# Control of a magnetic fluid drop moving in a viscous fluid inside a cylinder

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## Abstract

An investigation has been made of the dynamic behaviour of a magnetic fluid drop settling in a viscous fluid inside a vertical cylinder in response to impressed magnetic fields. Two coils were placed so as their axes coincided with the cylinder axis in order to provide the magnetic field for the tests. The Reynolds number Re (Re = $av_z/\nu$) is in the range of 0.001–0.037. Here, $a$ is the scale of the magnetic fluid drop, $v_z$ is the settling velocity of the drop and $\nu$ is the kinematic viscosity of the machine oil. Near the upper coil, the centre of the drop is forced upwards, but the velocity of the drop is not always decreased. At the middle point between the two coils, the drop tends to extend along the field. Due to the change of the shape of the drop, the drag on the drop is reduced and the velocity of the drop is increased.
*Keywords: low Reynolds number, magnetic fluid, cylindrical wall, viscous fluid.*

## 1 Introduction

A magnetic fluid is a homogeneous colloidal suspension of magnetic particles in a solvent. Various physical phenomena relating to the flows of magnetic fluids have been studied by Rosensweig [1].

A number of interesting phenomena are exhibited by the magnetic fluids in response to impressed magnetic fields [2–4]. A certain interest is shown to magnetic fluids as carriers of drug. The magnetic field can pilot the path of a magnetic fluid drop in the body, bringing drugs to a target site [5], and the drugs can be retained there for as long as necessary. This means that it is important to investigate the motion of a magnetic fluid drop travelling inside a tube in an external magnetic field.

 
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This paper is concerned with the motion and the formation of a magnetic fluid drop settling in a stagnant viscous fluid inside a vertical cylinder under the influence of a magnetic field. First, we seek the difference of the settling velocity between magnetic fluid drop and an iron sphere under the influence of a magnetic field. The surface of the magnetic fluid drop is free, then the shape of the drop is deformed by the applied magnetic field and the settling velocity of a drop is changed. The shape of the iron sphere does not change and the velocity of it depends on the magnetostatic force. Second, it is shown that the velocity of the magnetic fluid varies at the middle point between two coils only due to the change of the shape of the magnetic fluid drop.

## 2 Experimental method

The experimental apparatus is shown in Fig. 1. A vertical glass cylinder about 150cm long and of internal diameter 2.0cm is used. To eliminate the optical distortion in viewing a particle or a drop through the cylinder, a square section duct made of transparent plates was set outside the cylinder. Another square section duct was set outside this square section duct. Water of constant temperature circulates between these two square section ducts. The temperature of the room was controlled by an air-conditioner not to vary more than $\pm 1^{o}$C

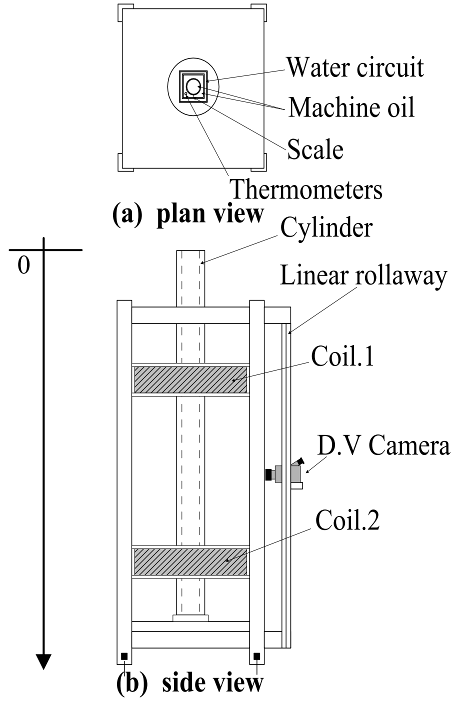


Figure 1: Experimental apparatus.

from the set point. Three thermometers were inserted between the cylinder and inner square section duct at upper, middle and lower points. Before each run, the temperatures of three thermometers were read to 0.1°C. The temperature variation was checked whether it was less than 0.1°C. Two coils, arranged as a Helmholtz pair, placed as their axes to be coincide with the cylinder axis and provided the magnetic field for the tests. The current supply was measured by an ammeter.

