Study on sedimentation stability of magnetorheological fluids based on different lubricant formulations

Su Zhibin, Luo Yiping, Wang Ying, Luo Jiao and Ji Dongsheng

School of Mechanical and Automotive Engineering, Shanghai University of Engineering Science, Shanghai 201620, People’s Republic of China

1 Author to whom any correspondence should be addressed.
E-mail: lyp777@sina.com

Keywords: lubrication additive, magnetorheological fluids, sedimentation stability, wettability

Abstract

Magnetorheological Fluids (MRFs) is rapidly emerging as a type of new fluid intelligence material that is controllable and low-energy consuming with high output and fast response. It has already received widespread attention from many international scholars. In this paper, the orthogonal test of MRFs configuration with six different types of lubricating additives (oleic acid, hydrogenated castor oil, teflon, boron nitride, molybdenum disulfide, graphite) is conducted to study the wettability, zero-field viscosity and yield stress of MRFs under different solid lubricants. According to the size of contact angle, the ability of anti-sedimentation stability of MRFs under different lubricants is compared. The zero-field viscosity of MRFs is tested by viscometer, and the strength of viscosity under the zero-field condition is compared. The yield stress is measured by a self-made yield stress device, and then the sedimentation stability characteristics of MRFs are analyzed. Finally, through the analysis and evaluation of experimental data, it is concluded that molybdenum disulfide as a lubricating additive can effectively improve the anti-sedimentation stability of MRFs, and the general rules of lubricating additives used in MRFs formulations with excellent performance are summarized.

1. Introduction

As one of the rapidly developing intelligent materials, MRFs have unique magnetorheological properties. MRFs have been the focus of many domestic and international researchers in the field of smart materials. The MRFs with excellent performance should have excellent frictional abrasion, high shear yield stress, and magnetic saturation strength, as well as being resistant to sedimentation, fast and reversible, corrosion-resistant, long life and temperature stable. However, with the researchers’ experimental research on MRFs, it is found that the sedimentation stability of MRFs not only has an impact on the environment and performance output of the MRFs but also has an important influence on the service life of MRFs.

As one of the important properties of MRFs, the stability of MRFs is an important basis for long-term preservation [1]. Good stability of MRFs can reduce the agglomeration of ferromagnetic particles and their sedimentation, prevent irreversibility of the process, and keep them in an evenly dispersed status. If the stability is poor, the comprehensive performance of the MRFs will be affected, and the service range and life of the MRFs will be reduced as well, thus causing losses due to the functional failure of the MRFs. Ashour et al [2] have made an important contribution to the study of the properties of MRFs by carrying out experimental studies on the sedimentation stability and preparation techniques of MRFs; Gorodkin et al [3] designed an inductive centrifugal device to accelerate MRF settlement, and then measure the sedimentation coefficient of MRFs. Ngatu [4] studied the sedimentation velocity of MRFs measured by the single-coil inductance method. Hu Lin et al [5] designed a sedimentation potential meter to detect the sedimentation of magnetic particles. The researchers found that the addition of the surfactant made the hydrophilic group in contact with the base liquid, increased the repulsive force between magnetic particles, avoided agglomeration, and improved the sedimentation

© 2020 The Author(s). Published by IOP Publishing Ltd
stability of the MRFs [6, 7]. In this paper, the effects of lubricants on the stability of MRFs anti-sedimentation are investigated by testing the wettability, viscosity, and yield stress of MRFs under different lubricants.

