Magneto-Archimedes levitation properties for metals by ferromagnetic material arrangement in magnetic fields

Daiki Yamamoto, Kenichi Yamagashi, Osuke Miura

Dept. of Electrical Engineering and Computer Science, Tokyo Metropolitan University, JAPAN

Motivation of this study

・There are a lot of valuable resources (rare earth, rare metal, precious metal) in urban mine.
As one of the effective methods for physical resource recovery from urban mine,
→We focus on a magnetic separation using magneto-Archimedes effect.

Characteristic of this study

・In this research, valuable materials can be separated only by physical methods.
・This method depends on only two parameters, density[g/cm^3] and magnetic susceptibility[-]

Subject of this study

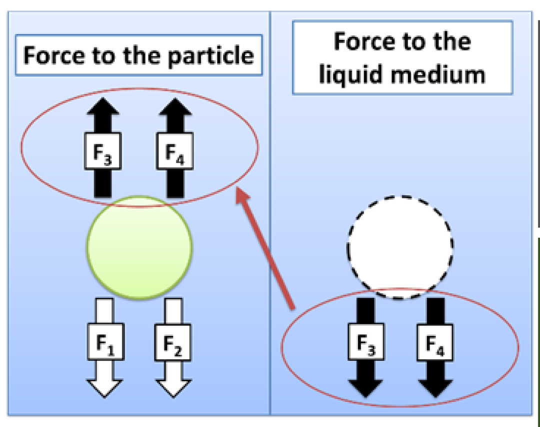
・We made it possible to separate in lower magnetic fields by enhancement of dB/dz.
・We confirmed that horizontal uniformity of BdB/dz was improved by ferromagnetic cylinders array.

Conclusion

・By setting a ferromagnetic cylinders array at the center of the magnetic field, the maximum of BdB/dz dramatically increased from -434 T^2/m to over -2500 T^2/m.
・The ferromagnetic cylinders array made them levitate uniformly in a horizontal direction.
・The levitation start-up magnetic field with ferro-magnetic cylinders array was lower.

Theory of magneto-Archimedes effect

Magneto-Archimedes effect is a phenomenon that materials levitate at a particular position in a paramagnetic medium by applying magnetic field gradient due to the difference of magnetic susceptibility and density between the medium and the materials.



Gravity to the liquid medium $F_3 = \rho_f V g$

Magnetic force to the liquid medium $F_4 = V\frac{\chi_f}{\mu_0}B\frac{dB}{dz}$

Gravity to the particle material $F_1 = \rho_p V g$

Magnetic force to the particle material $F_2 = V\frac{\chi_p}{\mu_0}B\frac{dB}{dz}$

Levitating condition

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

χ_f: magnetic susceptibility of liquid
χ_p: magnetic susceptibility of the material
ρ_f: density of liquid
ρ_p: density of the material

High gradient magneto-Archimedes effect and magnetic field simulation

‣We could enhance BdB/dz by setting a ferromagnetic cylinders array in magnetic field.
‣We calculated Bz and BdB/dz enhanced by setting a ferromagnetic cylinders array in magnetic field.

