Research on Magnetism and Magnetization Intensity of Magnetic Fluid

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Abstract. Magnetic fluid is a liquid magnetic material with high magnetization, fluidity and superparamagnetism. The composition and the performance of magnetic fluid in magnetic field were introduced. Magnetic model of magnetic fluid for application was established. Magnetic particles could be seen as magnetic needles with certain N-S directions whose direction could be controlled by external magnetic field. Magnetization mechanism of magnetic fluid was researched. Measurement principle of magnetization intensity was studied and the formulas were deduced. The working principle of vibrating sample magnetometer was introduced and the magnetization curve of magnetic fluid was measured and plotted. It was concluded that magnetic fluid has superparamagnetism which means that the remanence and coercivity of aggregation of magnetic fluid are both zero. Magnetism is an important characteristic of magnetic fluid for engineering applications that magnetic fluid with high magnetization intensity will be explored and researched.

1. Introduction

Magnetic fluid is a novel liquid magnetic material which has high magnetism, fluidity and superparamagnetism. Magnetic fluid has potential applications such as sensors[1-4], sealing[5-7], biomedical engineering[8-9], and so on. Magnetism of magnetic fluid is a key property for applications. In magnetic fluid sensors, the sensitivity of sensors is determined by susceptibility of magnetic fluid which is proportional to the magnetism of magnetic fluid. In magnetic fluid sealing, the magnetism could influence the resistance of the sealing to the pressure. In magnetic fluid biomedical applications, the magnetic fluid controlled by magnetic field could convey the medicine to the target place for treating cancer. Magnetism of magnetic fluid is so important for applications[10-12] that the measurement of magnetism is important for research.

Magnetic fluid is composed of magnetic particles, surfactant and base carrier liquid[13-14]. There are lots of characteristics of magnetic fluid being researched for applications[15-18]. Magnetic fluid could be controlled by magnetic field applied around. By controlling the magnetic field, the parameters and location of magnetic fluid could be changed and controlled. Figure 1 shows the performance of magnetic fluid in magnetic field.
2. Magnetic Model and Magnetization Mechanism of Magnetic Fluid

2.1. Magnetic Model of Magnetic Fluid
Magnetic particles are key elements of magnetic fluid because the magnetism of magnetic fluid mainly depends on the particles’ performance. The magnetic particles possess magnetism because each magnetic particle could be seen as a magnetic needle. When there is an external magnetic field applied on magnetic fluid, all the nano-sized particles are applied magnetic force and the directions of the magnetic needles are consistent at once. When magnetic field removed, the directions of the magnetic needles restore the original disordered. Figure 2 shows the magnetic model of magnetic particles in the base carrier liquid.

2.2. Magnetization Mechanism of Magnetic Fluid
Magnetism is the most important characteristic of magnetic fluid. According to its magnetic susceptibility, magnetic fluid is a superparamagnetic material. However, its magnetization mechanism is different from that of paramagnetic material.

The magnetization of paramagnetic materials is the result that the orderly arrangement of the orbital plane of electrons moving in the material under the action of the external magnetic field. The nano-sized particles in magnetic fluid are ferromagnetic material. The magnetization of magnetic fluid is caused by the rotation of the magnetic domain, which is intrinsic. Another magnetization mechanism of magnetic fluid is that the self-rotation of the magnetic particles in the base carrier liquid, which is external exerted. The balance location is depended on the balance of magnetic energy and the thermal motion energy. The volume of ferromagnetic particles in liquid is about 10⁵ times that of atoms. So the magnetism of the particles is much stronger than that of the atoms, and the particles show superparamagnetism. The superparamagnetism is that magnetic fluid has high saturation magnetization intensity and no hysteresis phenomenon. The magnetization curve of magnetic fluid passes through the origin. There is no remanence and no coercive force, that is, Br and Hc are all zero.
3. Magnetism Measurement of Magnetic Fluid

3.1. Measurement Principle of Magnetization Intensity

When a piece of soft magnetic material is in an uneven magnetic field, a magnetic force will be generated to draw the material in a certain direction. The magnitude of the magnetic force is related to the magnetic field gradient, the quality of the material and the degree of magnetization. The direction of the magnetic force is related to the direction of the magnetic field gradient. This is the measuring principle for magnetization of magnetic materials. The magnetic force applied on magnetic fluid could be calculated by the following formula.

$$F = m \cdot \sigma \cdot \frac{dH}{dx}$$  \hspace{1cm} (1)

Where, $F$ is the magnetic force applied on the magnetic fluid in uneven magnetic field. $m$ is the mass of the magnetic material. $\sigma$ is the magnetization intensity of unit mass magnetic fluid in magnetic field. $\frac{dH}{dx}$ is the magnetic field gradient in a certain direction in the space where magnetic fluid is located.

