Magneto-Archimedes levitation of precious metals under a high magnetic field gradient

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Abstract. We studied the levitation properties for precious metals utilizing magneto-Archimedes effect under a high magnetic field gradient. In order to enhance the power factor of $\frac{dB}{dz}$ for the magnetic force in vertical direction cylindrical ferromagnetic materials were set into the room temperature bore of a 10 T superconducting solenoidal magnet. The maximum $\frac{dB}{dz}$ achieved the high value of $-1598 \text{ T}^2/\text{m}$ by the optimum configuration of ferromagnetic materials. The magnetic levitation properties for several kinds of precious metals such as silver, gold and platinum in manganese chloride aqueous solution as a paramagnetic liquid medium were studied. The experimental results showed that silver, gold and platinum levitated at each different height which was almost the same as its own theoretical one and could be controlled by changing configuration of ferromagnetic materials. This indicates the strong possibility of the selective separation of a target material from the solid mixture by utilizing magneto-Archimedes levitation under a high magnetic field gradient.

1. Introduction

We have been studying the selective separation of the valuable resource from the solid mixture on urban mine by utilizing magneto-Archimedes levitation [1]. The condition of stable levitation in vertical direction for materials in a liquid medium is expressed as follows,

$$B \frac{dB}{dz} = \frac{\rho_f - \rho_p}{\chi_f - \chi_p} \mu_0 g.$$  \hspace{1cm} (1)

Where $\rho_p$ is the density of the material, $\chi_p$ is the magnetic volume susceptibility of the material, $\rho_f$ is the density of the liquid medium, $\chi_f$ is the magnetic volume susceptibility of the liquid medium, $g$ is the gravitational acceleration, $\mu_0$ is the permeability of vacuum, $B$ is the magnetic flux density [2, 3]. Here the most important factor of magneto-Archimedes levitation force is $\frac{dB}{dz}$ which is generated by the magnet in itself. However, the maximum value of $\frac{dB}{dz}$ remains in $-434 \text{ T}^2/\text{m}$ for even in a standard high-field 10 T superconducting solenoidal magnet (JASTEC JMFTD-10T100SS). Therefore in order to levitate precious metals such as gold and platinum with the very high density and the low magnetic susceptibility, the further increase in $\frac{dB}{dz}$ is required.

In this study to increase the power factor, $\frac{dB}{dz}$ especially a magnetic field gradient some cylindrical ferromagnetic materials were set into the room temperature bore of a superconducting solenoidal magnet. The power factor significantly increased by means of the optimum configuration of ferromagnetic materials. We studied levitation properties of precious metals in this system.

2. Experimental

In order to increase the power factor $\frac{dB}{dz}$, especially a magnetic field gradient we carried out an idea of arranging ferromagnetic iron cylinders in the room temperature bore of a 10 T superconducting solenoidal magnet. The axisymmetric shaped cylindrical iron cylinders stably levitated at the centre of the magnet by the strong magnetic restoring force. Figure 1 shows $z$ axis distribution of $\frac{dB}{dz}$ at 10 T with a change in the diameter of 50 mm long iron cylinders. The maximum $\frac{dB}{dz}$ significantly increased from $-434 \text{ T}^2/\text{m}$ to $-1598 \text{ T}^2/\text{m}$ with a decrease in diameter of the cylinders. Moreover, it
was shown that a change in diameter of the cylinders made it possible to control the rate of change of $dB/dz$ related to the resolution of separation. Figure 2 shows $z$ axis distribution of $dB/dz$ at 10 T with a change in the length of 10 mm diameter iron cylinders. Maximum $dB/dz$ slightly increases with increase in length. From this result, we selected the iron cylinder with a diameter of 10 mm and a length of 50 mm generating the maximum $dB/dz$ of $-1060$ T$^2$/m in consideration of the experimental setup.

**Figure 1.** $z$ axis distribution of $dB/dz$ at 10 T with a change in the diameter of 50 mm long iron cylinders in a radial direction of $r = 0$.