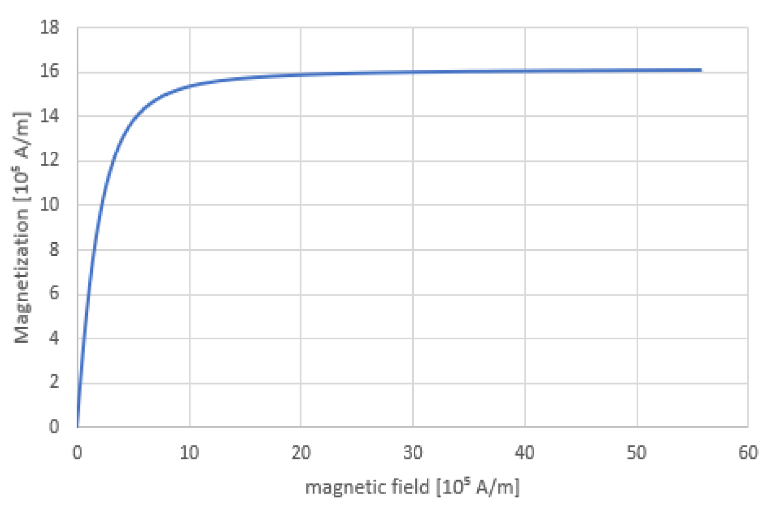


Fig. 1 Magnetization curve of ferromagnetic cylinder materials

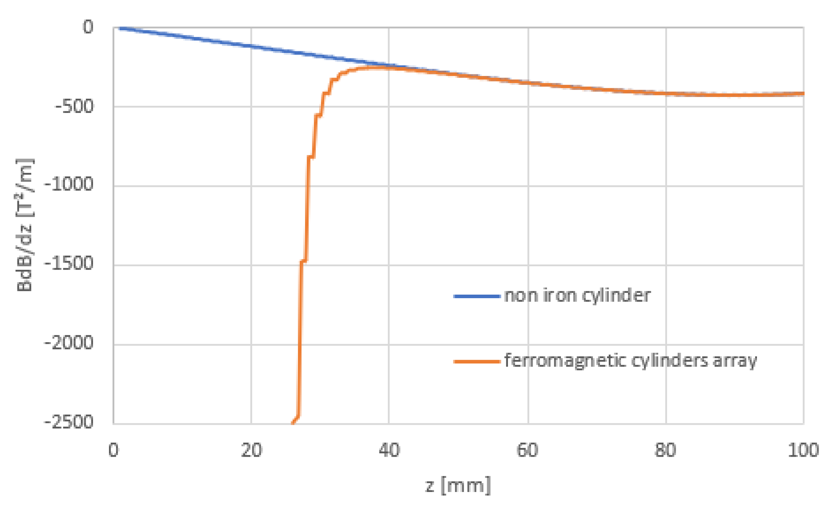


Fig. 2 z axis distribution of BdB/dz at 10 T for no iron cylinder and ferromagnetic cylinders array

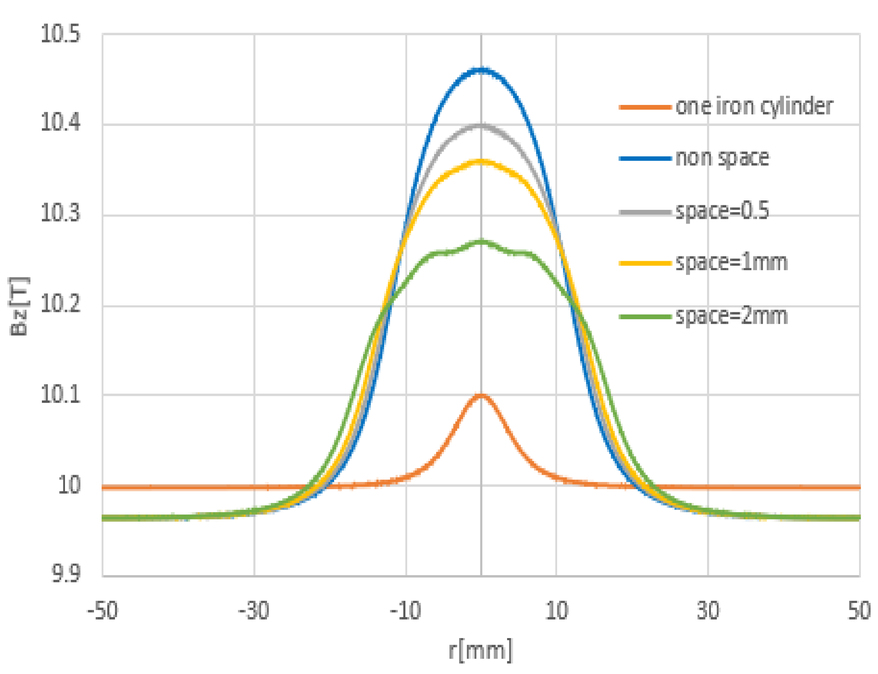


Fig. 3 r axis distribution of Bz at 10 T for various ferromagnetic cylinders array at z = 30 mm.

