Research on the Density of Magnetic Fluid and its Application in Mineral Separation

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Abstract. The density of magnetic fluid is important for some applications such as mineral processing. Magnetic fluid is a nano-sized magnetic material which has superparamagnetism. The density of magnetic fluid with no magnetic field was introduced. The measuring method was studied and the calculating formula was deduced. Since magnetic fluid could be magnetized, it could be controlled by magnetic field. The density of magnetic fluid could be changed by magnetic field. The buoyancy of magnetic fluid in magnetic field was researched and it was concluded that the buoyancy force of magnetic fluid in magnetic field is related to the mass, the volume, the permeability, the magnetization of magnetic fluid and the gradient of magnetic field. For a certain magnetic fluid, the parameters of itself are fixed. Then the gradient of magnetic field is the mainly factor influencing the magnetic force. A density measuring method for magnetic fluid in magnetic field was introduced. A mineral separation device based on magnetic fluid was introduced. And the principle of the mineral separation device with magnetic fluid was studied. More kinds of magnetic fluid and applications could be explored by researching magnetic fluid.

1. Introduction
Magnetic fluid is a novel magnetic material which is the composition of nano-sized magnetic particles coated surfactant in carrier liquid such as kerosene, water, ester group, and so on. Magnetic fluid is a liquid material which could be magnetized by magnetic field[1]. So it could be controlled by magnetic field in some certain conditions. The magnetic particles should be dispersed in the carrier liquid evenly, and there is no agglomeration and settlement in magnetic fluid. The magnetism of magnetic particles contributes to the magnetism of magnetic fluid. So the ratio of the magnetic particles and the carrier liquid is important for the magnetism of magnetic fluid.

Magnetic fluid has an important performance shown in Fig.1. If there is magnetic field gradient, the magnetic particles dispersed along the magnetic field line. So the surface instability shown in Fig.1 appeared.
The working principle of mineral processing is that different minerals with different density could be separated by controlling the density of magnetic fluid. By controlling the magnetic field exerted on magnetic fluid, the density of magnetic fluid could be adjusted to float up the mineral or to sink the mineral\cite{2}.

In many applications of magnetic fluid\cite{3-8}, especially in mineral separation\cite{9}, the density of magnetic fluid is important for separating the different minerals.

2. **Density of magnetic fluid with no magnetic field**

2.1 *Density*. In physics, density is a measure of the mass in a specific volume. The density is equal to the mass of the object divided by the volume. It can be expressed by the symbol $\rho$. In the international system of units and the legal unit of measurement in China, the unit of density is $\text{kg} / \text{m}^3$.

For magnetic fluid, if there is no magnetic field around, magnetic fluid has no difference with other liquid. The density could be described by the mass in per volume, which could be calculated in the following formula.

$$\rho = \frac{m}{V}$$  \hspace{1cm} (1)

So, the density of magnetic fluid with no magnetic field around could be calculated by measuring mass and volume of magnetic fluid.

2.2 *Measuring method of the density with no magnetic field*. The density of magnetic fluid can be measured by measuring cylinder method, pycnometer method, densimeter method, buoyancy method and floating body method. The commonly used methods are measuring cylinder method and pycnometer method. The basic principle of these two methods is to obtain density by measuring the mass and volume of a certain amount of magnetic fluid. The difference is that the volume is fixed when using the pycnometer method, and the measurement error is mainly caused by the measurement of mass. The cylinder method will produce errors in the measurement of both mass and volume. So the pycnometer method measures the density relatively accurately.

In the experiment, if there is no magnetic field around magnetic fluid, pycnometer method is used to measure the density of magnetic fluid. Fig.2 is the gravity bottle for measuring the density of magnetic fluid.
At room temperature, assuming that $m_0$ is the mass of the gravity bottle, $V_0$ is the volume of the gravity bottle, $m$ is the mass of magnetic fluid in the gravity bottle, so the density of magnetic fluid could be calculated by formula (2).

$$\rho = \frac{m - m_0}{V_0}$$  \hspace{1cm} (2)

### 3. Density of magnetic fluid in magnetic field

3.1 Density of magnetic fluid in magnetic field. If magnetic fluid is put in a magnetic field, then magnetic fluid is magnetized by magnetic field. Magnetic fluid is exerted a magnetic force by magnetic field, while the magnetic field is not uniform[10]. Assuming that taking a unit volume of micro element in magnetic fluid, $f_m$ is the magnetic force exerted on the unit volume. $\mu_m$ is the magnetic susceptibility of magnetic fluid. $H$ is the magnetic intensity of magnetic field. $M$ is the magnetization intensity of magnetic fluid. So the magnetic force exerted on the unit volume of magnetic fluid is

$$f_m = \mu_m M \cdot \nabla H$$  \hspace{1cm} (3)

Where, $\nabla H$ is the gradient of magnetic field.

