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Numerical Simulation of Magnetorheological Liquid Sedimentation Character

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In this paper, numerical simulation is used to simulate the sedimentation process of magnetorheological fluid (MRF), and the sedimentation time of MR fluid is predicted by this method. Firstly, based on the existing literature simulation method and its improvement, a numerical simulation method is proposed to simulate the MR fluid sedimentation process. Finally, a variety of MR fluid samples are prepared to detect the accuracy of the simulation results of the constructed numerical simulation method. It can be proved by comparing the measured sedimentation time with the simulated sedimentation time, and the method constructed in this paper can predict the sedimentation time of the more complicated MR fluid well, which has good practicability.

Keywords : magnetorheological fluid, sedimentation time, numerical simulation, experimental measurements

1. Introduction

A new intelligent material composed of magnetic particles, base liquid and additives is being widely studied and applied. The intelligent material is magnetorheological fluid. When an external magnetic field is applied, the magnetorheological fluid changes from liquid to solid-like; when the external magnetic field is removed, the magnetorheological fluid changes from solid to liquid. The transition time between two phases is millisecond.

With the further study of MR fluid, it is found that its sedimentation problem is inevitable. Therefore, the improvement of MR fluid preparation method is focused on prolonging the sedimentation time of MR fluid without affecting the shear yield strength of MR fluid. Numerical simulation is a new method to study magnetorheological fluids. This method simulates the motion of magnetic particles in a base liquid by analyzing the force or energy it receives when moving in the base liquid. Liu [1] from the point of view of energy, the chain forming process of magnetorheological fluid in magnetic field is simulated by Monte Carlo method. Considering that the magnetorheological fluid is subjected to magnetic force, viscous resistance and repulsive force, Ly [2] and so on, according to Newton's second law, the chain forming process of magnetorheological fluid is formation process of magnetorheological fluid. Li [3] the kinetic model of magnetic particles was established and the chain formation process of magnetic particles was simulated. Han [4] proposed a computational framework for the numerical study of magnetorheological fluids and proposed a two-stage modeling and simulation strategy to achieve reasonable accuracy and computational efficiency. Many researchers in China have also studied the numerical simulation method of magnetorheological fluids. Melle [5] *et al*. carried out two-dimensional numerical simulation of MR fluid chaining process and shear process by analyzing the force of solid particles in MR fluid and using the velocity Verlet algorithm in molecular dynamics studied the main factors affecting chaining and shearing. Sheng Fang [6] and so on through the numerical simulation of the motion of a certain number of particles in the magnetorheological fluid under the action of rotating magnetic field. Gorodkin [7] designed a centrifugal magnetorheological fluid sedimentation stability measuring device. The device is also based on the capacitive characteristics of MR fluids. Although centrifugal method can accelerate the sedimentation rate of MR fluid, the error of the results measured by this method is very large due to the large change of the velocity in the centrifugal process.

In this paper, numerical simulation is used to measure the sedimentation time of MR fluid, avoiding the complexity of manual operation and the long time period. In addition, an inductance type sedimentation measuring device is designed, and the experimental data are com-

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pared with the numerical simulation data to ensure the accuracy of the numerical simulation method.

2. Construction of Numerical Simulation Model

2.1. Dynamic Simulation

1) Force Analysis of Magnetic Particles

• Viscous damping force F^v

As the magnetic particles are roughly spherical, the Stokes formula is used to calculate the viscous damping force F^v of the magnetic particles in the base fluid.

$$F^v = 3\pi\eta d\Delta u \tag{1}$$

The formula : η is the kinematic viscosity of the base solution, d is the particle size of the magnetic particles, Δu is the velocity difference between the magnetic particles and the base solution.

• Repulsion between magnetic particles F^r

The magnitude of the repulsive force is equal to the magnitude of the magnetic force between two magnetic particles when the central line of the two magnetic particles is parallel to the direction of the magnetic field and in contact with each other. The formula is

$$F^r = F_0 \exp\left[-\beta\left(\frac{r_{ij}}{2R}-1\right)\right]\vec{r}_{ij} \tag{2}$$

The formula: β is a manually set parameter, as long as it can ensure that most of the magnetic particles do not contact each other during the simulation; r_{ij} is the center distance of the two magnetic particles; R is the radius of the magnetic particles; r_{ij} is the direction vector on the center line between the two magnetic particles; and F_0 refers to the magnetic force on which the center line of the two magnetic particles is parallel to the direction of the magnetic field and in contact with each other.

• Gravity and Buoyancy F^g

Gravity and buoyancy of magnetic particles can be calculated from the following formula. In addition, for convenience, the resultant force of gravity and buoyancy is referred to as gravity

$$F^g = \frac{4}{3}\pi R^3 \Delta\rho g \tag{3}$$

The formula: the R is the radius of the magnetic particle; the $\Delta\rho$ is the density difference between the magnetic particle and the base liquid; and the g is the acceleration of gravity.

• Van der Waals Force F^w

Van der waals force is a short-range force, and the force decreases rapidly with increasing intermolecular spacing. When the molecular spacing increases to three to four times the molecular diameter, the van der waals force decreases to almost negligible. According to the Hamek formula, the van der Waals force of magnetic particles subjected to other magnetic particles is [8]

$$F^w = \frac{A}{6}\frac{64R^6}{r_{ij}^3(r_{ij}^2-4R^2)^2}\vec{r}_{ij} \tag{4}$$

The formula: A is the Kamek constant of the magnetic particles; R is the radius of the magnetic particles; r_{ij} is the center distance between the two magnetic particles; $\vec{r}_{ij}$ is the unit vector in the direction of the center line between the two magnetic particles.

• Brownie F^b

Because the Brownian forces on magnetic particles are not correlated at different times, the Brownian forces can be regarded as Gaussian white noise with zero mean. The formula is

$$F^b = \beta \bullet \sqrt{\frac{12\pi R\mu K_B T}{\Delta t}} \tag{5}$$

The formula: the β is a Gaussian random number; the R is the radius of the magnetic particles; the μ is the dynamic viscosity of the base solution; the K_B is the Boltzmann constant; the T is the thermodynamic temperature; and the Δt is the time interval, where the step time of the simulation program is used instead.

• Magnetic force between magnetic particles F^m

According to the theory of magnetic dipole, it can be deduced that the magnetic force of magnetic particles subjected to magnetic particles around them is

$$F_i^m = \sum_{j\neq i}\left[\frac{3\mu_0}{4\pi r_{ij}^5}\left(\vec{m}_i \bullet \vec{m}_j - 5m_{ir}\bullet m_{jr}\right)\vec{r}_{ij} + \frac{3\mu 0}{4\pi r_{ij}^4}(m_i m_j + m_j m_i)\right] \tag{6}$$

The formula: the μ_0 is the vacuum permeability, the $\vec{r}_{ij}$ represents the vector of the relative position between the two particles, and the m_{ir} and m_{jr} represent the magnetic moment $\vec{m}_i$ and $\vec{m}_j$ the components along the r_{ij} direction.

2.2. Simplification of the Force on Magnetic Particles

Haitao Li [9] and so on are measured by magnetic force. After comparing the size, the numerical simulation of magnetorheological fluid in magnetic field only needs to consider magnetic force, repulsive force and viscous damping force, and the other forces can be ignored. The simulation is the state of natural sedimentation of magnetic particles without magnetic field, so gravity is used

Table 1. Parameters used in calculations.

Name	Numerial number	Unit
permeability χ	1	
permeability of vacuum μ	$4\pi \times 10^{-7}$	(H/m)
Viscosity η	0.01	(Pa·s)
acceleration of gravity g	9.8	(m/s^2)
Density difference between magnetic particles and carrier fluid Δρ	7.8×10^3	(Kg/m^3)

as the criterion to determine whether Brownian and van der Waals forces can be ignored. The calculation parameters used in the comparison process are shown in Table 1.

