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Study of sedimentation stability of magnetorheological fluid

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Abstract: Magnetorheological fluid settlement issue has been one of the major issues that affect the performance of the magnetorheological fluid, it was focused by major enterprise and research institutions as new intelligent materials. This paper describes the settlement issue and analyses the reasons that causing settling of MRF at zero field strength. It comments the ways to improve the stability of magnetorheological fluid sedimentation problems, and makes a comprehensive introduction of the improvement measures. for instance: adding a surfactant and stabilizer, the organic polymer is wrapped in the surface of the magnetic particles, the soft magnetic particles are coated in non-metallic surface, the magnetic particle surface coated with a layer of metal powder, using improved version of the preparation process, adjusting ball feed ratio and milling time appropriately, adding in nanomaterials, etc.

Keywords: Magnetorheological Fluid, Settlement, Stability

1. Introduction

MRF (Magnetorheological Fluids) is a kind smart materials that is mainly composed of magnetic particles, carrier fluid and additives. MRF own it's unique controllable magnetic properties, it expresses as a Newtonian fluid state in absence of external magnetic field situation. When the external magnetic field is applied, the MRF turns to the solid-state immediately, the degree of conversion varies with the changing of the strength of magnetic field. It will become a Newtonian fluid in millisecond, once the external magnetic field is removed. MRF has been a focus of research and associated engineering aerospace engineering and military, because of its unique rheological properties of magnetic[1].

The sedimentation stability problems of MRF has been the focus of attention in practical applications. MRF should be required not only good magnetic rheological properties, but also possess a better stability. The issue of sedimentation stability affects the performance of the MRF, which will affects the development of MRF, to a certain extent, delay the development of industry. There were some professionals making several researches about the factors of stability of the MRF sedimentation and improving relevant research methods at home and abroad. Under the zero-field strength, the magnetic particles will make a relative motion easily, duo to great different density between the magnetic particles and carrier fluid. Magnetic particles makes a settlement under the action of gravity field. The molecules of carrier fluid will make a strike to magnetic particles in the role of Brownian motion, which may cause a certain degree of influence on the settlement. And the force between the magnetic particles will also influence the settlement of MRF. Currently, there are some measures to improve the sedimentation stability of MRF at home and abroad. Here are several measures: adding some additives, improving the preparation process and parameters, pulling in some nanomaterials, adding some oxidant, etc.

2. Analyzing the Settlement of MRF in a Zero-Field Intensity

2.1. The Influence of Gravity

Magnetorheological fluid exhibits low viscosity Newtonian fluid properties under zero-field conditions. The magnetic particles and carrier fluid will occur relative motion that will result in a great settlement under the Earth's gravitational field, due to the great difference of density which already achieves 7~8g/cm3 between the carrier fluid and the magnetic particles[2]. It assumed that the shape of magnetic particles are spherical, without considering the collisions between particles in the process of settlement. Thus magnetic particle in the fluid is mainly affected by the gravity, buoyancy and resistance movement which causes by fluid

$$G=\frac{4}{3}\pi\left(\frac{d}{2}\right)^3 g\rho=\frac{\pi}{6}\rho g d^3 \quad (1)$$

$$F=\frac{4}{3}\pi\left(\frac{d}{2}\right)^3 g\rho_0=\frac{\pi}{6}\rho_0 g d^3 \quad (2)$$

where,

G	the gravity of the magnetic particle, N;
F	the buoyancy of the magnetic particle, N;
f	the resistance movement of fluid, N;
ρ	the density of the magnetic particle, kg/m^3;
d	the diameter of magnetic particle, m;
ρ_0	the density of carrier fluid, $\mathrm{Kg/m^3}$;
g	the acceleration of gravity, m/s^2;

The magnetic particles are affected by the a viscous drag of carrier fluid, and it will change with the relative velocity between fluid and magnetic particles. It could be calculated as the way to calculate the flow resistance of fluid[3].

$$f=\varepsilon A\frac{\rho_0 u^2}{2} \quad (3)$$

where,

A ---the surface area of the ball, m^2;

u ---the sedimentation rate of granule, m/s;

ε ---the damping factor of fluid, $N/m\cdot s$;

In the carrier fluid, at the beginning the magnetic particles accelerated decline and then make a uniform motion. Where the u_t is the sedimentation rate while magnetic particles making a uniform motion. The force of the magnetic particles are canceled each other when magnetic particles makes a uniform motion.