From formula (3), if the magnetic field is uniform, that is $\nabla H = 0$, then the magnetic force exerted on magnetic fluid $f_m = 0$. While $\nabla H \neq 0$, there is a magnetic force exerted on the unit volume of magnetic fluid. If the gravity of the unit volume is $f_0$, then force value on the unit volume of magnetic fluid is

$$f = f_0 + f_m = mg / V + \mu_m M \cdot \nabla H$$  \hspace{1cm} (4)

The formula (4) could change to be formula (5).

$$f / g = (f_0 + f_m) / g = m / V + \mu_m M \cdot \nabla H / g$$  \hspace{1cm} (5)

The apparent density of magnetic fluid $\rho_m$ is defined as

$$\rho_m = f / g = (f_0 + f_m) / g = m / V + \mu_m M \cdot \nabla H / g$$  \hspace{1cm} (6)

From the formula (6), the apparent density of magnetic fluid could be changed with the magnetic field gradient changing. So, generally the apparent density of magnetic fluid could be controlled by controlling magnetic field gradient.
In physics, buoyancy refers to the resultant force of the fluid pressure (liquid and gas) on each surface of the object in the fluid (liquid and gas). The definition of buoyancy is the gravity of the discharged liquid when the object sinks. So, the calculating formula of the buoyancy is shown in formula (7).

\[ F = \rho_n gV = \mu_m + \mu_m k dV \nabla H \]  \hspace{1cm} (7)

From formula (7), the buoyancy of the object in magnetic fluid may exceed the gravity of the object in magnetic fluid. The principle of the buoyancy may be larger than the gravity of the object in magnetic fluid is called the buoyancy principle of magnetic fluid.

Since the buoyancy exceeds the gravity of the object in magnetic fluid, the object may float on the surface of magnetic fluid. The apparent density changing could be applied in engineering fields such as classification for objects with different density. For example, mineral processing is a typical application of the apparent density.

3.2 Measuring method for density in magnetic fluid. A device could be designed for measuring the density of magnetic fluid in different areas. An object could be put in the magnetic fluid for measuring. The object is exerted forces such as buoyancy \( F_b \), gravity \( G \) and an artificial force \( F_a \) shown in Fig.3. So there is formula (8).

\[ F_b + G + F_a = 0 \]  \hspace{1cm} (8)

A container was designed to contain magnetic fluid with different magnetic intensity. The gravity \( G \) of the object was measured by a force measuring device. Then the object was put in the magnetic fluid with the arm connected on a device for measuring the force \( F_b \). An artificial force \( F_a \) was applied to keep the object in a certain position in magnetic fluid. Then from formula (7), the density of magnetic fluid could be got by calculation from formula (9).

\[ \mu_m = \frac{F_b}{gV} \]  \hspace{1cm} (9)

Where, \( V \) is the volume of the object in magnetic fluid, \( g \) is the acceleration of gravity.

4. Application in mineral processing
Mineral processing with magnetic fluid is a key technology in magnetic separation, including hydrostatics separation with magnetic fluid and hydrodynamics separation with magnetic fluid[11]. Since magnetic fluid is a superparamagnetic liquid medium for separating things with different density, it could be aggravated under the action of magnetic field. Different minerals could be separated by magnetic fluid in controlled magnetic field according to the difference of magnetic and density or the difference of magnetism.

For coarse selection of ores with low recovery rate, hydrodynamics separation with magnetic fluid is a suitable method for ores selection. The hydrodynamics separation with magnetic fluid is a kind of
separation method for different minerals based on the difference of density, specific magnetization coefficient and conductivity between minerals with strong electrolyte solution as separation medium under the combined action of magnetic field (even or uneven) and electric field.

In the traditional heavy medium beneficiation, the heavy medium carries on the high efficiency for heavy medium beneficiation. The hydrostatics separation with magnetic fluid is similar to the heavy liquid separation. It takes superparamagnetic fluid and ferromagnetic colloid (water-based magnetic fluid or organic solvent liquid) suspension as separation medium. Under the action of gravity field, centrifugal force field and magnetic field, floating and sinking can separate solid particles. It can be used as the separation method in diamond dressing. If the magnetic fluid has the varying density gradient distribution under the action of different magnetic fields, it can replace the heavy medium in traditional beneficiation. which is the magnetic fluid separation.

From the analysis in part 3, if a nonmagnetic object is put in magnetic fluid which is magnetized by magnetic field, then the status of the object could be controlled as go up, suspension or sink. The principle of mineral processing is shown in Fig.4. The container (1) is full of magnetic fluid (2) whose density could be controlled by the magnetic gradient produced by the magnets (4). (5) and (6) are containers for collecting objects with larger density relatively. (7) is the object with lower density which would float on the surface of magnetic fluid. Because of the magnetic gradient caused by the magnets, the density of magnetic fluid could be adjusted to an appropriate area for the minerals to separate and select the objective minerals.

![Fig.4. Principle of mineral processing with magnetic fluid](image)

The density of magnetic fluid could be controlled by controlling the electric current of the coil or the parameters of the magnet which produced the magnetic field. More kinds of magnetic fluid could be explored to satisfy the needs of engineering applications.

5. Conclusions
Magnetic fluid is a nano-sized magnetic material which could be applied in many fields. The parameters of magnetic fluid are mainly density and superparamagnetism. The density of magnetic fluid with no magnetic field was introduced and the measuring method was introduced. Since magnetic fluid could be magnetized by magnetic field. The density of magnetic fluid could be controlled by magnetic field. By calculating, the density of magnetic fluid was researched and the measuring method was studied. A density measuring method was introduced based the apparent density theory. The application on mineral separation based on magnetic fluid was introduced and studied. The gradient of magnetic field is the most important factor for mineral separation. The density of magnetic fluid could be controlled by controlling the electric current of the coil or the parameters of the magnet which produced the magnetic field. More kinds of magnetic fluid and application could be explored for engineering.
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