If the magnetic field $H$ is large enough and the magnetic field gradient is uniform, the value $\frac{dH}{dx}$ in equation (1) is constant and $\sigma$ tends to be saturation value $\sigma_s$. Then equation (1) could be changed to be

$$F = m \cdot \sigma_s \cdot \frac{dH}{dx}$$  \hspace{1cm} (2)

Then formula (2) could be changed to be

$$\sigma_s = \frac{F}{m \cdot \frac{dH}{dx}}$$  \hspace{1cm} (3)

So the saturation magnetization of magnetic fluid $\sigma_s$ could be calculated by measuring the saturation magnetic force of magnetic fluid $F$ in magnetic field.

In the experiment, the magnetic fluid was tested and compared with the standard sample with known value $\sigma_s$ by comparison. For standard sample,

$$F_a = m_a \cdot \sigma_{sa} \cdot \frac{dH}{dx} = I_a \cdot \alpha$$  \hspace{1cm} (4)

For the tested sample,

$$F_x = m_x \cdot \sigma_{sx} \cdot \frac{dH}{dx} = I_x \cdot \alpha$$  \hspace{1cm} (5)

Where, $I_a$ and $I_x$ are the reading values of the standard sample and the tested sample in the measuring instrument respectively, and $\alpha$ is the reading unit of the measuring instrument. Combine formulas (4) and (5), formula (6) is deduced.

$$\frac{m_x \cdot \sigma_{sx}}{I_a} = \frac{m_x \cdot \sigma_{sx}}{I_x}$$  \hspace{1cm} (6)

So formula (7) is deduced.

$$\sigma_{sx} = \frac{m_a}{m_x} \cdot \frac{I_x}{I_a} \cdot \sigma_{sa}$$  \hspace{1cm} (7)

According to the saturation magnetization of standard sample, we could calculate the saturation magnetization of magnetic fluid.
3.2. Measurement for Magnetization Intensity of Magnetic Fluid

Figure 3 shows the main working principle of vibrating sample magnetometer which is used for measuring magnetization intensity. The vertical drive reference signal is applied on a vibrator which could drive the sample rod move periodically, which drives the sample adhered to the lower end of the vibrating rod to vibrate in the same frequency and phase. The s.c magnet Helmholtz-configuration whose power is supplied by a D C power supply produces a magnetic field $H$ which magnetized the sample magnetic fluid. Then the inductance signals are produced and tested in the ‘pick-up’ coils. The signals are amplified by a pre amp and recorded to the y-axis of the recorder. The output of the millitesla meter used to measure the magnetic field is fed back to the x-axis of the recorder. In this way, when the DC power supplier changes for a period, the recorder will trace the hysteresis loop.

![Figure 3. Working principle of Vibrating Sample Magnetometer](image)

The parameters of the vibrating sample magnetometer in the experiment are shown in table 1. The magnetic curve of magnetic fluid measured by vibrating sample magnetometer is shown in figure 4. The saturation magnetization intensity of the sample magnetic fluid measured is 23emu/g. The remanent magnetization and coercive force are 0.85emu/g and 1 Oe respectively. The values remanent magnetization and coercive force are so small that they could be ignored.

**Table 1. Parameters of the vibrating sample magnetometer in experiment**

| Sensitivity  | Error  | Resolving power | Testing magnetic field |
|--------------|--------|-----------------|-----------------------|
| $5 \times 10^6$ emu | ± 1% | 0.05%           | 20000Oe               |

![Figure 4. Magnetization Curve of Magnetic Fluid](image)
From figure 4, it could be concluded that magnetic fluid has an important characteristic which is superparamagnetism. Superparamagnetism refers to that, the ferromagnetic materials in single domain structure when their grains are smaller than critical dimensions show paramagnetism when temperature is lower than Curie temperature and higher than block temperature. However, their paramagnetic susceptibility is far higher than that of ordinary paramagnetic materials under the effect of external magnetic field, and this is called as superparamagnetism.

From figure 4, it could be also concluded that superparamagnetism has two most important characteristics. First, if a figure is plotted with magnetization intensity M as Y-axis and H/T as X-axis, where H is the magnetic field intensity applied, and T is absolute temperature, then magnetizing curve is measured under different temperatures in the temperature range when single domain particle aggregation shows superparamagnetism. These magnetizing curves are certainly coincident. Second, no hysteresis will appear, that is, the remanence and coercivity of aggregation both are zero.

4. Conclusions
Magnetic fluid is a novel nano-sized liquid magnetic material which has fluidity, high magnetism and superparamagnetism. The composition of magnetic fluid was introduced. Magnetic model and magnetization mechanism of magnetic fluid was studied. Magnetic particles were seen as magnetic needles whose direction could be controlled by magnetic field. Magnetization mechanism of magnetic fluid was researched. The measurement principle for mechanism of magnetic fluid was deduced and calculated. Then the working principle of vibrating sample magnetometer was introduced and the magnetization curve of magnetic fluid was measured and plotted. It was concluded from the magnetization curve that magnetic fluid has superparamagnetism. The remanence and coercivity of aggregation are both ignored. So magnetic fluid with high magnetization intensity should be explored and researched for more engineering applications.

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6. References
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