1) Comparison of Brownian Force and Gravity

According to force analysis, the ratio of gravity to Brownian force is *P*,

$$P = \frac{F^g}{F^b} = \frac{4}{3}\frac{\pi R^3 \Delta\rho g}{\beta\sqrt{\frac{12\pi R\mu K_B T}{\Delta t}}} \tag{7}$$

Since the formula of Brownian force contains Gaussian random number β, it is impossible to calculate the ratio *P*, directly. Taking into account that the β satisfies the standard normal distribution, this paper first calculates the variation of the ratio *P* with the Gaussian random number, and then looks up the table to obtain the probability of the occurrence of the β satisfying the situation.

In Fig. 1, when gravity is equal to the Brownian force β = 0.1317. because of the gaussian random number at β, the standard normal distribution is satisfied.

$\beta(|\beta < 0.14|) = 0.113$ can be obtained by looking up the table. This means that the probability of Brownian force is only 11.3 % less than gravity, while 88.7 % may be greater than gravity. Therefore, the Brownian force should be taken into account in the numerical simulation of magnetorheological fluid sedimentation.

2) Comparison of van der Waals Force and Gravity

Considering that the central line of two magnetic particles is parallel to the gravity direction, and assumption $r_{ij} = \lambda R \quad (2 < \lambda < 3)$. The van der Waals force F^w can be expressed as:

$$F^w = \frac{A}{3}\frac{32}{\lambda^5 - 4\lambda^3}\frac{1}{R} \tag{8}$$

Draw the variation of van der Waals force and gravity with λ, as shown in Fig. 2.

From Fig. 2, we can see that the ratio of gravity to van der Waals force decreases rapidly with the increase of the distance between two grains, and at $r_{ij} = 2.1R$, the gravity is about 302.8 times that of van der Waals force. Therefore, the van der Waals force of magnetic particles can need not be considered in the simulation of the deposition of MR fluid.

2.3. Formula for calculating repulsive force based on Hertzian contact theory

Because the repulsive force of the magnetic particles comes from the elastic deformation caused by the contact between the two magnetic particles, the two particles are in the state of point contact. If the distance between two magnetic particles is r_{ij}, the repulsive force between two magnetic particles is calculated by Hertz contact theory.

Hertz contact theory was proposed by Hertz in 1882

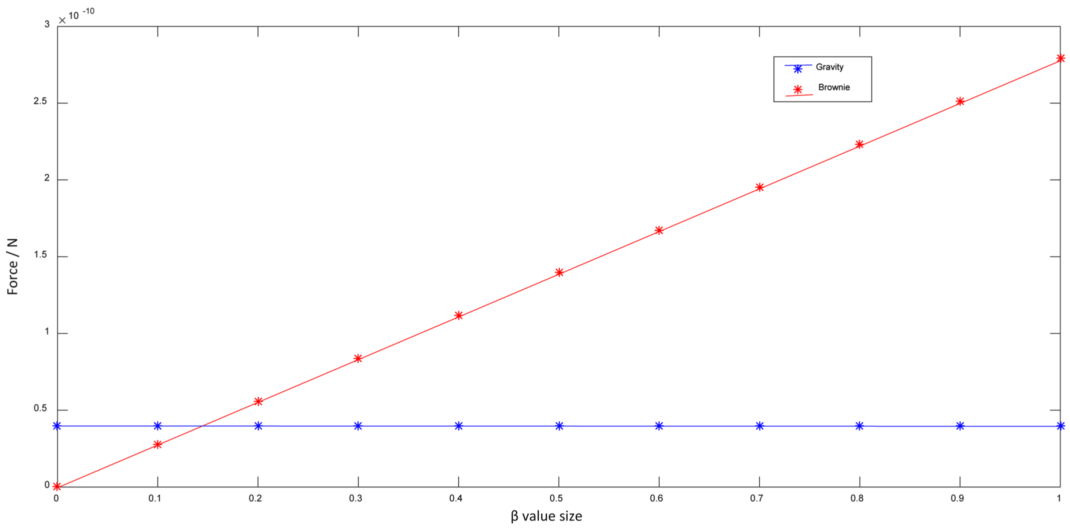

Fig. 1. (Color online) Shows the variation trend of Brownian force as the Gaussian random number β increases.

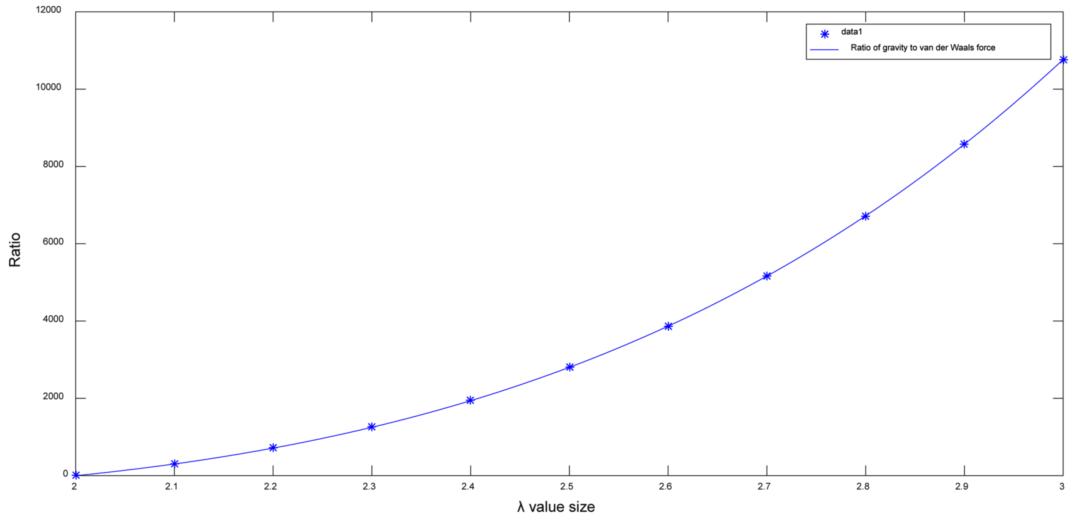

Fig. 2. (Color online) Trend of the ratio of gravity to van der Waals force with λ value.

[10]. This theory is often used to solve the contact problem of tiny elastic deformation on tiny elastic plane. reference [11] uses this theory to solve the compressive stress distribution between two contact smooth spheres.

The relationship between repulsive force and center distance between two magnetic particles can be obtained.

$$F = \sqrt{\frac{32}{9} R(2R - r_{ij})3 \frac{E}{1 - v^2}} \tag{9}$$

The formula: the R is the radius of the magnetic particles; the r_{ij} is the center distance of the two magnetic particles; the E is the elastic modulus of the magnetic particles; and the v is the Poisson's ratio of the magnetic particles.

2.4. Connection between simulation results and experimental results

Since the numerical simulation of a magnetorheological fluid requires the calculation of each magnetic particle, no matter which method is involved in the simulation, the number of magnetic particles is not large, which limits the simulation of the numerical simulation. Generally speaking, the length of the simulation area selected for numerical simulation is usually several hundred microns. But the container in the actual situation is much larger than a few hundred microns, so it is necessary to link the simulation results with the actual sedimentation results.