The magnetic field between the coils was measured by using a gaussmeter with Hall probe. The magnetic fluid used in the experiments was water-based ferricolloid W-40 (density 1.392 g/cm$^3$). The stagnant fluid used in the experiment was machine oil. Spheres are of the ball bearing with a diameter 0.982mm (density 7.79 g/cm$^3$). Its accuracy was checked and error was less than 1μm. The test section, 30 cm long, was located in the central section of the 150cm long glass cylinder to reduce any errors due to end effects. A pipette is used for injection of the magnetic fluid drop. The volume of the drop ranged from 0.26 to 2.10mm$^3$. After the drop or the iron sphere had fallen down through the upper coil 1, the current was supplied and the magnetic field was imposed. The positions of the particle or drop, the shape of the drop, and the time were recorded by a digital video camera. The velocities of iron spheres and magnetic fluid drops were calculated from the time data and the trajectory data. The velocity of a sphere or drop under no magnetic field is recorded above the upper coil 1.

## 3 Experimental results

In Fig. 2 and Fig. 3, the vertical component of magnetic field and the gradient of it between two coils are shown.

The current supply I to two coils was 3A or 7A. The upper and lower coils are at the vertical position z=40cm and 70cm respectively.

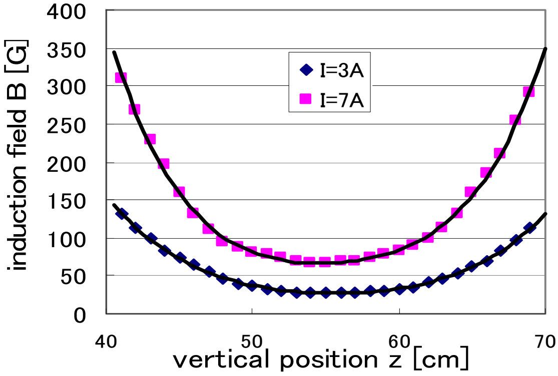


Figure 2: Magnetic field.

Settling velocities of iron spheres and magnetic fluid drops were calculated from the time data and the trajectory data. Figure 4 shows the settling velocity $v_z$ of a single iron sphere normalized with respected to the mean velocity of an iron sphere. When the current (4A) was supplied to two coils, the velocity of a single iron sphere varies in proportion to the gradient of the magnetic field. This

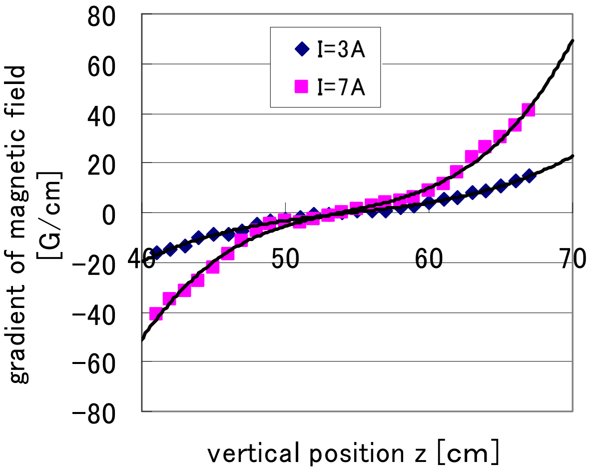


Figure 3: Gradient of a magnetic field.

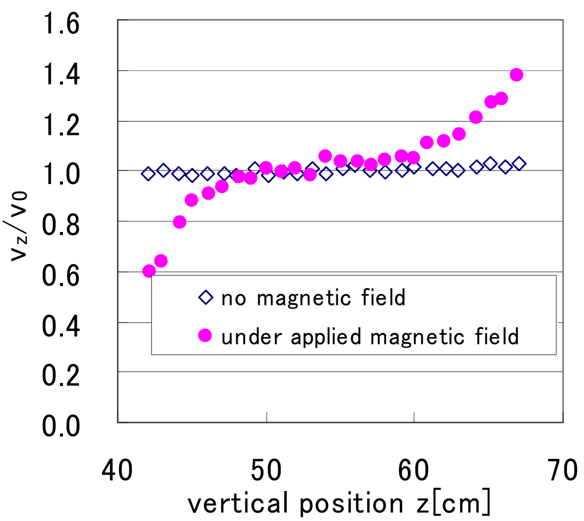


Figure 4: Settling velocity of a single iron sphere.