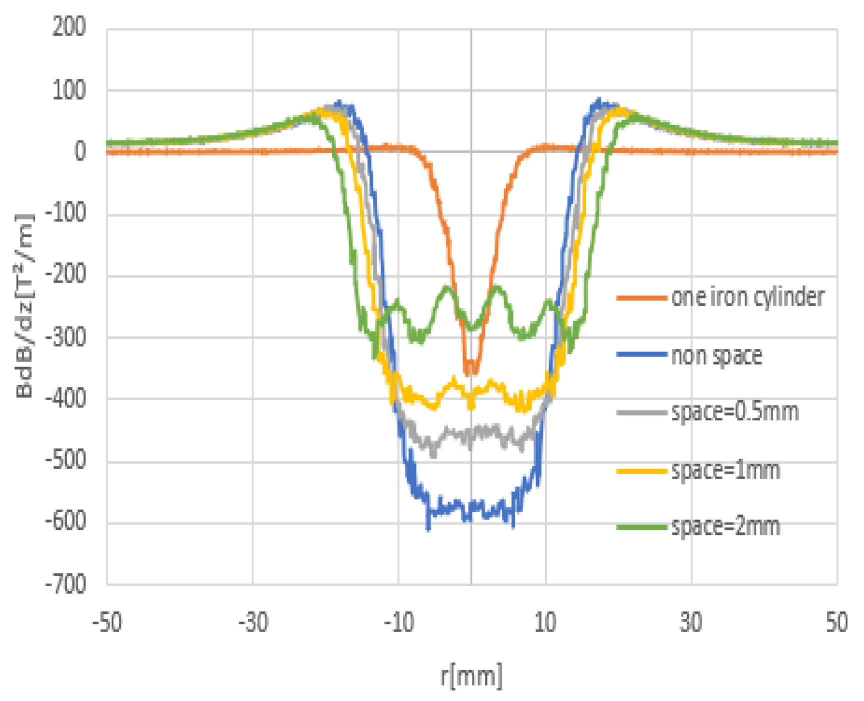


Fig. 4 r axis distribution of BdB/dz at 10 T for various ferromagnetic cylinders array at z = 30 mm.

‣We used the iron cylinder with diameter of 5 mm and length of 50 mm.

‣By setting ferromagnetic cylinders array, the maximum BdB/dz enhanced from -434 T^2/m to -2500 T^2/m(z=26mm). The enhancement area ranged at 25-40 mm.
‣The maximum value of Bz was 10.45 T (z=30 mm), BdB/dz was -600 T^2/m (z=30 mm) for the ferromagnetic cylinders array without core spacing at 10 T.

‣In the case of spacing of ferromagnetic arrays ≦1mm, the BdB/dz is uniform in the horizontal direction.