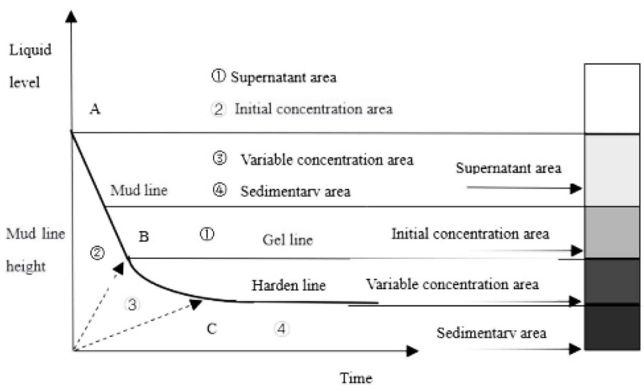

Fig. 3. Sedimentation Process of Suspension.

The curves in Fig. 3 are typical sedimentation curves. When the liquid begins to settle, the mud line begins to drop at a uniform speed because the particles begin to sink. due to the increase in the number of particles in the lower layer, the gel line and the plate junction line began to rise. until the mud line coincides with the gel line, the initial concentration region disappears, and then the mud line continues to decrease and the plate junction line continues to rise. The variable concentration region gradually decreases and the plate junction region gradually increases. In this section, the decreasing rate of the mud line is decreasing because of the increasing particle concentration in the variable concentration region. when the plate junction line coincides with the mud line, the variable concentration region disappears. At this time, there are only two regions in the sedimentation system: the upper clear liquid area and the plate junction area. so that the sedimentation process ends.

According to the above sedimentation theory, the sedimentation velocity of the sedimentation system is only related to the concentration of the particles. So, when the width of the simulated area does not affect the sedimentation process of MR fluid, the average sedimentation velocity obtained by numerical simulation should v_m be equal to the average sedimentation velocity

v_t measured experimentally. That is, the relationship between the numerical simulation results and the experimental results is:

$$v_m = v_t \tag{10}$$

2.5. Simulation Algorithm of Magnetic Particles

2.5.1. Input parameters for numerical simulation program

1) Particle size of magnetic particles

Since the magnetorheological fluid configured in this paper is oleic acid coated, the magnetic particles in this magnetorheological fluid are a spherical shell structure. The core of the magnetic particles is hydroxyl iron powder, and the outer layer is surfactant coated layer. The particle size of magnetic particles can be calculated by formula (11).

$$d_{particle} = d(t) + 2 * h(c) \tag{11}$$

The formula: $d(t)$ is the particle size of hydroxyl iron powder when the ball milling time is t, and the thickness of oleic acid coating when the oleic acid concentration is c when the reaction is sufficient.

2) Density of magnetic particles

The density of magnetic particles is the density of the whole magnetic particles, and the density of magnetic particles can be obtained from formula (12).

$$\rho_{particle} = \rho_1 + (\rho_1 - \rho_2)\frac{d^3(t)}{(d(t)+2h(c))^3} \tag{12}$$

Formula: ρ_1 is the density of oleic acid, ρ_2 is the density of hydroxyl iron powder.

3) Number of magnetic particles

The mass of the magnetic particles is input to find the number of magnetic particles. Number of magnetic particles N can be obtained from formula (13).

$$N = \frac{2S}{\pi d^2_{particle}} \bullet \frac{\omega\rho_1}{\omega\rho_1 + (1-\omega)\rho_2} \tag{13}$$

The formula: S is the simulated area; $d_{particle}$ is the particle size of magnetic particles; ω is the mass fraction of magnetic particle; ρ_1 is the density of oleic acid; and ρ_2 is the density of hydroxyl iron powder.

4) Base liquid viscosity

The viscosity of the base solution is affected by the viscosity of the base solution itself and the mass fraction of thixotropic agent added to the MR fluid. the specific variation relationship needs to be measured by experiments.

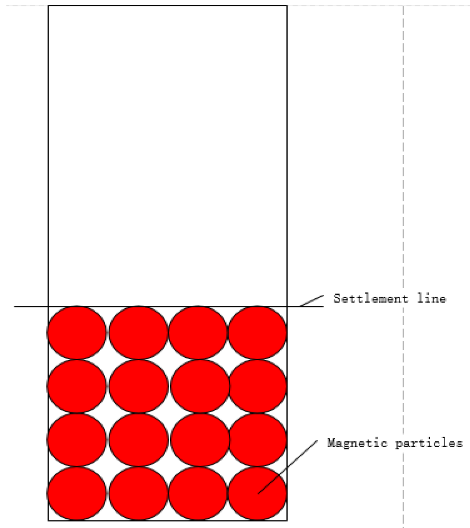

Fig. 4. (Color online) Schematic diagram of the sedimentation line.

2.5.2. End condition of simulation program

As shown in Fig. 4, it is assumed that all magnetic particles accumulate at the bottom of the simulated area in a simple cubic stacking mode, and then draw a line at the position where the magnetic particles in the top layer are located, which is called the mud line. In the numerical simulation, if all the magnetic particles are below the mud line, the magnetorheological fluid sedimentation is considered complete, and the simulation program is terminated.

2.5.3. Boundary conditions

According to the existing sedimentation theory, the sedimentation process of the particles is not affected by the vessel wall only if the width of the container is 100 times the size of the magnetic particle. Then the numerical simulation area should not affect the sedimentation process of magnetic particles. So the periodic boundary conditions used on the left and right sides of the simulated region.

The lower boundary of the numerical simulation area is equivalent to the bottom of the container, so the rebound boundary condition is adopted. In order to prevent magnetic particles from leaving the upper boundary of the simulated region, the upper boundary of the numerical simulation region also adopts the rebound boundary condition.

2.5.4. Motion Simulation Algorithm

According to the force analysis above, the gravity, buoyancy, repulsive force, damping force and Brownian force of magnetic particles should be calculated in the numerical simulation of the sedimentation of MR fluid. So according to Newton's second law:

$$ma = m\frac{d^2r}{dt^2} = \sum F = F^g + F^v + F^b + F^r \tag{14}$$

The velocity of each magnetic particles after a step is calculated according to the acceleration.

$$v(t+\Delta t) = v(t) + 0.5[a(t) + a(t+\Delta t)]\Delta t \tag{15}$$

Then the displacement of each magnetic particles after a step is calculated according to the velocity acceleration.

$$r(t+\Delta t) = r(t) + v(t)\Delta t + 0.5a(t)\Delta t^2 \tag{16}$$

And then the magnetic particles are randomly dispersed in the simulation area, and the verlet-velocity algorithm is used for iteration. The position of the magnetic particles is updated after calculating the displacement of the playing magnetic particles at each step until all the magnetic particles settle below the mud line.

In order to speed up the running time of the program, this paper adopts the method of variable step size. the step size of the program is determined by the average distance between magnetic particles and the initial distance.

$$dT = dt * k \tag{17}$$

The dt is the initial step size and the k is the ratio of the average distance between magnetic particles to the particle size

The number of particles above the dividing line is calculated after each iteration. if the number of particles is zero, the simulation process ends. The result of the simulation program is the average velocity of magnetorheological fluid deposition.

$$v = \frac{n * dt}{h_1} \tag{18}$$

The formula: the simulation result v is the average sedimentation velocity of MR fluid; the n is the number of iterations; the dt is the step size; and the h_1 is the height of the upper liquid.

3. Design of Sedimentation Testing Device

3.1. Establish and Design of Inductance Type Sedimentation Detecting Device

Figure 5 is an inductive type sedimentation detection device designed in this paper. The main part of the device is a solenoid equal to the test tube. When in use, the solenoid is wrapped in a test tube filled with magnetorheological fluid, and the inductor sensor is used to measure the inductance change of the solenoid. Inductor sensor uses open source hardware, with real-time measurement and recording functions. The inductance value can be recorded according to the time interval according to the procedure. If the change of inductance value of three consecutive time intervals is less than 0.1 *uH*, the sedimentation process of MR fluid is considered to be over and the time *T*. is recorded. The average sedimentation velocity of the sample measured was $v = H/T$ H, the height of the supernatant was measured with a ruler.