2. Theoretical analysis

2.1. Magnetorheological fluids gravity at zero field

Zero field gravity is the gravity of MRFs under zero magnetic field, showing a Newtonian fluid characteristic of low viscosity. At the same time, because of the difference in density between the dispersed and continuous phases, and the downward gravitational influence, the ferromagnetic particles, and the carrier fluid move towards each other and settle. Assuming that the ferromagnetic particles are regular spheres and do not collide with each other, the magnetic particles are mainly subject to gravity, buoyancy, and motion resistance in the carrying liquid. The formula is as follows:

\[ G = \frac{4}{3} \pi \left( \frac{d}{2} \right)^3 \rho \gamma = \frac{\pi}{6} \rho \gamma d \]  
\[ F = \frac{4}{3} \pi \left( \frac{d}{2} \right)^3 \rho \rho_0 = \frac{\pi}{6} \rho \rho_0 d^3 \]  

\( \rho \) - particle density; \( d \) - particle size; \( \rho_0 \) - carrier liquid density; \( g \) - gravitational acceleration;

At the same time, magnetic particles will be subject to the viscous resistance of the liquid carrier, making the relative motion between particles and fluid change. This resistance can be calculated by the fluid resistance formula, as shown below:

\[ f = \frac{\epsilon \rho_0 u^2}{2} \]  
\[ \epsilon = \frac{24}{Re_t} \]  

\( s \) - particle surface area; \( u \) - particle sedimentation velocity; \( \epsilon \) - damping coefficient of the fluid; \( Re_t \) - reynolds number (particle and liquid phase movement);

The movement of particles in the liquid carrier is accelerated first and then at a uniform speed. The sedimentation velocity at a uniform speed is called \( u_t \), and the force balance of particles at this time is as follows:

\[ G = F + f \]  

According to formula (5), the velocity formula of the falling ferromagnetic particles can be deduced, as shown below:

\[ u^2 = \frac{\pi d^2 g (\rho - \rho_0)}{12 \pi^2 \epsilon \rho_0} \]  
\[ u_t = \sqrt{\frac{d g (\rho - \rho_0)}{3 \epsilon \rho_0}} \]  

\( r \) - particle radius; According to formula (7), the sedimentation velocity is not only related to the density and dispersed particles but also related to the particle size and damping coefficient. Meanwhile, according to Stokes’ Law, the sedimentation velocity of its particles can also be expressed as follows:

\[ u = \frac{2 g r^2 (\rho - \rho_0)}{9 \eta} \]  

\( \eta \) - viscosity of carrier fluid.

It can be seen from equation (8) that the sedimentation velocity of particles is inversely proportional to the viscosity and directly proportional to the particle size. The larger the particle size is, the faster the sedimentation speed will be [8]. Moreover, the influencing factors in the Stokes formula are consistent with those in the formula derived in this paper [9], which is of great help to future research on the properties of MRFs.

2.2. Gravitation between magnetic particles and van der Waals magnetic force

The influence of gravitational forces between magnetic particles in MRFs is considerable, with magnetic field forces between them, and particles in an applied magnetic field, it can be seen as a dipole. The reason for particles’ sedimentation in MRFs is mainly because the magnetic potential energy is greater than the thermal motion energy of the particles. The potential energy between its dipoles is as the following equation (9): where \( E_{dd} \) is the magnetic potential energy, \( \mu_0 \) is the vacuum permeability, \( M_i \) and \( V_{ij} \) is the magnetic moment and volume, respectively, \( n_i^0 \) is the unit vector in the n direction, and \( r_0 \) is the unit vector in the r direction.
According to the properties and characteristics of the MRFs, $M = M_1 + M_2, V_{01} = V_{02} + V_{p1}, r = d_p + d_s$, where $d_p$ is the diameter of the particles, $d_s$ the inter-surface agreement between the particles. When a magnetic field is applied $\gamma^0 \times n_1^0 = 1, \gamma^0 \times n_2^0 = 1$, then the potential energy is obtained by bringing in the above formula (9).

$$E_{dd} = \frac{\mu_0}{4\pi\gamma^3} (M_1 V_{01})(M_2 V_{02}) \cdot [n_1^0 \cdot n_2^0 - 3(\gamma^0 \cdot n_1^0)(\gamma^0 \cdot n_2^0)]$$

From equation (10), we know that the potential energy is maximum when the distance between the surface particles is 0. If the particles do not agglomerate, the following inequality holds.

$$2Ck_0T \geq \frac{1}{12}\mu_0 M^2 n_{p1}$$

$C$ is the kinetic energy coefficient of the thermal motion of the molecule, $k_0$ is the Boltzmann constant ($1.38 \times 10^{-23}$), $T$ is the absolute temperature.