Experimental method

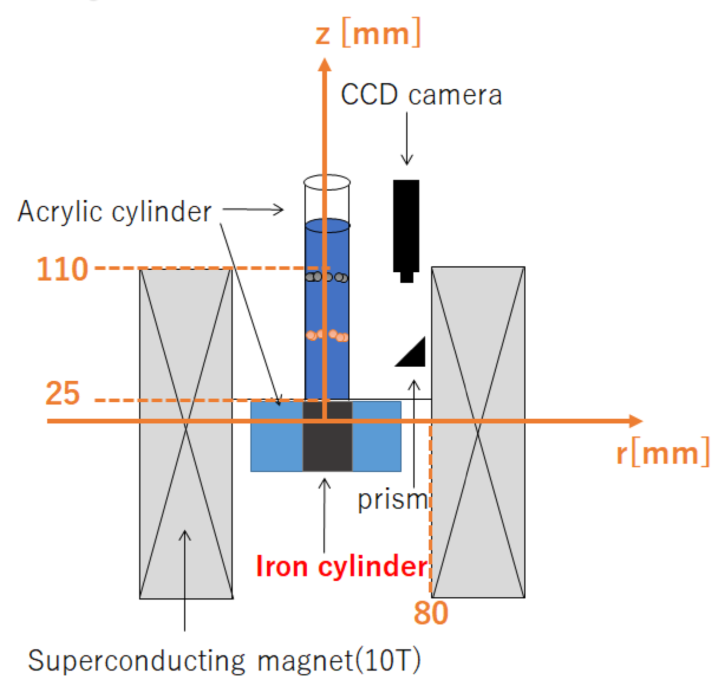


Fig. 5 The experimental devices

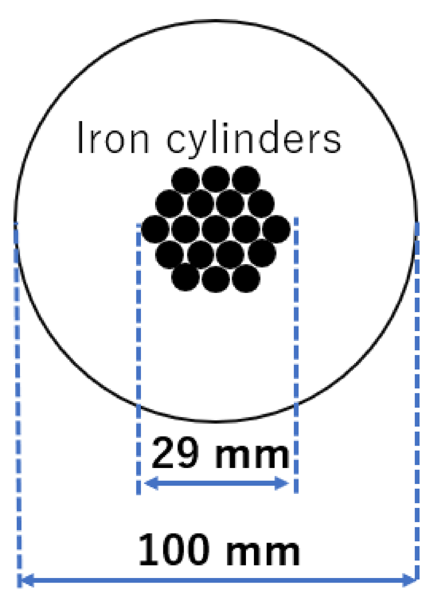


Fig. 6 ferromagnetic cylinders array (spacing=1 mm)

The ferromagnetic cylinders arranged in a triangular grid in acrylic cylinder were set at the center of the room temperature bore of a 10 T superconducting solenoidal magnet. $MnCl_2$ 40 wt% aqueous solution was used as a paramagnetic liquid medium.

Material properties of materials

‣the density (literature data) and the magnetic susceptibility measured by a SQUID magnetometer for each metal and $MnCl_2$ aqueous solutions used in the experiment

Table1 Physical properties of materials in experimental condition.

Materials	Density [g/cm³]	Magnetic susceptibility[-]
Platinum(grain)	21.5	2.64×10^{-4}
Gold(grain)	19.3	-3.45×10^{-5}
Silver(grain)	10.4	-2.41×10^{-5}
Copper(grain)	8.93	-2.25×10^{-5}
Copper(powder)	8.93	-2.03×10^{-6}
Manganese chloride aqueous solution (40 wt.%)	1.33	4.13×10^{-4}

Experimental results

① ***levitation properties of metal grains for ferromagnetic cylinders array (BdB/dz =-2500 T^2/m in 10 T)***

‣In order to expand the range of the high magnetic field gradient, we designed the ferromagnetic cylinders array.
→When it was used, stable levitation was obtained.
‣The diameter of the metal grain is 2 mm.

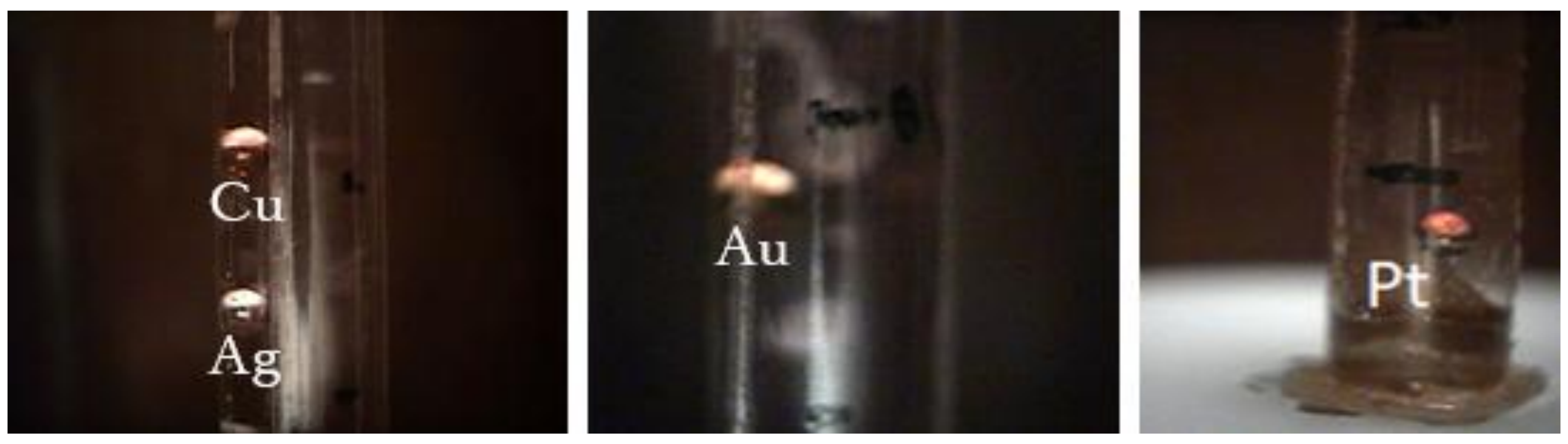


Fig.7 Levitating Silver, Copper, gold and platinum

Table2 The comparison levitation properties between theoretical value and experimental value