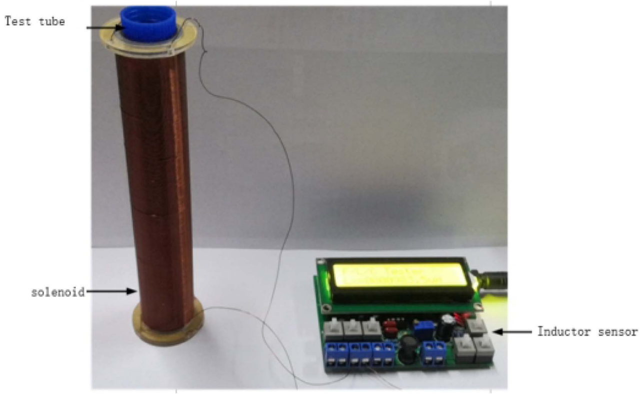

Fig. 5. (Color online) Inductive type device for measuring sedimentation time of magnetorheological fluid.

3.2. Design principles

In the case of other conditions unchanged, the inductance value of the solenoid is related to the core in the solenoid. The permeability of the magnetic core changes continuously during the process of MR fluid sedimentation. If the magnetorheological fluid is divided into two parts according to the mud line and the coil inductance above the mud line is L_1, the inductance below the mud line is L_2. Since two coils are actually one coil, the L_1 and L_2 are in series relationship. Then according to the calculation formula of solenoid inductance can be obtained.

$$L = L_1 + L_2 = \frac{kS}{d^2}[\mu_2 l - (\mu_2 - \mu_1)l_1] \tag{19}$$

The L is the total inductance of the coil, the k is the long Gang coefficient, the S is the cross section area of the coil, the μ_1 is the permeability of the upper liquid, the diameter of the cross section of the copper wire, μ_2 is the permeability of the magnetorheological fluid under the mud line, l_1 is the height of the upper liquid, l the total height of the liquid.

As the magnetorheological fluid settles, the height of the upper supernatant increases and the l_1 rises. At the same time, as more magnetic particles enter below the mud line, the permeability of the magnetorheological fluid μ_2 rise below the mud line. Under such circumstances, it is difficult to determine the change trend of the L according to the height change of the l_1. Since the permeability of the MR fluid is μ_2 greater than that of the upper liquid, if the μ_2 is considered to be far greater than μ_1.

$$L = L_1 + L_2 = \frac{kS}{d^2}[\mu_2(l - l_1)] \tag{20}$$

The permeability of MR fluid is obviously related to the volume fraction of magnetic particles in MR fluid. Because the total number of magnetic particles in the sample under sedimentation is constant. The change of volume fraction is equal to the change of the height of the magnetorheological fluid under the mud line. Then the inductance value of the solenoid can be obtained with the change trend of the height of the upper liquid.

$$L = \frac{kS\mu_0}{d^2}(l - l_1)^2 \tag{21}$$

Formula: μ_0 the permeability of the magnetorheological fluid at the beginning of sedimentation.

3.3. Experimental measurements

This section uses a simple magnetorheological fluid to detect the designed inductive magnetorheological fluid sedimentation. firstly, 5 μm hydroxy iron powder and the silicone oil nominal to 50 cs were poured into the beaker according to the mass ratio of 6:4. And then stirred with a mixer for 20 min, to disperse the magnetic particles in the magnetorheological fluid evenly. The magnetorheological fluid was dripped into the test tube using a rubber dropper after preparing the simple magnetorheological fluid used in the experiment (Haimen Xingrui Experimental Equipment Factory, caliber 20 mm, height 153 mm). The solenoid is then sheathed on a test tube filled with magnetorheological fluid, and the inductance value of the solenoid is detected using an inductor sensor, which is recorded every two hours.

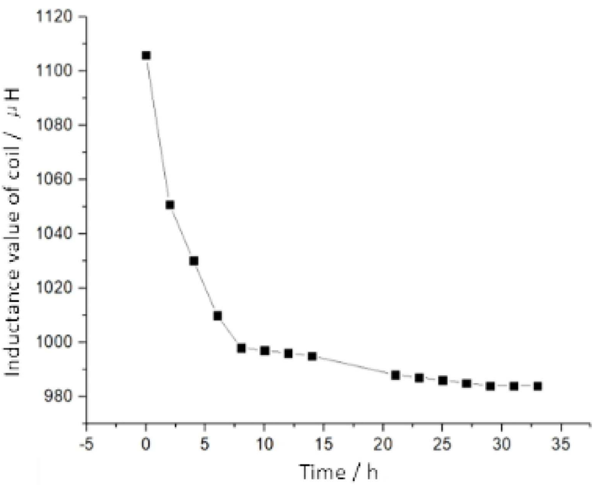

Fig. 6. Relation of inductance with time when using inductive magnetorheological fluid sedimentation time measuring device.

Figure 6 shows the measured inductance value versus time curve. The change trend of the curve accords with the sedimentation process of MR fluid. The inductance measured by the inductive sedimentation detection device is large, which can better observe the sedimentation process.

4. Accuracy Test of Numerical Simulation Method

4.1. Accuracy Test for Simulating Simple MR Fluid

In this paper, a simple magnetorheological fluid is used to verify the accuracy of the proposed numerical simulation. The simple magnetorheological fluid is composed only of base liquid and magnetic particles, the structure is simple, and the influence of each part is clear. for simple magnetorheological fluids, there are three factors that affect the sedimentation process of magnetorheological fluids: the particle size of magnetic particles, the mass fraction of magnetic particles and the viscosity of the base solution.

4.1.1. Sample preparation

In this paper, hydroxy iron powder is used as magnetic particle, and silicone oil is used as the base liquid of MR fluid. The configuration of simple MR fluid sample only needs to put hydroxy iron powder and silicone oil into beaker according to certain mass ratio, then stir well with mixer.

Table 2. Proportion of simple MR fluids.

Sample No.	Silica oil viscosity	Particle size of hydroxyl iron powder	Quality score
1	76 mPa.s	3	80 %
2	76 mPa.s	5	80 %
3	76 mPa.s	7	80 %
4	76 mPa.s	10	80 %
5	76 mPa.s	5	10 %
6	76 mPa.s	5	40 %
7	76 mPa.s	5	60 %
8	1.12 mPa.s (Alcohol)	5	80 %
9	354 mPa.s	5	80 %
10	973 mPa.s	5	80 %

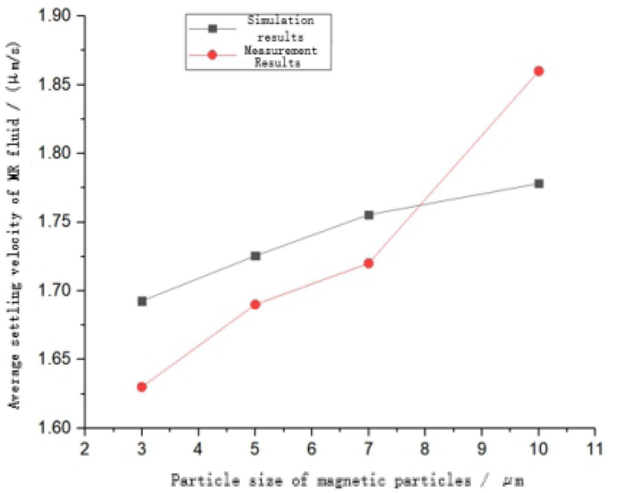

Fig. 7. (Color online) Comparison of simulation results with experimental results.