The van der Waals force is generated by pulsating orbital electrons in a microparticle to induce an oscillating dipole in another particle and present in the among any molecule. The dipole pulsation energy formula is shown below.

$$E_f = \frac{A}{6} \left[ \frac{2}{l^2 + 4l} + \frac{2}{(l + 2)^2} + \ln \frac{l^2 + 4l}{(l + 2)^2} \right]$$

where $A$ is the Hamaker constant, $l$ is the surface distance, and $d$ is the particle diameter. From the equation, we can see that the pulsating energy of the dipole is inversely proportional to the distance between the particles. When an additive is added, an energy barrier forms between the particles and this energy fortress effectively suppresses the van der Waals force which plays a buffer role to prevent inter-particle agglomeration and sedimentation.

3. Effects of lubricants on MRFs

3.1. Wettability studies

3.1.1. Wettability test

Wettability exists between two mutually incompatible liquids and solids [10]. It refers to the wetting degree of one kind of liquid to one kind of solid, that is, the spreading ability or tendency exhibited by a drop of liquid onto the surface of a solid, which is of great importance for the study of the solubility and disintegration properties of some liquids and solids. Therefore, the wettability of carbonyl iron powder in MRFs acts as an important reference for the study of anti-sedimentation stability.

The contact angle is an important measure of wettability experiments, used to indicate the strength of solid surface wettability. The contact angle refers to the tangent of the gas-liquid interface made at the intersection of gas, liquid and solid at the liquid-solid liquid junction line. The angle of intersection, which is a measure of the degree of wetting, as shown in figure 1 below.

Wettability is mainly related to the system interface tension, when liquid drops on the surface of a solid level, and the tension of solid-liquid-gas three-phase interface balance, the basic equation of wettability is as follows, also known as Young’s equation.

$$\sigma_{g-s} = \sigma_{l-s} + \sigma_{l-g} \cos \theta$$

$$\cos \theta = \frac{\sigma_{g-s} - \sigma_{l-s}}{\sigma_{l-g}}$$

where: $cos \theta$ - interface contact angle; $\sigma_{g-s}$ - solid-gas contact surface; $\sigma_{l-s}$-solid-liquid contact surface; $\sigma_{l-g}$-liquid-air contact surface.

The above formula shows that the contact angle is a function of the free energy of the three interfaces. The size of the contact angle is related to the characteristic of the three phases, which is used to measure the size of the solid surface wettability factor is the angle between. The solid is lyophilic when $\theta < 90^\circ$, the liquid can wet the solid. The smaller the angle is, the stronger the wettability is; when $\theta > 90^\circ$, the solid is hydrophobic, the liquid cannot wet the solid and is prone to move on the surface of the solid, so the wettability is poor. By setting the
90° angle as the dividing line, the following wetting interfaces can be summarized: when $\theta = 0$, the surface is completely wetting and spreading; the boundary between wetted and non-wetted is at $\theta = 90^\circ$ with non-wetted at $\theta > 90^\circ$. When $\theta = 180^\circ$, there is no wetting at all, and the liquid is beaded on the solid surface.

The more commonly used contact angle measuring instrument at present are mainly image analysis method contact angle measuring instrument \[11\], plug-in contact angle measuring instrument, etc. The droplet contact angle measurement instrument (DSA25) used in this paper is a type of impact analysis measurement instrument. This instrument uses image projection to measure the contact angle. The measurement is mainly done by projecting a drop of liquid that meets the required volume and let it fall freely on a prepared solid platform, Then image analysis is performed through projection to measure and calculate the angle between the liquid and solid. Contact angle measurements can be made for liquids in the range from $-30^\circ$ to $160^\circ$. However, there are some errors due to lacking a precise scale when moving the sample stage; and the samples of poor reusability can only be used once. These factors add to the workload.