$$\frac{\pi}{6}\rho_0 d^3+\varepsilon A\frac{\rho_0 u_t^2}{2}-\frac{\pi}{6}\rho g d^3=0 \quad (4)$$

$$u_t=\sqrt{\frac{4gd(\rho-\rho_0)}{3\varepsilon\rho_0}} \quad (5)$$

It is concluded by Actor Analysis Method

$$\mathrm{Re}_t=\frac{du_t\rho}{3\rho\varepsilon} \quad (6)$$

Where, ε ---the function of Re_t (Reynolds number) ε can be expressed at the range of Stokes Law ($10^{-4}<\mathrm{Re}_t<1$)

$$\varepsilon=\frac{24}{\mathrm{Re}_t} \quad (7)$$

$$u_t=\frac{d^2(\rho_s-\rho_0)}{18\mu} \quad (8)$$

u_t is simplified by equation (5),(6),(7)

2.2. The influence of Orientation Force and Brownian Motion

Intermolecular forces can be divided into three styles: dispersion force, induction force, and orientation force. The mainly force between the magnetic particles is orientation force in carrier fluid. The magnetic particles and the carrier liquid are made to be double layer particles, due to particles are dispersed in a carrier liquid sufficiently. The spacing between the particles plays a role in the force which is produced between the particles. The attractive fore greater than repulsion, due to the distance of opposite electrode is father than the same electrode. Then two particles will attract each other because of the affection of attractive force. The attractive fore and repulsion will achieve a kind of balance while the distance of two particles is closed to a certain extent.

Brownian motion of particles is related to the size of particles and the temperature. The smaller the particle is, the more obvious the Brownian motion will be. The higher the temperature is, the more obvious the Brownian motion will be. Though the Brownian motion between carrier fluid molecules is obvious. It is not obvious that molecular motion of the carrier fluid impacts particles, due to the size of magnetic particle is micron level that is great different with magnetic particles'. Meanwhile, the Brownian motion of magnetic particles is not obvious due to the great size of magnetic particles. Thus, it has little influences in settlement of magnetic particles that caused by Brownian motion at the zero-field intensity and room temperature.

There are several factors impacting the settlement of MRF that mentioned above. It is expressed as formula (8) that the rate of the settlement is inversely proportional to the viscosity of the carrier fluid and differences between the density of magnetic particles and carrier fluid, and it is proportional to the radius of the magnetic particles. Therefore, here are several factors that affect the settlement:

1 The zero field viscosity of MRF. The more greater Zero-field viscosity of MRF is, the more slowly it settles. So stability of MRF is better. The zero-field viscosity of MRF is too much to affect the rheological properties of MRF, though the excellent MRF should possess not only the good stability but also great rheological properties [5];

2 Interaction of particles with the carrier fluid. It can make the surface of the magnetic particles coated with the active substance by ball milling method. So the particles with adsorption layer hold the same polarity. It will produce a kind of repulsive force which may

Prevent the particles sinking rapidly when the magnetic particles close to each other;

3 The volume fraction of particles. MRF is belong to the suspension system. Increasing the volume fraction of the particles in the suspension system, on the one hand, it can increase the viscosity of the system that will enlarge the settlement resistance of magnetic particles, on the other hand it Intensifies interactions between particles. So it may decrease the settlement of MRF[6];

4 The size of the particles and viscosity of carrier fluid. It can be reflected from Stokes settlement formula that the settling rate of particles is proportional to the square of the diameter of the particles, inversely proportional to he viscosity of the carrier fluid. So it can be appropriate to reduce the size of particles, increase the viscosity of carrier fluid. But it will enlarge the Brownian motion if the size of magnetic is too small, meanwhile the rheological properties of MRF will be reduced.