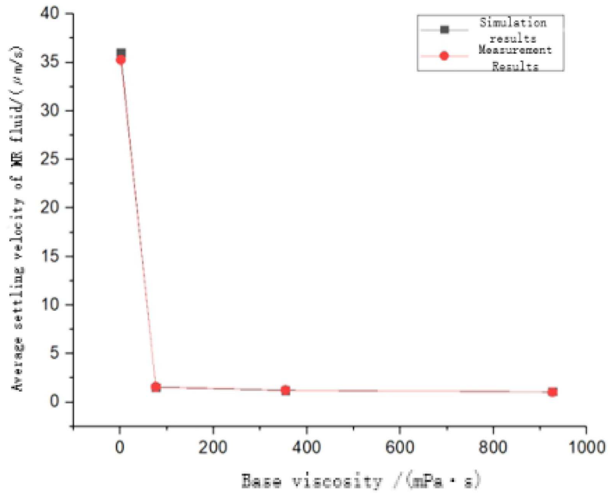

Fig. 9. (Color online) Comparison of experimental results and simulation results with different viscosity of base solution.

4.1.2. Comparison of experimental and simulated results

1) Comparison of results with different particle sizes

Figure 7 shows the comparison of the average sedimentation velocity measured and the simulated sedimentation velocity with different particle sizes. The samples selected in the experiment are samples 1, 2, 3, 4 in Table 2. It can be seen from Fig. 7 that different particle size will change the average sedimentation velocity of MR fluid. The average error between the experimental results and the simulation results in Fig. 7 is 3.10 %, and the maximum error is 4.41 %.

1) Comparison of results with different mass fraction

Figure 8 shows the comparison between the experimental results and the simulation results with different mass fractions. samples 2, 5, 6, 7 in Table 2 were selected in the experiment. From the experimental results alone, the mass fraction has a great influence on the sedimentation velocity of MR fluid, and the sedimentation time of MR fluid increases rapidly with the increase of mass fraction. Compared with the experimental results and simulation results, it can be proved that when the mass fraction of magnetic particles changes, the simulation results are also not different from the experimental results. The average error is 3.92 % and the maximum error is 4.78 %.

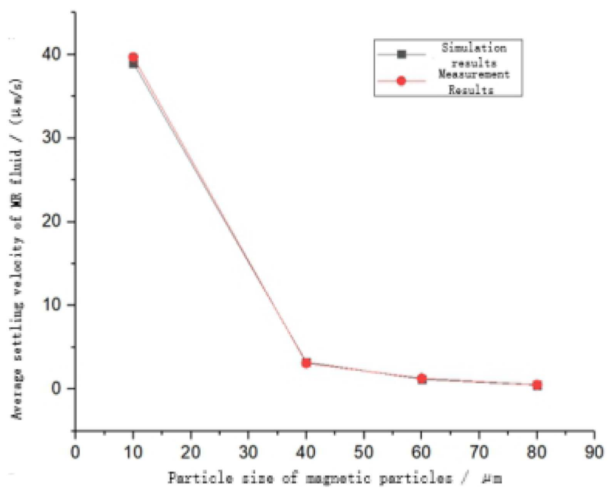

Fig. 8. (Color online) Comparison of experimental and simulated results with different mass fractions.

2) Comparison of results with different viscosity of base liquid

Figure 9 shows the comparison between the experimental results and the simulation results with different mass fractions. Samples 2, 8, 9, 10 in Table 2 were selected in the experiment. From the experimental results alone, the viscosity also has a great influence on the sedimentation velocity of magnetorheological fluid. With the increase of viscosity, the sedimentation time of magnetorheological fluid increases rapidly. The average error is 4.01 % and the maximum error is 6.80 %.

4.2. Accuracy Test for Simulation of Complex Magnetorheological Fluid

4.2.1. Preparation Method of Complex Magnetorheological Fluid

The oleic acid coated magnetorheological fluid preparation method used by jianjian yang [12] is used in this paper. In order to further prolong the sedimentation time of magnetorheological fluid, in this paper, we also refer to the research results of qiuyue guo [13] and others to add nano-silica as thixotropic agent to the magneto-rheological fluid. The preparation of MR fluids is as follows:

1) Put the magnetic particles, alcohol and grinding ball into the ball grinding tank according to the 1:1:1 mass ratio. The addition of a certain amount of grinding balls in the ball mill tank is divided into five mm, 7 mm and 10 mm, and the mass ratio is 6:3:1. The proportion of grinding ball is determined according to the instructions of ball mill.

2) The ball grinding tank is placed in the ball mill and the ball mill is started so that the surfactant and magnetic particles are fully mixed.

3) After the ball milling is finished, the ball mill tank is put into the vacuum drying box to dry until the alcohol in the ball mill tank is completely evaporated.

4) Pour the magnetic particles in the ball mill tank and silicone oil and thixotropic agent into the beaker in a certain proportion, and use the blender to mix the materials evenly.

4.2.2. Effect of Preparation Process on Numerical Simulation Parameters

Ball milling time, surfactant concentration and thixotropic agent mass fraction will affect the simulation parameters.

1) Particle size test method based on contour recognition

Because the ball milling time and surfactant concentration will affect the particle size of magnetic particles, it is necessary to measure the particle size. At present, the measuring instruments for abrasive materials include optical microscope, American sedimentation tube, scanning photoelectric sedimentation instrument, Kurt (resistance) counter and laser particle size meter [14]. There are two kinds of instruments available in the laboratory: optical microscope and laser particle size meter.

Figure 10 shows a sample of magnetic particles taken using an optical microscope. From the figure, we can see that there are many particles agglomerated together.

In this paper, optical microscope is used to measure the particle size of magnetic particles, and contour recognition technology is used to measure the particle size to avoid the influence of artificial measurement of low efficiency, subjective and other factors.

The specific test steps are as follows:

1) To ensure the accuracy of the results, each sample should take 10 photos in different locations, as shown in Fig. 10.

2) A single magnetic particle is cut out from the photograph using the Photoshop, as shown in Fig. 11.

3) Obtain the profile of each magnetic particle after binarization and multiple expansion corrosion using matlab programming, as shown in Fig. 12.

4) Use the function to find the contour length L and find the equivalent diameter. At the same time, screening was carried out to remove the measurement results of the particle size less than 0.5 μm and larger than the nominal particle size of the raw material.

According to this method, more than 500 particles can

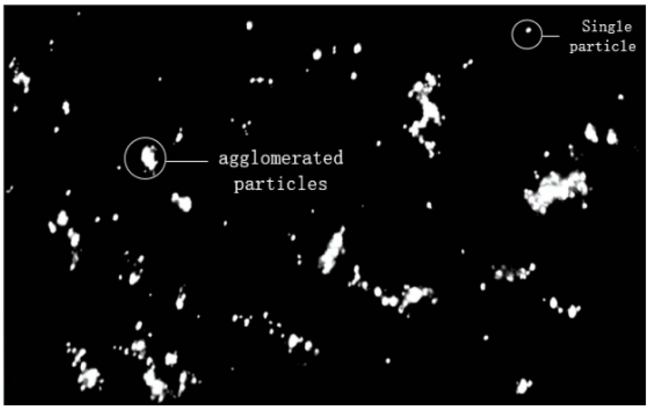

Fig. 10. Comparison of experimental results and simulation results with different viscosity of base solution.

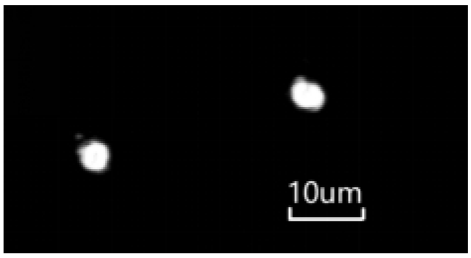

Fig. 11. Use Photoshop split photos.