The MRFs applied in this experiment are prepared according to the same ratio, that is, the mass fraction of carbonyl iron powder is 73%, the mass fraction of surfactant is 0.5%, and the mass fraction of thixotropic agent is 0.5%. The main material for this experiment is a sample of 2%-mass-fraction-lubricant MRFs with good frictional properties. Since a droplet contact angle meter can only measure solid and liquid, and the purpose of this wettability experiment is to measure the wettability of dimethyl silicone oil to carbonyl iron powder under different types of lubricants, so the modified carbonyl iron powder is first made into a solid. Then the modified carbonyl iron powder in the mold is pressed using a drawing press, as shown in figure 2 below, and the prepared solid is placed into the pre-prepared sample tank until all six samples have been made (six samples of carbonyl iron powder under different lubricants).

When measuring the contact angle, the difference in drop volume can have a significant impact on the results of the experiment. Therefore, it is important to clarify the droplet volume parameter settings before dropping, i.e., volume measurement of the droplet. A set of molybdenum disulfide-modified carbonyl iron powder solid compression tablets is selected, and injection parameters of different sizes are set for measurement. Finally, the optimal injection parameter volume is derived.

Next, the droplet contact angle measurement is performed. Applied the prepared dimethyl silicone oil in a specific syringe, then inject the droplet, free fall the droplet onto the solid, rest 20–30 s, the contact angle is observed as shown in figure 3 below. Finally, the effect of contact angle on the surface of carbonyl iron powder under different lubricants is obtained.

3.1.2. Experimental results and analysis

(a) Analysis of droplet volume of injection.

Based on the determined droplet volume parameters, droplets of different injection volumes appeared to have different sizes of contact angles. Figure 4 below shows a solid tablet of carbonyl iron powder with molybdenum disulfide as a lubricant. According to figure 4, when the volume fraction is small, the contact angle is larger, and conversely, when the volume fraction increases, the contact angle it also gradually becomes larger, but when the droplet volume reaches 15ul, it reaches the peak contact angle stable at about $20^\circ$ and does not change. Therefore, the droplet volume parameter of this wettability experiment is set to 15ul.

(b) Analysis of the wettability of carbonyl iron powders under different lubricants.
The purpose of this experiment is to investigate the performance study of MRFs under different lubricants, while the wettability experiments focus on the study wettability of dimethyl silicone oil by modified carbonyl iron powder. Based on the contact angle test experiment under six lubricants [12], the smallest average contact angle measured when a drop of liquid is placed on a solid molybdenum disulfide sheet; and the largest measured when drops are applied to the boron nitride solid compression tablet, and then the solid-liquid wettability is the lowest. As shown in figure 5 below, it can be seen that for the wettability of the drops (dimethicone), the best performer is molybdenum disulfide which average contact angle is $20.95^\circ$. It can be considered that most of the wetting with the carrier liquid dimethyl silicone oil can be achieved after modification. The molybdenum disulfide ferromagnetic particles and the carrier liquid wet each other better, allowing the ferromagnetic particles to disperse uniformly in the carrier liquid. Comparatively speaking, oleic acid is the next best with an average contact angle of $27.25^\circ$, the wettability is good. From the comparison of the average contact angle of teflon, graphite, and hydrogenated castor oil, it is known that the modified ferromagnetic particles with partial wetting of dimethyl silicone oil. For the contact angle analysis of boron nitride, its wettability with dimethyl silicone oil is relatively small with an average contact angle of $45.2^\circ$.

According to the above graphical analysis, the contact angle of the carbonyl iron powder pressure plate under all lubricants is compared, it is clear from the graph that the contact angle of molybdenum disulfide is the smallest, and its wetting effect is the best, thus making the ferromagnetic particles in the carrier liquid more uniformly dispersed, the more can improve the sedimentation stability of the MRFs.

### 3.2. Study of viscosity properties

#### 3.2.1. Viscosity characteristic test

Viscosity characteristic is one of important properties of reactive MRFs application environment, also called zero-field viscosity.