3. Methods to Improve the Sedimentation Stability

3.1. Adding Additives

At present, people always uses surfactant and thixotropic agent as additives to improve the stability of MRF. Surfactant is a kind of oligomer which holds amphiphilic. Its molecular structure is composed of two parts in which one end is Lipophilic group of non-polar oleophilic and another end is hydrophilic group of polarity and hydrophilic. Carbonyl iron powder is used to be as a discrete phase of MRF. Due to carbonyl iron powder is hydrophilic substances. MRF will occur coagulation and agglomeration phenomenon, while the carbonyl iron powder disperses in a hydrophobic carrier fluid(for instance: silicone oil). One end of surfactant molecules is hydrophilic group which will be adsorbed on the surface of the carbonyl iron powder and the other end is Lipophilic group which will be spread to carrier fluid, while surfactant has been sufficiently contacted with a carbonyl iron powder. The way to reducing inter-particle agglomeration due to collide each other is making surfactant wrapped in carbonyl iron surface which not only increases the volume of the carbonyl iron powder, and increases the repulsive force between the particles. At the same time, it will form an interaction three dimensional skeleton inside the carrier fluid, which will reduce the particles sedimentation that caused by the density difference between magnetic particles and carrier fluid[8]. There is a great difference between the density of magnetic particles and carrier fluid which reaches to 7~8g/cm3. The greater difference of density, the greater sedimentation rate will be that can be reflected in equation(8). According to the structure of the surfactant, the surfactant may be classified into ionic type, non-ionic type and special surfactant. And the ionic also can be classified into anion type, cation type and amphoteric surfactant. Here are some surfactants which are used to improve the sedimentation stability of MRF: sodium dodecyl benzene sulfonate, polyethylene glycol, oleic acid, carboxylic acid organic salt, alkylamine phosphate ester, OP emulsifier, trionlein, CH-1D hyper-dispersant, silane coupling agent, etc [9-11]. Jin Baoyan [12] had prepared three MRF samples, number one without surfactant in, number two was used oleic acid as surfactant and number three was used CH-1D hyper-dispersant as surfactant. He analyzed the settlement and rheology properties of three samples.

It can been seen clearly from Fig.1 and Fig.2 that the sedimentation stability and mechanical properties of number one sample were both worst than other samples. And the properties had been improved with adding surfactant. besides, the performance of samples with CH-1Dhyper-dispersant is the greatest than others'.

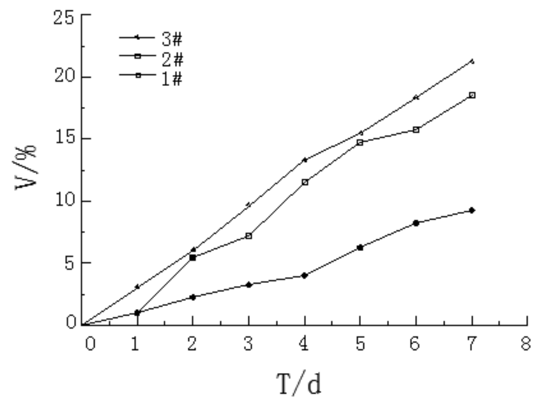

Fig. (1). *Settlement of samples*

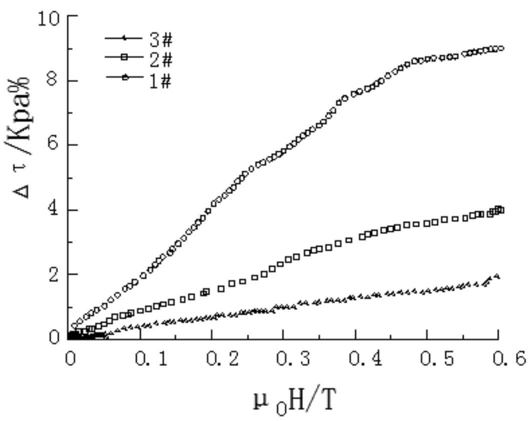

Fig. (2). *Hysteresis shear stress of samples*

When the fluid system was affected by shear force, viscosity of the system will change with variation of shear force. The moment it stop to shear, the viscosity of the system will recover. It could be a three dimensional network structure that may support the particles which were settling caused by gravity, when thixotropic agent was dissolved in the fluid system. Therefore, it may improve the settlement problem of MRF. Here are some thixotropic agent which are used to improve the sedimentation stability of MRF: nano-silica, organobentonite, diatomite, etc. They are used to be thixotropic agent because of their relatively stable chemical properties and small harm[9-11].