**Figure 2.** $z$ axis distribution of $dB/dz$ at 10 T with a change in the length of 10 mm diameter iron cylinders in a radial direction of $r = 0$.

The experimental devices for magneto-Archimedes levitation studies are shown in figure 3. The iron cylinder sheathed in acrylic was set at the centre of the room temperature bore of a 10 T superconducting solenoidal magnet. MnCl$_2$ 50 wt% aqueous solution was used as a paramagnetic liquid medium. The graduated cylinder filled with the medium was put on the iron cylinder and
observed by a CCD camera with a right-angle prism. We studied the magnetic levitating properties for several kinds of precious metals such as gold, silver, copper and platinum. Table 1 shows the density and the magnetic volume susceptibility measured by a SQUID magnetometer for the materials and MnCl₂ concentration used in the experiment.

Figure 3. The experimental devices for magneto-Archimedes levitation studies.

Table 1. Physical properties of the materials in the experimental condition.

| Materials                    | Density [g/cm³] | Magnetic susceptibility [-] |
|------------------------------|----------------|-----------------------------|
| Gold                         | 19.3           | -1.70×10⁻⁴                  |
| Silver                       | 5.56           | -2.91×10⁻³                  |
| Copper                       | 8.96           | -2.25×10⁻³                  |
| Platinum                     | 21.5           | 1.05×10⁴                    |
| Manganese chloride aqueous solution (50 wt.%) | 1.33           | 4.13×10⁻⁴                  |

3. Result and discussion

Figure 4 shows the magneto-Archimedes levitation for each precious metal in MnCl₂ aqueous solution at 10 T. It was clearly observed that all of the precious metals levitated on the iron cylinder under the high magnetic field gradient. The platinum levitated at \( z = 28 \) mm with \( BdB/dz \) of \(-809\) T²/m, the gold levitated at a height of \( z = 33 \) mm with \( BdB/dz \) of \(-380\) T²/m, the silver levitated at \( z = 153 \) mm with \( BdB/dz \) of \(-170\) T²/m, and the copper levitated at \( z = 158 \) mm with \( BdB/dz \) of \(-140\) T²/m. Table 2 shows the comparison of levitation properties between calculated values by equation (1) and experimental ones for each metal. We confirmed that the levitation height for each metal was almost the same as its own calculated value. The small differences between them for silver and copper may be caused by impurities of the metals. The levitation gap between two materials (platinum and gold, silver and copper) was 5 mm in this experiment. When considering practical use, it’s necessary to expand the gap by controlling the variation of \( BdB/dz \) via change in diameter of cylinders. This indicates the strong possibility for the selective separation of a target material from the solid mixture by utilizing magneto-Archimedes levitation under a high magnetic field gradient.
Figure 4. The magneto-Archimedes levitation for each precious metal in MnCl₂ solution at 10 T.

Table 2. The comparison of levitation properties between calculated values and experimental ones for each metal.

|                | $BdB/dz$ [T²/m] | Levitating height [mm] |
|----------------|-----------------|-----------------------|
|                | Calculated value | Experimental value     | Calculated value | Experimental value |
| Platinum       | -809            | -809                  | 28              | 28               |
| Gold           | -380            | -380                  | 32              | 33               |
| Silver         | -234            | -170                  | 141             | 153              |
| Copper         | -215            | -140                  | 145             | 158              |

4. Conclusion
We studied the levitation properties for precious metals utilizing magneto-Archimedes effect under a high magnetic field gradient. We made it possible to generate a high magnetic field gradient by arranging ferromagnetic iron cylinders at the center of the superconducting magnet. The magnetic force factor of $BdB/dz$ in vertical direction achieved the high value of $-1598 \text{T}^2/\text{m}$ by the optimum configuration of ferromagnetic materials at 10 T. The experimental results showed that silver, copper, gold and platinum levitated at each different height which was almost the same as its own theoretical one, and could be controlled by changing the configuration of ferromagnetic materials. This indicates the strong potential for the selective separation of a target material from the solid mixture by utilizing magneto-Archimedes levitation under a high magnetic field gradient.

References
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