Magnetic capture of falling magnetic fluid droplet

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Abstract. As a fundamental research on magnetic drug targeting, trial was made to catch the magnetic fluid droplet falling in the water. The motion of the droplet was experimentally observed and analyzed, and was numerically simulated. Motion of the magnetic droplet is mainly classified into three types according to the strength of the magnetic force. The condition of capture is examined.

1. Introduction

One of the medical applications of the magnetic force is to target the magnetic drug to the diseased part by means of the magnetic force [1-6]. For this purpose the magnetic droplet or the magnetic emulsion should be caught to the wall surface of the vessel in the flow of the blood.

In the present research as a basic approach, the magnetic fluid droplet falling in the water is tried to be captured by the magnetic force. The motion and the trace of the droplet are experimentally analyzed, and are also numerically simulated. The magnetic droplet is directly captured, slides on the wall or falls away according to the strength of the magnetic force. The effects of the size and the concentration of the magnetic fluid on the condition of capture are examined.

2. Experiments

2.1. Experimental arrangements

As shown in figure 1 an experimental setup is consisted of a long reservoir, a nozzle and a permanent magnet. The reservoir is 35 x 35 mm in square cross section and 500 mm in height and is filled with water. The diameter of the nozzles is 1.80, 2.20 and 3.45 mm, through which the magnetic fluid is pushed out to form the droplet by the pressure of the air.

The magnetic fluid is kerosene-base HC-50 manufactured by Taiho Ind. Co. Ltd., which does not blend with the water. The specific gravity is 1.40 and the saturation magnetization is $3.78 \times 10^4$ A/m. It is diluted to the concentration of 100% (original), 80 and 60 % in volume. The diameter of the droplet depends on the diameter of the nozzle and the concentration of the fluid, and it ranges from 2.6 to 6.6 mm.

The magnet is a rectangular rare-earth magnet with the size of 50 mm in length, 20 mm in height and 5 mm in width. The distribution of the magnetic flux density is shown in figure 2. s is the distance from the surface of the magnet. The strength of the magnetic force on the droplet is controlled with the distance between the reservoir and the magnet.

The motion and the shape of the droplet are observed with a high-speed CCD camera, and the trace
of the droplet is analyzed with the motion analyzing software.

**Figure 1.** Experimental setup.

**Figure 2.** Strength of magnetic field.

(a) $s=5\text{mm} (B=14.5\text{mT})$. (b) $s=15\text{mm} (B=7\text{mT})$. (c) $s=25\text{mm} (B=4\text{mT})$. (d) $s=35\text{mm} (B=1\text{mT})$.

**Figure 3.** Observed trace of droplet.

2.2. Experimental results

The terminal velocity of the droplet without the magnetic field is $122.5 \sim 171.8 \text{mm/s}$ depending on the diameter of the droplet and the concentration of the magnetic fluid, which is consistent with the velocity of the blood flow in the aorta, $100 \sim 200 \text{mm/s}$.

The case of the droplet diameter of $2.6 \text{mm}$ and the concentration of $100\%$ is shown as a typical example: As shown in figure 3, when the magnetic field is strong, the droplet is accelerated toward the
wall and is directly captured to the wall surface (figure 3(a)) or captured after sliding on the wall (figure 3(b)). If the magnetic field is weaker, the droplet is drawn to the wall surface but slides away on the wall without being stopped (figure 3(c)). If the magnetic field is weak enough, although the trace of the droplet is curved toward the wall, the droplet continues falling away (figure 3(d)).

3. Numerical simulation

The equation of motion of the droplet is numerically solved, assuming that the droplet is a solid sphere and the magnetic flux density $B$ is curve-fitted as shown in figure 2. The magnetic force $F_m$ which attracts the droplet toward the magnetic pole is represented as

$$ F_m = \frac{2\chi V B^2}{\mu_0 r} $$

where $\chi$ is the magnetization, $V$ the volume of the droplet, $\mu_0$ the permeability. $r$ is the distance between the droplet and the magnetic point-pole, which is slightly under the surface of the finite-sized magnet. The depth is assumed to be the thickness of the magnet times $\sin(\pi/2)$. Then $r$ is nearly equal to $s$ in figure 2. The gravity force $F_g$ reduced by the buoyancy is

$$ F_g = V \left( \rho_m - \rho_w \right) g $$

where $\rho_m$ is the density of the magnetic fluid, $\rho_w$ the density of the water, $g$ the acceleration of gravity.

The trace of the droplet of diameter of 2.6 mm and concentration of 100 % is shown in figure 4. $x$ and $z$ are the horizontal and vertical axes, respectively. The droplet is released at the center of the reservoir cross-section ($x=0$ mm), and the magnet is placed at $z=0$ mm. The wall of the reservoir is at $x=17.5$ mm. When the distance $a$ between the magnetic pole and the wall is less than 15 mm, the droplet is captured to the wall surface. When $a$ is 16-18 mm, the droplet is drawn to the wall surface but slides away on the wall without being stopped. When $a$ is larger, the trace is only curved toward the wall but the droplet continues falling. This is consistent with the experimental results.

4. Condition of capture

Whether the droplet is captured or not depends on the balance between the gravity force $F_g$ and the component of the magnetic force along the wall which is related to the magnetic force $F_{m_w}$ on the wall

$$ F_{m_w} = \frac{2\chi V B_w^2}{\mu_0 a} $$

where $B_w$ is the magnetic flux density on the wall and $a$ the distance between the wall and the magnet. Figure 5 show the experimental and simulated limits of capture. Solid symbols show the case that the
droplet is captured and open symbols the case not captured in the experiments for each

\[ F_{mw}/F_g \]

concentration. Static balance between the magnetic and gravitational forces shows that the limit of capture is \( F_{mw}/F_g > 1.93 \), which is consistent with the experimental results. Simulated limit is slightly higher due to neglect of the surface tension and inertia of the droplet. The size of the droplet has almost no effect on the limit, because the volume of the droplet \( V \) is contained in both of \( F_{mw} \) and \( F_g \), and is cancelled. The concentration of the fluid \( \alpha \) has little effect, because the magnetization in \( F_{mw} \) and the density of the fluid in \( F_g \) are represented as

\[ \chi = \alpha \chi_0 \]
\[ \rho_m = \rho_k + \alpha(\rho_{m0} - \rho_k) \]

where \( \chi_0 \) is the magnetization of original magnetic fluid, \( \rho_k \) the density of kerosene, \( \rho_{m0} \) the density of the original magnetic fluid. Then \( \alpha \) is almost cancelled in \( F_{mw}/F_g \).

5. Conclusions
(1) Motion of the magnetic droplet is classified according to the strength of the magnetic force into three types: The droplet is captured on the wall, is drawn to the wall but slides away, and the trace is only curved but the droplet continues falling.
(2) The condition of capture is approximately determined by the balance between the magnetic force and the gravity force and is almost not affected by the size and the concentration of the droplet.

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