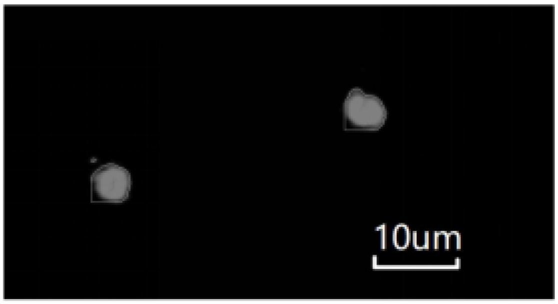

Fig. 12. Profile Recognition Results.

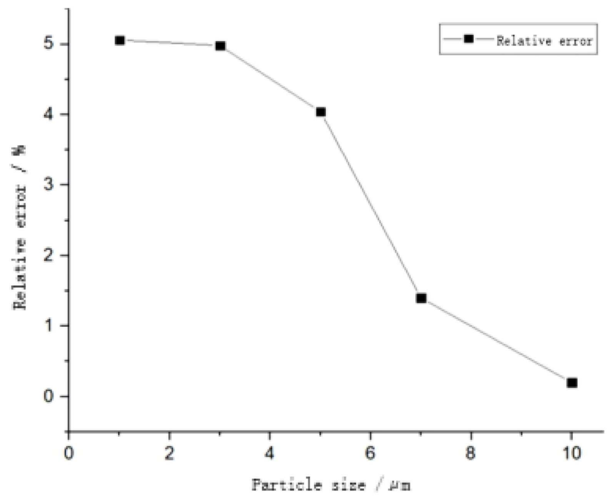

Fig. 13. Relative error in particle size measurement using optical microscopy.

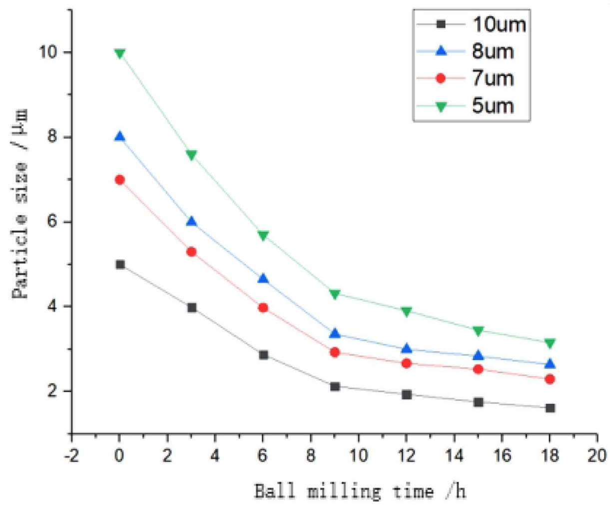

Fig. 14. (Color online) Relationship between magnetic particle size and ball milling time.

be measured at a time, which meets the requirement of measuring more than 300 magnetic particles by using optical microscope for particle size measurement. At the same time, this method uses the program to measure, avoiding the influence of artificial factors on the measurement results. But the accuracy of this method is still in doubt, so this paper uses the above method to measure the hydroxyl iron powder (cnyx shield alloy) with a nominal 3 μm, 5 μm, 7 μm, 10 μm to verify the accuracy of this method. the measurement results are shown in Fig. 13.

In Fig. 13, measuring 1 μm magnetic particles using the above method is the largest error produced, with a relative error of 5.06 %. And the smallest measurement error is 10 μm of magnetic particles, and the relative error is only 0.2 %. This shows that the accuracy of the measurement results can be guaranteed by using the above method.

4.2.3. Effect of ball milling time on magnetic particle size

This subsection uses magnetic particles with particle sizes of 5 μm, 7 μm, 8 μm and 10 μm, and the ball milling time is set to 3*h*, 6*h*, 9*h*, 12*h*, 15*h*, 18*h*. The preparation process is similar to that of simple MR fluid. the particle size measurement is shown in Fig. 14.

It can be seen from Fig. 14 that the particle size of magnetic particles is smaller with the longer milling time. In addition, the particle size decreases with the increase of ball grinding time. the particle size of 3 *h* is 1.01 smaller than that of 0 *h* for 5 μm, while the particle size of 18 *h* is only 0.14 μm. smaller than that of 15 *h*. Compared with four kinds of magnetic particles with different initial particle size, it can be seen that the change trend of magnetic particles size with ball grinding time is basically the same. Figure 15 shows the magnetic particle size as a percentage of the original particle size after ball milling.

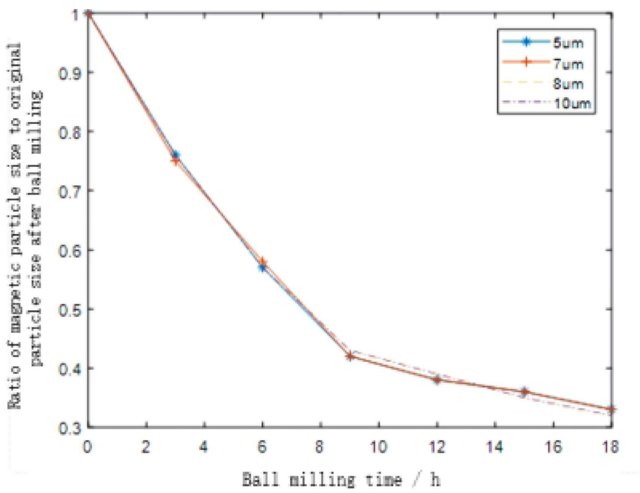

Fig. 15. (Color online) Variation of the ratio of magnetic particle size to original particle size with milling time after ball milling.

It can be seen from Fig. 15 that although the initial particle size is different, the particle size of magnetic particles decreases with the ball grinding time to the same extent. The curves in Fig. 15 are available using the matlab cruel fiting toolbox.

$$f(h) = 0.1h^2 - 0.23h + 0.45 \qquad 0 < h < 18 \tag{24}$$

$f(h)$ is the ratio of the particle size to the original particle size after ball milling. The standard deviation between the fitting function and the measured value is only 0.00209, with high accuracy.

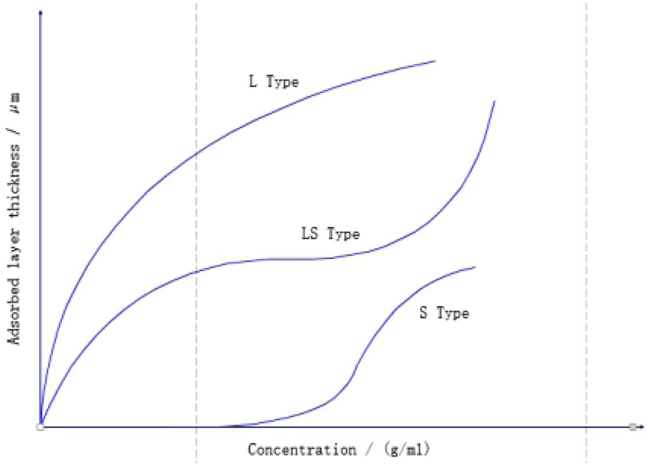

Fig. 16. (Color online) Isotherm adsorption curves of surfactants.

4.2.4. Effect of Surfactant Addition on Magnetic Particle Size

Surfactant is an amphiphilic substance. The molecules of this substance have two groups, hydrophilic group and hydrophobic group. The surfactant in the solution is adsorbed on the surface of the solid due to van der Waals force or chemical change. At a certain temperature, there is a equilibrium relationship between the adsorption amount of surfactant and the concentration of surfactant, and the curve of the reaction is isothermal adsorption curve. Usually, there are three kinds of isothermal adsorption curves of surfactants: L type, LS type and S type, and the schematic diagram is shown in Fig. 16.