 
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phenomenon occurs as an iron sphere is subjected to the force $\mu_0 \boldsymbol{M} \cdot \nabla H$, where $\mu_0$ is the permeability of free space, $\boldsymbol{M}$ is the magnetization and $H$ is the magnetic field.

At the place right below the upper coil, the magnetostatic force acts on the iron sphere upward. On the other hand, at the place right above the lower coil, the magnetostatic force acts on the iron sphere downward. At the middle point between two coils, the iron sphere experiences no magnetostatic force.

In the present experiment, Reynolds numbers (=0.03-0.06) are very low and Stokes's law may be applied. When a sphere moves in a fluid under the magnetic field, it experiences the drag, gravitational, magnetic and buoyancy force.

$$\frac{4}{3}\pi a^3 \rho_1 \frac{d^2 z}{dt^2} = \{(\rho_1 - \rho_2)g + \mu_0 \boldsymbol{M} \cdot \nabla H\}\frac{4}{3}\pi a^3 - 6\pi\rho_2 \nu \frac{dz}{dt} a \tag{1}$$

In the eqn (1), $\rho_1$ (=7.79) and $\rho_2$ (=0.875) are the density of iron and that of the machine oil respectively, $z$ is the vertical position of the sphere, and $g$ is the gravitational acceleration. When there is no magnetic field, it is easy to solve this equation and the time to reach 99% of the terminal velocity is obtained as 0.02 second.

Figure 5 shows the settling velocity $v_z$ of a magnetic fluid drop. At the place right below the upper coil, the magnetostatic body force $\mu_0 \boldsymbol{M} \cdot \nabla H$ acts on the magnetic fluid drop upward. However, at that place the velocity of magnetic fluid drops of volume 0.821 and 1.997 mm$^3$ were faster than those at middle

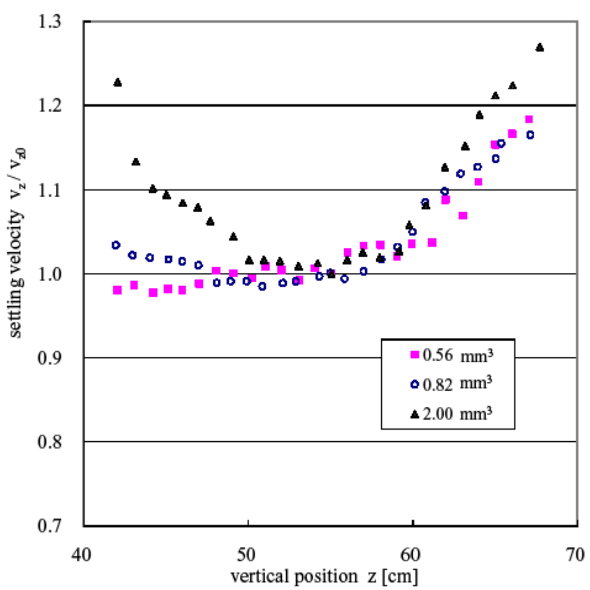
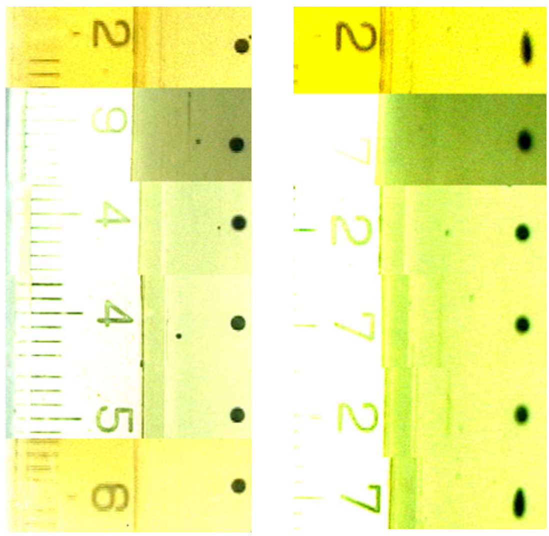



Figure 5: Settling velocity of a magnetic fluid drop.

point. Initial shapes of magnetic fluid drops were sphere with volumes 0.56, 0.82 and 2.00 mm$^3$ and the current I supply to two coils was 2A. The velocity is normalized with respect to the velocity $v_0$ at the middle point between two coils.