For the viscosity test, the material selected is an MRFs with a 2% mass fraction of different lubricants with the best coefficient of friction. The NDJ-5 digital rotary viscometer with four rotors and four rotational speeds can measure the viscosity of a wide range of liquids. In order to prevent the influence of temperature on viscosity and to make the experimental values more accurate, a thermostatic water bath is used to control the temperature. To ensure the true value of the zero-field viscosity of the MRFs. The basic operation is as follows.

The configured MRFs are first stirred homogeneously to prevent sedimentation and then introduced into a beaker or flat-bottomed container with a diameter of not less than 60 mm. Use a thermostatic water bath to control the temperature of the liquid under test, set to 25 $^\circ$C. Place the beaker with the MRFs in the thermostat bath and keep it warm for 2–3 h. Measure with the biggest rotor (size 4) of the viscometer, set the rotation speed at 6 r min$^{-1}$. Turn the lift button and slowly immerse the beaker in the rheological fluid to be measured. Fluid until the rotor level mark (notch or scale on the rotor rod) is level with the fluid level. Adjust the level standard of
Start the viscometer again so that the air bubbles in the balance scale are within the intermediate balance range. Start the viscometer and wait for 30 s. When all data are stable, start reading and record the viscosity value. Repeat the test until all samples have been measured.

3.2.2. Results and analysis

According to the comparative analysis of the zero-field viscosity values shown in table 1 above, the zero-field viscosity of the MRFs of formulations 2–7 is lower than that of formulation 1. The zero-field viscosity of the MRFs after adding lubricant is lower than the zero-field viscosity of the MRFs without lubricant. The main reason is that the surface of the unlubricated magnetorheological carbonyl iron powder is not modified by activation, which leads to agglomeration in the carrier fluid, thus hindering the development of the magnetorheological products. The collision between the particles of the movement, easy to settle the phenomenon, making the viscosity increase. The viscosity of the MRFs with lubricating additive is decreased because the lubricating additive forms a coating layer on the surface of the ferromagnetic particles. The purpose of this coating is to counteract most of the van der Waals forces and prevent agglomeration of the ferromagnetic particles, resulting in reduced viscosity.

At the same time, when the viscosity data for formulations 2–7 are collated and analyzed under the same mass fraction, it is found that the molybdenum-disulfide lubricant has a maximum zero-field viscosity of 955 mPa · s. The zero-field viscosity of MRFs with graphite, teflon, and boron nitride is 710–760 mPa · s, the

![Figure 3. Contact angle of carbonyl iron powder under different lubricants.](image-url)
Figure 4. Contact angle at different droplet volumes.

Figure 5. Wettability contact angle of carbonyl iron powder under different lubricants.

| Number | Lubricant         | Speed     | Zero field viscosity (mPa·s) |
|--------|-------------------|-----------|-----------------------------|
| 1      | no                | 6 r min⁻¹ | 1000⁺                       |
| 2      | molybdenum disulfide | 6 r min⁻¹ | 955                         |
| 3      | hydrogenated castor oil | 6 r min⁻¹ | 953                         |
| 4      | graphite          | 6 r min⁻¹ | 756                         |
| 5      | teflon            | 6 r min⁻¹ | 715                         |
| 6      | boron nitride     | 6 r min⁻¹ | 712                         |
| 7      | oleic acid        | 6 r min⁻¹ | 495                         |
anti-sedimentation stability is second to molybdenum disulfide and hydrogenated castor oil, and the zero-field viscosity of oleic acid is the lowest, which is between 710 and 760 mPa·s.

In order to test the effect of rotational speed on the viscosity of the MRFs, the viscosity of the MRFs is tested for different lubricants at different rotational speeds, as shown in figure 6 above. According to the diagram, the viscosity of the MRFs under each lubricant decreases as the rotation speed increases, and when the rotation speed exceeds 6 r min$^{-1}$, the viscosity change of the MRFs under the six lubricants is almost similar because the viscosity range corresponding to each rotation speed is different. The viscometer stipulates that the larger the speed, the smaller the measurement range, so when the speed is greater than 6 r min$^{-1}$, the instrument range is not enough to measure the viscosity of the MRFs so that the viscosity value reaches the saturation of the speed, that is, 12 r min$^{-1}$, 30 r min$^{-1}$ and 60 r min$^{-1}$ of the MRFs viscosity value is basically consistent (to the maximum state).