3.2. Improving Magnetic Particles

Rheology and settlement stability of MRF which is prepared by different magnetic particles are different. There are some normal magnetic particles, such as Fe3O4, Fe3N, Fe and the mixture of Fe, Co, Ni. Carbonyl iron powder are used to be magnetic particles due to its greater saturation magnetization and cheaper, meanwhile it can be got easily on the market. Here are several measures to improve the the settlement of MRF by improving the magnetic particles: Yao Jinguang [13] has done some researches on polymer-coated magnetic particles which are prepared by Ball milling to make the organic polymer wrapped in the surface of the magnetic particles. It will Strengthen the dispersed phase and the continuous phase combination; Soft magnetic particles are wrapped in the surface of the nonmetallic material, which may reduce the density of the particles to slow down the sedimentation. Iron oxide is used to be as shell to prepare an ideal spherical particle[14]; It may improve the settlement of MRF with the measure of electroless plating to make a layer of nickel powder coated in the surface of carbonyl iron powder[15]; It may get the great performance of MRF with low viscosity in the initial zero-field and small density of particles by the way to adjusting the thickness of the coated which is according to the ratio of reaction time and bath lotion. And the effective density of particles can be reduced to 2~3g/cm3. It will be reverted by shaking slightly, while it appears phenomenon like delamination. sedimentation stability will be greatly improved due to the less difference of the density between the magnetic particles and carrier fluid. But the rheological property of MRF will be worse; It also can improve the stability of MRF by mixing different sizes of magnetic particles. American Lord Corporation was one of the earlier companies that had done some study on preparing MRF and the property of MRF. In addition, Carlson and Weiss had reported the way to prepared MRF with six alloys[16].

3.3. Improving the Process and Parameters of Preparation

Both of process and parameters of preparing MRF are playing an important role in sedimentation stability of MRF. It is necessary to find out a better process and parameters for different materials, which may improve the property of MRF. Kong Yanan who had done a study of improving the process of preparation. He added a high-speed milling process at the based of traditional process. It can significantly improve the sedimentation stability of MRF, even though the new process is more complex than traditional. It made additives and magnetic particles in sufficient contact with each other with high-speed milling process, volume fraction of the magnetic particles will be decreased and the difference of density between carrier fluid and magnetic particles, that may improve the settlement issue of MRF.

Both of ball-to-powder weight ratio and milling time have an influence on the stability of MRF, If the MRF is prepared using high-speed milling method. Yao Jinguang[18]had done several researches on the effects of sedimentation of MRF with different period. The results show that the viscosity of MRF under the zero-field is increased first, then decreased and the sedimentation rate of MRF is increased first, then decreased with the enlarging of milling time. Besides, the milling time is not the longer the better, it will not only wear out the polymer additives coated in the surface of magnetic particles, but also affect the shape of magnetic particles due to the longer milling time, that will affect the properties of MRF seriously.

Sedimentation stability problems of MRF can be improved with changing the ball-to-powder weight ratio in the same prepared material and the process conditions. Some related researches[19] show that the viscosity of MRF under the zero-field is decreased first, then increased. Besides, the viscosity under the zero-field will be the least, while the ball-to-powder weight ratio achieves to 3:9. On the contrary. On the contrary the sedimentation rate of MRF is increased first, then decreased.

3.4. Adding Nanomaterials

Sedimentation stability of MRF may be improved by adding nanoscale materials which can enhance the viscosity of MRF. In addition, nanoscale materials can't sink due to the Brownian motion may overcome the settlement caused by gravity. Besides nanoscale materials could be fixed to a kind of spatial which formed by the minimum of second energy around the coarse particles caused by the long-range molecules interaction[20]. It is beneficial to improving the settlement stability of MRF with adding Nanoscale silica particles, nano-silica, styrene, etc. to MRF[21]. Hou Peng had done several researches which show that rheological property and settlement stability of MRF will be improved significantly with adding a small amount of iron-cobalt alloy powder[22].

3.5. Adding Oxide

The stability of MRF could be improved by adding oxide, in addition, and it is proportional to the number of oxide[21]. But the number of oxide are too many to affect the property of MRF, due to the saturated magnetic intensity of oxide which will form magnetic saturate is much less. Thus, appropriate amount of oxide can improve the property of MRF.

4. Conclusion

1 This paper analyzes the main force of the magnetic particles under zero-field intensity, studies main factors of settlement of MRF, such as the size of magnetic particles, the difference of density between magnetic particles and carrier fluid, the viscosity of the carrier fluid, etc.

2 Currently, there are some measures to improve the sedimentation stability of MRF at home and abroad. Here are several measures: adding appropriate additives and surfactant, adding magnetic particles coated with

organic polymer, improving the preparation process and parameters, adding composite magnetic particles, pulling in some nanomaterials, adding some oxidant, etc.

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