1) Experimental Methods

First, 5 μm of hydroxy iron powder, alcohol and grinding ball according to the mass ratio of 1:1 into the grinding tank, and then add a certain amount of oleic acid. And then put the ball mill tank into the ball mill and stir for several (3*h*, 6*h*, 9*h*) hours. Then the ball mill tank is placed in a vacuum drying box until completely dry. Finally, the particle size of magnetic particles was measured using an optical microscope. Assuming that the particle size of hydroxyl iron powder is only related to ball milling time and is not affected by surfactant, the difference between the measured particle size without surfactant and the measured particle size when adding surfactant can be considered as the thickness of surfactant coating.

2) Experimental Results

Figure 17 is the variation curve between the thickness of oleic acid coating and the concentration of oleic acid. From Fig. 17, it can be seen that the change curve shows a gradual upward trend in the thickness of surfactant coating when the surfactant concentration is lower than 0.08 g/ml, and the thickness of surfactant coating is basically no longer increased with the increase of surfactant concentration at higher than 0.08 g/ml. This indicates that the dissolution and adsorption of surfactants have reached equilibrium after the concentration is higher than 0.08 g/ml, and increasing the concentration of surfactants will not make more surfactants adsorbed on the surface of magnetic particles. In addition, it can be found that the difference between the three curves is small and all of them keep the same trend. It can be seen that the ball milling time of 3 hours is enough to make the mixture of oleic acid and hydroxyl iron powder even, and the longer time of ball milling can not increase the coating thickness of surfactant.

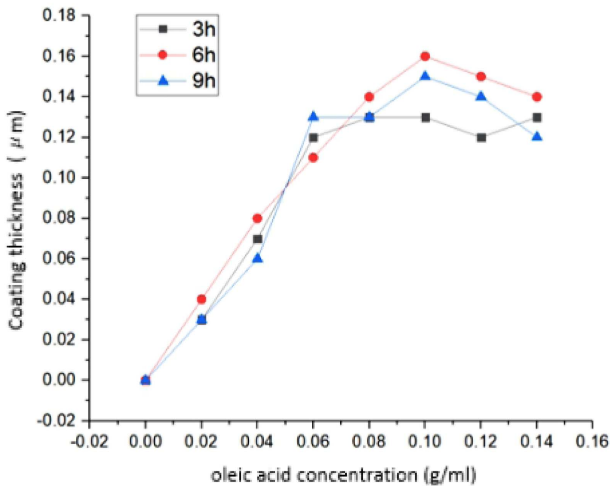

Fig. 17. (Color online) Variation of oleic acid coating thickness with oleic acid concentration.

3) Curve Fitting

From Fig. 17, it can be seen that the isothermal adsorption curve of oleic acid at the solid interface is the same as that of the L type of surfactant. the matlab cruel fiting toolbox was used to fit the variation curve of ball milling time of 3 *h* in Fig. 17 the standard deviation of fitting curve is 0.0108, which has high accuracy.

$$h(c) = \begin{cases} 1.75c & 0 < c < 0.08 \\ 0.13 & c \geq 0.08 \end{cases} \tag{25}$$

The formula: *h* is the thickness of the oleic acid coating on the surface of magnetic particles, and the *c* is the concentration of oleic acid.

4.2.5. Effect of Thixotropic Agent on Viscosity of Base Liquid

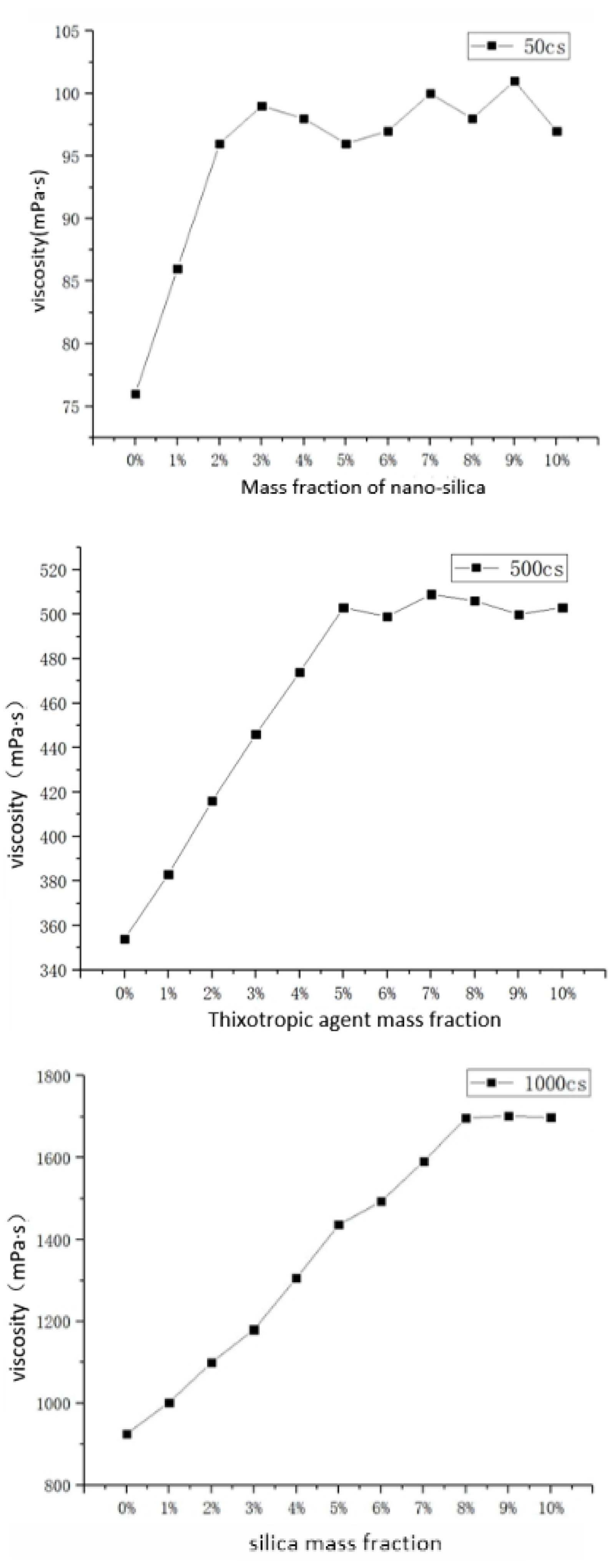

Fig. 18. Effect of viscosity of base solution and mass fraction of nano silica.

This section mainly explores the change curve of the viscosity of the base liquid with nano-silica as thixotropic agent and silicone oil as.

1) Experimental Methods

This paper selects three kinds of silicone oil *cs* (50*cs*, 500*cs* and 1000*cs* brands as Dow Corning). the viscosity of the sample was measured using the second rotor (rotational speed 6 r/min) of the NDJ-5S digital display viscometer.

At first, nano-silica and silicone oil were added into the beaker proportionally. According to the requirements of viscometer, the diameter of the beaker was 80 mm. and then stirred with a stirrer for 10 min to ensure the uniform dispersion of nano-silica in silicone oil. After that, the rotor of the viscometer is inserted into the mixed sample and statically set for 10 min to ensure that the nano-silica has enough time to generate the spatial structure. Final use of viscometer to measure the viscosity of the sample.

2) Experimental results

The measurement results are shown in Fig. 18.

3) Experiment analysis

It can be seen from the measurement results that the viscosity of MR fluid increases first and then becomes stable with the increase of thixotropic nano silica. because the viscosity changes of three different viscosity silicone oil after adding nano silica are different, the three curves are fitted separately using matlab in this paper.