### 3.3. Study of yield stress

#### 3.3.1. Yield stress test

In order to better study the relationship between viscosity, yield stress, and sedimentation stability, a representative group of tests is selected for this experiment material with a lubricant mass fraction of 2% of the MRFs under six formulations of 12 samples. And a homemade yield stress test device is made on the principle of the lifting method $^{[13, 14]}$. As shown in figure 7 below, the basic steps of the experiment are as follows.

The test uses 24 V DC power supply, the V4896H2-display is switched to peak mode with the motor speed at 60 r min$^{-1}$ and the magnetic field induction strength to 0.4 T. The sample to be tested (2% of the lubricant mass in the MRFs) is prepared on the test bench shelf to avoid vibration, and then place the pull-out block vertically into the reservoir, recording the height $h_1$ that the pull-out block drops. Then fix the liquid reservoir, turn on the motor’s ‘forward’ switch, and start the yield stress test. When the puller is lifted out of the reservoir, it indicates that the MRFs has already yielded, then press the motor ‘reverse’ button to bring the puller back to the original position, then press the pause button and mark the display of the pressure sensor at this point.

Repeat the above experiments, recording the height of the lifting fast and the pressure sensor indications, respectively, until all samples have been measured. The experimental data are then used to plot the variation of yield stress for MRFs with different lubricants under different magnetic fields, plotting the yield stress - magnetic field curves.

#### 3.3.2. Results and analysis

As shown in table 2 below, the values of yield stress for different lubricants at the same rotational speed and at the same time are not the same. And this experiment measured data values by mass KG (to reduce test error, each lubricant is configured with two identical sample materials of MRFs, taken as mass average), which is converted by the following equation (16) to obtain the yield stress value (KPa). According to the data analysis, the maximum yield stress of boron nitride is 82.554 KPa, followed by molybdenum disulfide and oleic acid. The minimum, yield stress value is 31.768 KPa.
From the viscosity experiments above, it is known that molybdenum disulfide has the highest zero-field viscosity and the yield stress is second only to boron nitride, indicating that this substance as an additive can have a good effect. The greater the viscosity under the same magnetic field and the greater the yield stress, the better the anti-sedimentation stability of the MRFs and the slower the particle drop. As shown in figure 8 below, the fluctuation of the curve is relatively large, indicating that the addition of lubrication additives has a great impact on the yield stress of MRFs. The influence of oleic acid as a lubricant additive can be seen to be minimal in both viscosity value and yield stress value, indicating that oleic acid is the most effective lubricant additive. The MRFs are less stable against sedimentation.

4. Conclusion

This paper investigates the anti-sedimentation stability of MRFs under different lubricants, based on the wettability experimental contact angle, the viscosity property experiments, and yield stress experiments under different lubricants, the performance comparison of different lubricants with the mass fraction of 2% is described respectively. Through analysis and research, we can see that: the larger the contact angle, the worse the wettability is; the higher the viscosity is while ensuring the MRFs rheological properties, the better the anti-sedimentation stability is; the higher the yield stress is, the better the MRFs performance. The addition of

\[ \tau = \frac{F}{2S} \] (16)

F-test tension; S-area of the pulling block (41.56 mm²)

Table 2. Yield stress under different lubricants.

