition, the result of separation experiment by using continuous separation apparatus indicated the prospect of massive separation. For the next stage, we are trying to design a larger continuous separation apparatus using superconducting magnet for further improvement of the separation speed and accuracy.

#### Reference

- [1] Association of Japan Cartridge Re-manufactures (AJCR) 2016 *Fact Book* vol 7 p 2
- [2] Ikezoe Y et.al. 2002 *Energy Conversion and Management* **43** 417-425