① 50*cs* Silicone oil

$$\eta_{50cs}(\phi)=\begin{cases}10\omega_{si}+76 & 0<\omega_{si}<3\% \\ 96 & \omega_{si}\geq 3\%\end{cases} \tag{26}$$

② 500*cs* Silicone oil

$$\eta_{500cs}(\phi)=\begin{cases}30\omega_{si}+324.5 & 0<\omega_{si}<6\% \\ 500 & \omega_{si}\geq 6\%\end{cases} \tag{27}$$

③ 1000*cs* Silicone oil

$$\eta_{1000cs}(\phi)=\begin{cases}96.48\omega_{si}+920.4 & 0<\omega_{si}<9\% \\ 1700 & \omega_{si}\geq 9\%\end{cases} \tag{28}$$

4.2.6. Verify the Accuracy of Using Numerical Simulation Method to Predict The sedimentation Time of MR Fluid

● Accuracy of prediction results l adding surfactant

1) Sample Preparation Method

Mix oleic acid with alcohol and stir well; then add 5 μm of hydroxy iron powder, oleic acid alcohol solution into the ball mill tank at 1:1:1 mass ratio, the ball mill time is 3 *h*. After the ball mill, put the ball mill pot into the vacuum drying oven until all the alcohol evaporates completely. Then mix the modified magnetic particles with silicone oil at mass ratio of 6:4 and stir well with mixer.

2) Comparison of measurement and simulation results

According to the preparation method, 6 kinds of MR fluids with different oleic acid concentration were prepared. The measuring time is measured by an inductive sedimentation device, and the sedimentation time of the magnetorheological fluid is simulated by the numerical simulation method. Fig. 19 shows the comparison between the measurement results and the simulation results. From the comparison results, it can be seen that the difference between the measurement results and the simulation results is not large, the average error is 3.25 %, and the maximum error is 8.83 %. This indicates that the sedimentation time of MR fluids modified by surfactants can be well predicted using the constructed numerical simulation method.

● Accuracy of prediction results after addition of thixotropic agent

1) Sample Preparation Method

5 *μ*m hydroxy iron powder, silicone oil (nominal 500 *cs*, viscosity 973 mPa.s) were added to the beaker at a mass ratio of 6:4, then nano-silica with different weights was added to the beaker and the mixture was stirred evenly using a mixer.

2) Comparison of measurement and simulation results

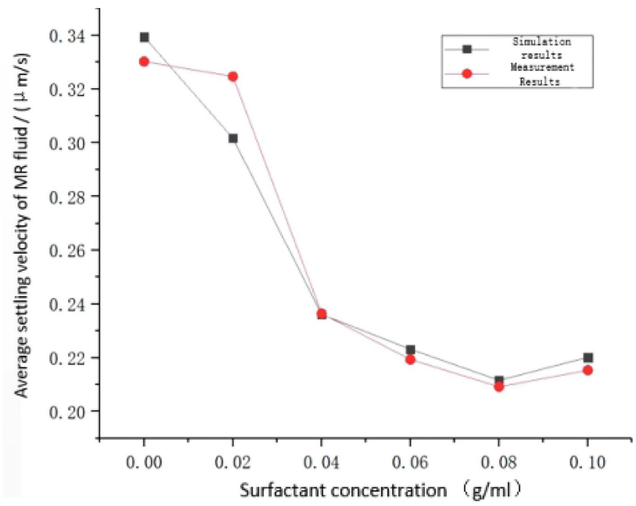

Fig. 19. (Color online) Comparison of simulation results with experimental results when only surfactant is added.

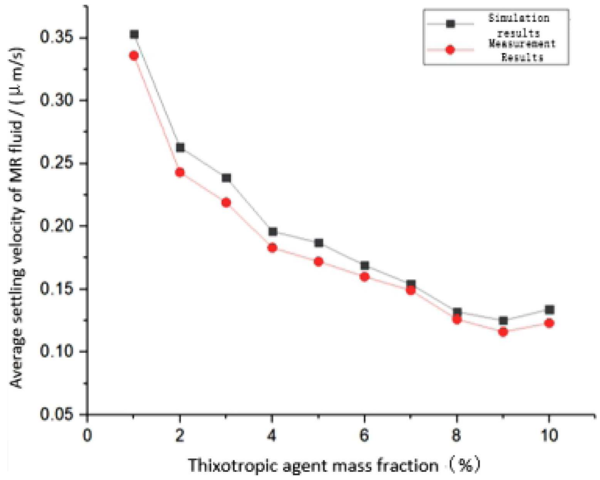

Fig. 20. (Color online) Comparison of simulation results with experimental results when only thixotropic agents were added.

According to the mass fraction of thixotropic agent, 10 different MR fluids were prepared. the contrast results are shown in Fig. 20. It can be seen from the comparison results that the simulation results have good agreement with the measurement results. The average error of the simulation results is 6.87 %, and the maximum error is 9.13 %. The results obtained by the numerical simulation method deviate from the experimental results, and the experimental results are always smaller than the simulation results.

● Accuracy of prediction results after addition of thixotropic agent and surface activity

It can be seen from Fig. 21 that when considering two additives of thixotropic agent and surfactant, the average error of the simulation results is 6.75 % and the maximum error is 9.83 %. This shows that the numerical simulation method constructed in this paper can

Table 3. Formula of MR fluid after addition of thixotropic agent and surfactant.

Sample No.	Silica oil viscosity	Particle size of hydroxyl iron powder	Quality score
1	76 mPa.s	3	80 %
2	76 mPa.s	5	80 %
3	76 mPa.s	7	80 %
4	76 mPa.s	10	80 %
5	76 mPa.s	5	10 %
6	76 mPa.s	5	40 %
7	76 mPa.s	5	60 %
8	1.12 mPa.s (Alcohol)	5	80 %
9	354 mPa.s	5	80 %
10	973 mPa.s	5	80 %

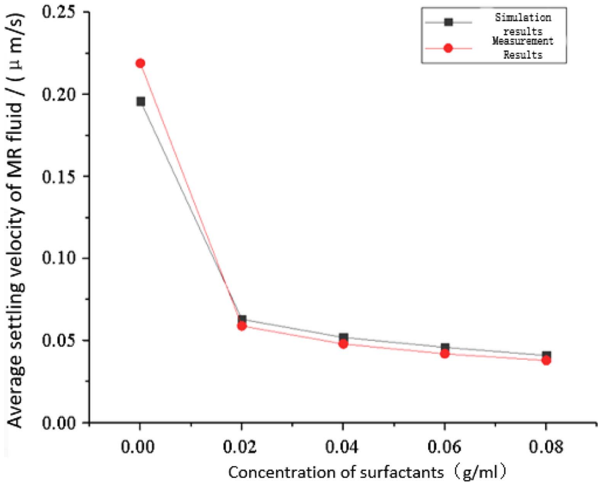

Fig. 21. (Color online) Comparison of the Results of Complex MR Fluid.

accurately simulate the addition of oleic acid and nano-silica magnetorheological it is proved that it is feasible to use numerical simulation method to simulate the sedimentation time of MR fluids.

5. Conclusion

In this paper, numerical simulation is used to predict the sedimentation time of MR fluid. In this paper, a simple MR fluid containing only magnetic particles and base solution and a surfactant-coated MR fluid coated with oleic acid were used to verify the accuracy of the proposed MR fluid deposition simulation method. Because the concentration of oleic acid and the ball milling time and the mass fraction of thixotropic agent added in the mixing stage will affect the sedimentation time of MR fluid. The effect of these factors on each component of MR fluid is first studied in this paper. After verification, the proposed method can predict the sedimentation time of MR fluid well. The error between the simulation results and the actual measurement results is not more than 9.83 %. This method can be used to guide the improvement of MR fluid formulation and reduce the time for research.

Acknowledgments

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