Figure 6 shows the shapes of a settling magnetic fluid drop of volume 1.12mm$^3$ settling in the machine oil inside a cylinder. The right figure shows the deformation of a magnetic fluid drop under the influence of a magnetic field.



under no magnetic field

under the influence of a magnetic field

Figure 6: Shapes of a settling magnetic fluid drop (volume 1.12mm$^3$).

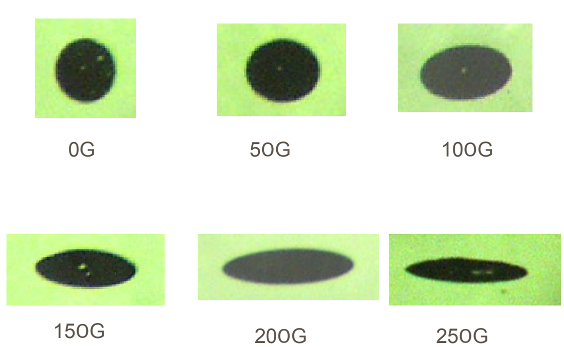



Figure 7: Change of the shape of a magnetic fluid drop (0.36cm$^3$) under the horizontal magnetic field.

The current supply I to two coils was 2A. Near the upper and lower coils, the drop elongated. This deformation reduced the drag on the drop and it was accelerated.

Change of the shape of a magnetic fluid drop under the magnetic field is shown in Fig. 7. It extended along the magnetic field. In order to avoid the influence of gravity, a horizontal uniform magnetic field was applied to a magnetic fluid drop.

At the middle point between two coils, the external uniform magnetic field cannot force the centre of the magnetic fluid drop inertia. However, due to the magnetic pressure jump takes place on the drop surface, the drop tends to extend along the field. Due to the change of the shape of the drop, the drag on the drop is reduced and the velocity of the drop is increased.

Figure 8 shows the velocity change of the magnetic fluid drop of the same volume 0.81mm$^3$ at the middle point between two coils as the magnetic field was

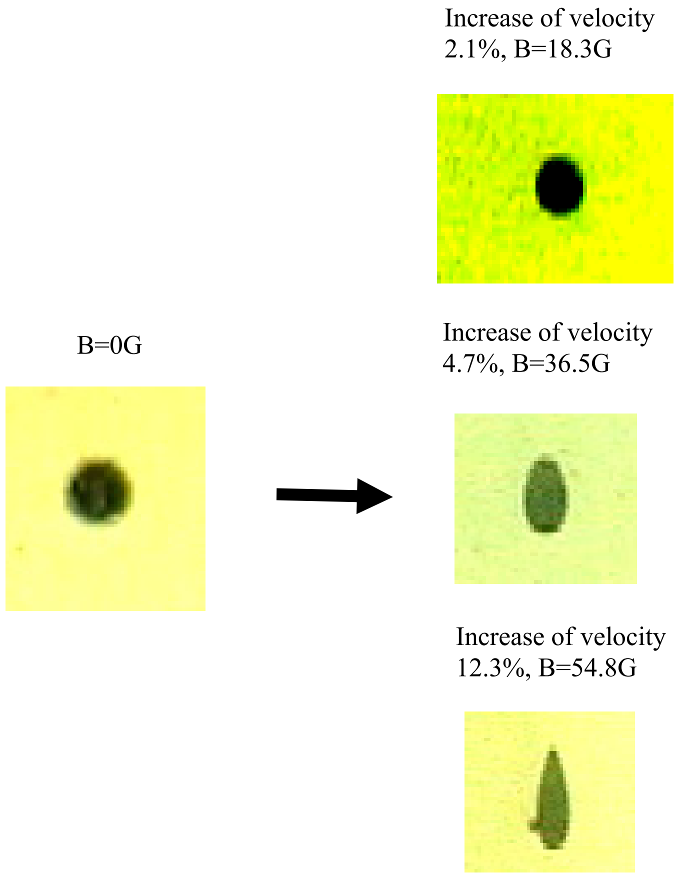



Figure 8: Increase of velocity under the magnetic field at the middle point between two coils (volume 0.81mm$^3$).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raised. Due to the change in the shape of the drop, the drag on the drop is reduced and the velocity of the drop is increased.