Materials	Levitating start-up magnetic field [T]		Levitation height at 10T [mm]	
	Theoretical value	Experimental value	Theoretical value	Experimental value
Platinum	6.7	6.8	29	36
Gold	4.6	4.9	128	137
Silver	3.2	3.4	157	165
Copper	2.7	3.1	164	175

Table3 The comparison levitation properties between non ferromagnetic cylinder and ferromagnetic cylinders array

Materials	Levitating start-up magnetic field [T]		Levitation height at 10T [mm]	
	Non array	Array	Non array	array
Platinum	-	6.8	-	36
Gold	8.4	4.9	118	137
Silver	6.0	3.4	146	165
Copper	5.6	3.1	153	175

- The experimental value of the levitation height for each metal at 10 T was almost the same as its own theoretical value.
- The levitation start-up magnetic field that means the magnetic field where the metal levitated at z=28 mm, also was agreement with its theoretical one.
- The levitation start-up magnetic field with ferromagnetic cylinders array lower than that.

② ***levitation properties of copper grains and powder for ferromagnetic cylinders array (BdB/dz =-2500 T^2/m in 10 T)***

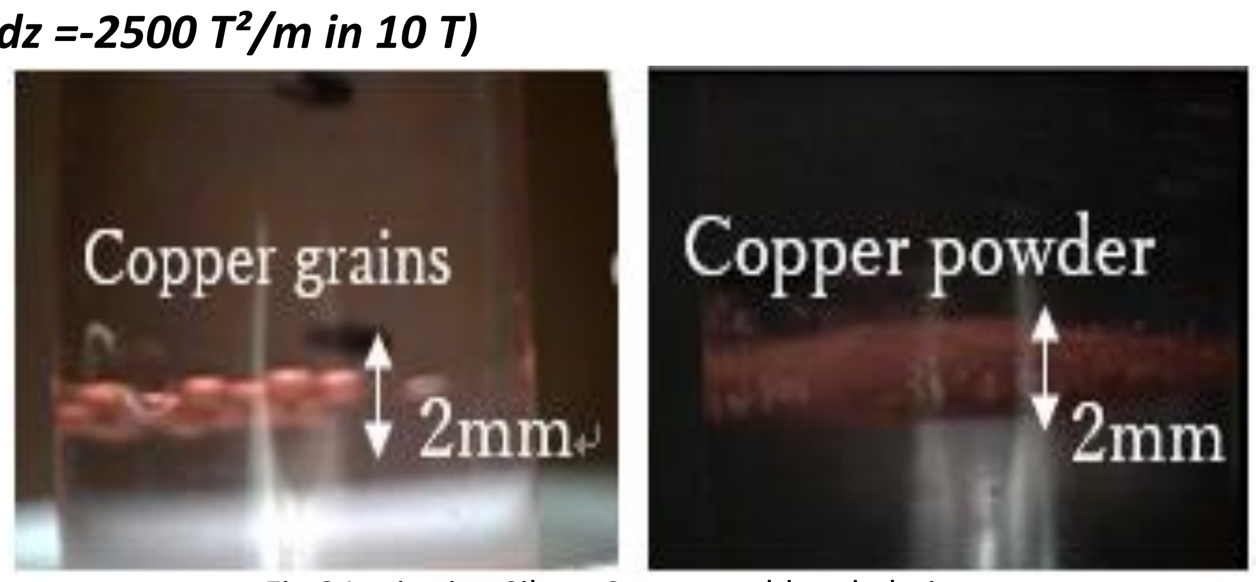


Fig.8 Levitating Silver, Copper, gold and platinum

- They levitated uniformly in a horizontal direction.
- The copper grains and powder levitated within the range of 2 mm.