| Number | Lubricant               | Speed     | Yield stress (KPa) |
|--------|-------------------------|-----------|--------------------|
| 1      | Boron nitride           | 60 r min⁻¹| 82.554             |
| 2      | Molybdenum disulfide    | 60 r min⁻¹| 74.246             |
| 3      | Teflon                  | 60 r min⁻¹| 65.724             |
| 4      | Graphite                | 60 r min⁻¹| 50.715             |
| 5      | Hydrogenated castor oil | 60 r min⁻¹| 43.61              |
| 6      | Oleic acid              | 60 r min⁻¹| 31.768             |
lubricant enables the ferromagnetic particles to be evenly dispersed in the carrier liquid, reducing the phenomenon of agglomeration and sedimentation; the lubricant can effectively improve the zero-field viscosity of the MRFs and the zero-field viscosity of the added lubricant is less than that of no lubricant. The zero-field viscosity and the effects on the value of yield stress of different lubricants are also different. Among the six lubricants, molybdenum disulfide has the smallest contact angle and the best wetting effect, followed by oleic acid; among the six lubricants, molybdenum disulfide and hydrogenated castor oil have the highest viscosity, and oleic acid has the lowest; The yield stress of molybdenum sulfide is higher and the oleic acid is the lowest, indicating that under the same magnetic field, the MRFs viscosity of boron nitride and molybdenum disulfide as lubricants is relatively large, and the anti-sedimentation stability is relatively good. Considering comprehensively, the comprehensive performance of the lubricant of molybdenum disulfide is far greater than that of other lubricants and can be used to configure MRFs with better performance, which also provides a new choice for the follow-up research of MRFs.

Acknowledgments

The support of Science and Technology Commission of Shanghai Municipality (Grant No. 19030501100).

ORCID iDs

Su Zhibin @ https://orcid.org/0000-0001-6231-9525
Ji Dongsheng @ https://orcid.org/0000-0002-9160-7283

References

[1] Xiong C 2011 Study on Improvement of Sedimentation Stability of Magnetorheological Fluids. Chongqing University (In Chinese)
[2] Ashour D 1997 Manufacturing and characterization of magnetorheological fluids Smart Materials Technologies Meeting. San Diego, USA: SPIE Proceeding 3030, 17184
[3] Gorodkin S R et al 2000 A method and device for measurement of a sedimentation constant of magnetorheological fluids Rev. Sci. Instrum. 71 2476
[4] Ngatu G T and Wereley N M 2007 Viscometric and sedimentation characterization of bidisperse magnetorheological fluids IEEE Trans. Magn. 43 2472476
[5] Hu Lin et al 2001 Modification of the subsidence stability in magnetorheological fluids and influence of profiles on rheological Journal of Guiyang University ( Natural Science) 18 176–81 (In Chinese)
[6] Chen W, Du C and Wan F 2010 Effect of surfactant and thixotropic agent on the sedimentation stability of magnetorheological fluid Journal of Magnetic Materials and Devices 41 55–7 65 (In Chinese)
[7] Xiong C, Peng X and Yi C 2011 Experimental investigation to effects of oleic acid and lauric acid on stabilization of magnetorheological fluids Functional Materials 42 1504 (In Chinese)
[8] Zhang M et al 2017 Analysis of magnetorheological fluid settling stability influence factors Metallic Functional Materials 24 29–32
[9] Zeng T 2007 Discusses ((the mathematicai analysis)) shallowly a stoke formula Science & Technology Information 35 122–3 (In Chinese)
[10] Wang Y, Li Z and Li B 2005 Experimental study on the alteration of rock surface wettability by biological enzymes *Petroleum Geology and Recovery Efficiency* **12** 71–2 (In Chinese)

[11] Wang H and He M 2009 Uncertainty evaluation of contact angle measurement of reference materials using drop shape analysis method *Measurement and Testing Technology* **36** 72–5 (In Chinese)

[12] Ding X, Chen P and Guan R 2008 Application of contact angle measurement technology *Chinese Journal of Analysis Laboratory* **27** 72–5 (In Chinese)

[13] Tian Z and Hou Y 2012 The Yield Stress Model of magnetorheological fluids *Journal of China University of Mining & Technology* **41** 299–309 (In Chinese)

[14] Pan S et al 1997 Yield stress and temperature effect of Magneto-rheological fluids *Journal of Functional Materials* **28** 264–7 (In Chinese)