Figure 9 shows the velocity change of the magnetic fluid drop when the same magnetic field is applied at the middle point between two coils for various volumes of magnetic fluid drops. When the external uniform magnetic field is applied, a magnetic pressure jump $\mu_0 M_n^2/2$ takes place on the drop surface. This pressure jump is balanced by increasing the surface curvature at the upper and lower points. The curvature of the larger drop is smaller than that of the smaller drop with the similar shape. Then the larger drop elongated remarkably and the drag on it is reduced.

The velocity change of the magnetic fluid drop when various magnetic fields are applied at the middle point between two coils for various volumes of magnetic fluid drops is shown in Fig. 10. The velocity of larger drop changed more than that of smaller drop.

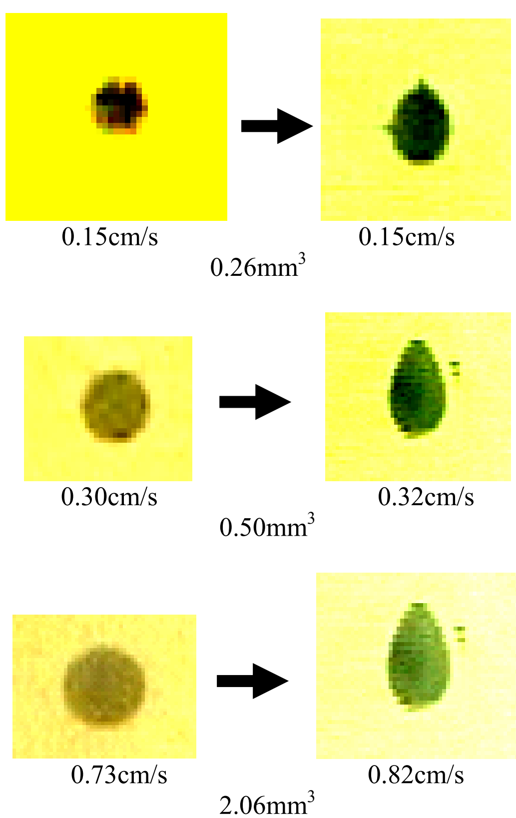


Figure 9: Change in the shape and the velocity of the magnetic fluid drop when the magnetic field [B=18.3G] is applied.

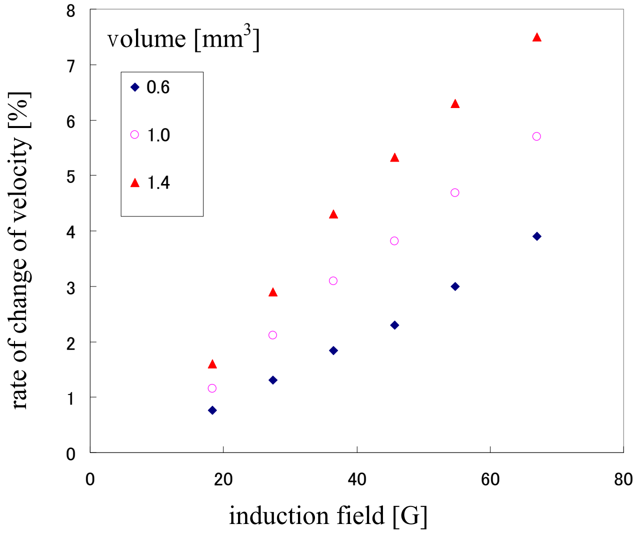


Figure 10: Change of the velocity of the magnetic fluid drop.

## 4 Conclusion

In the present work experimental results have been obtained on the velocity change of a settling magnetic fluid drop in an incompressible viscous fluid inside a vertical circular cylinder under the influence of the magnetic field.

Near the upper coil, the centre of the drop is forced upwards, but for the extension of the drop and the drag reduction, the velocity of the drop is not always decreased. Near the lower coil, however, the centre of the drop is forced downwards, for the extension of the drop and the drag reduction, the velocity of the drop is increased significantly.

The velocity of a single iron sphere varies in proportion to the gradient of the magnetic field.

At the middle point between two coils, the external magnetic field cannot force the centre of the magnetic fluid drop inertia. However, due to the magnetic pressure jump takes place on the drop surface, the drop tends to extend along the field. Due to the change in the shape of the drop, the drag on the drop is reduced and the velocity of the drop is increased. The velocity change of the magnetic fluid drop when various magnetic fields are applied at the middle point between two coils for various volumes of magnetic fluid drops is obtained. The velocity of a larger drop changed more than that of a smaller drop.

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