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Research on Preparation and Characteristics of a Novel Transmission Magnetorheological Fluid

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On the basis of orthogonal experiment, a novel transmission magnetorheological fluid with synthetic ester chain oil as carrier fluid is prepared. The effect of single additive content on the apparent viscosity and settling stability of magnetorheological fluid is analyzed, and the characteristic evaluations are also carried out. The results indicate that the magnetorheological fluid containing 60 wt% carbonyl iron powder has an apparent viscosity of 2.15 Pa·s and can attain the shear yield stress of 36 kPa when the magnetic field strength is 0.5T. Furthermore, the settlement rate of the MRF is less than 3 % after two weeks. In comparison with the silicone oil and mineral oil, the synthetic ester chain oil-based magnetorheological fluid has the lowest thermal expansion rate.

Keywords : preparation, settling stability, thermal expansion rate, magnetorheology, additives

1. Introduction

Magnetorheological fluid (MRF) which is mainly composed of soft magnetic particles, carrier fluid and additives is one of the most important branches of smart materials. After the application of an external magnetic field, it presents significant rheological properties which reveals that in the absence of magnetic field, the MR fluid appear the free flow state; while in the presence of magnetic field, it can changes from a free flow state to a solid body instantaneously with controllable shear yield stress. Because of its rapid response, reversibility and ease of control, MRF has been widely used in many fields such as automobile, machinery, aeronautics and astronautics, construction and medical treatment [1-6].

Many scholars at home and abroad have done a lot of research on soft magnetic particles, carrier fluid, additives types and content. Choi *et al.* [7] prepared hollow soft magnetic particles, which reduces the density of soft magnetic particles and the sedimentation rate of MRF. López-López *et al.* [8] obtain a MRF containing iron powder coated with oleic acid. Yan *et al.* [9 studied the influence of base oil species on rheological properties and stability of MRF. Guerrero-Sanchez *et al.* [10] prepared a MRF with an ionic base carrier solution. Wereley *et al.* [11] used high viscosity linear polysiloxanes as base carrier fluid. Chin *et al.* [12] increased the steric hindrance of carbonyl iron powder by adding the stabilizer Co-γ-Fe_2O_3 and thickener CrO_2 into the MRF to improve the stability and shear yield stress of the MRF. Song *et al.* [13] used nano magnetic particles as additives in their experiments. Cheng *et al.* [14] used the method of adding nano grade kaolin to make the sedimentation rate of MRF decrease significantly. Ashtiani *et al.* [15] investigated the influence of three kinds of organic additives (different carbon chain length) on the performance of MRF. Liu *et al.* [16] proposed a method to improve the stability of MRF by adding nano strontium ferrite ($SrFe_{12}O_{19}$) particles. Chen *et al.* [17] studied the influence of four different surfactants (oleic acid, OP4 emulsifier, SDBS and Tween80) on MRF and the results show that the sedimentation rate of MRF using oleic acid and Tween is lower and the viscosity of the zero field is smaller.

At present, the research on high temperature magnetorheological fluid for transmission occasion is insufficient, and it has great significance to develop transmission MRF to broaden the application field of MRF. In this paper, a MRF for transmission is prepared with high temperature chain oil as base carrier fluid, and the selection of component materials is carried out, the optimization of

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the preparation process and the evaluation of performances are also researched.

2 Materials and Methods

2.1. Materials

The carbonyl iron powders (CIP) from Hangzhou HengXin metal material Co., Ltd is used as soft magnetic particles in this paper, whose main size is 3 μm and the particle purity is 99 %, as shown in Fig. 1 which is obtained by scanning electron microscope (SEM). CIP is basically spherical, and is easier to be treated by surface activation.

High temperature chain oil is used as carrier fluid, whose main component is high temperature synthetic ester, with high temperature, low volatility, good lubricity and less coking. Its viscosity is 300cSt at room temperature and can work stably at 300 ºC.

Several additives with stable properties were screened, whose thermal decomposition failure temperature are all higher than 300 ºC, including active agents (Povidone K30, Tween 80, Glycerin, SDBS), coupling agent (Titanate coupling agent Y201) and nano magnetic particle additive (nano Fe_3O_4).

2.2. Methods

2.2.1. Preparation Methods

The preparation method is improved on the basis of base fluid replacement method. The active agents and thixotropic agent are added separately, and a repeated stirring process is introduced. Before preparation, CIP should be cleaned and dried to prevent the influence of impurities on surface modification.

The main technological process of preparing MRF is as follows: First, the CIP, which is washed and dried, is mixed with surfactant, organic solvent (anhydrous ethanol or isopropyl alcohol) at a temperature of about 45 ºC in water bath. It is then placed in a vacuum drying chamber and dried at 70 ºC completely. After drying, the modified particles are mixed with the carrier fluid and added thixotropic agent. The water bath is stirred at 60 ºC at high speed (the stirring speed is 20 r/s), and the stirring time is half an hour.

2.2.2. Test methods

One of the most important performance evaluation indexes of MRF is the shear yield stress, which can be measured by a disc type yield stress tester, as shown in Fig. 2, whose test principle is to obtain the value of shear yield stress according to the test torque. The lifting motor is responsible for the lifting of the work platform and can also control the distance between the rotary shear disc and the bottom rest shear disc. Torque sensor can display torque in real time. The bottom disk is a magnetic and temperature control module. The magnetic field intensity can control continuously from 0 to 1.0T and the temperature can adjust between room temperature and 270 ºC continuously. The main motor is responsible for providing rotational torque, whose speed range is 0-2000 r/min.

The apparent viscosity of MRF, mainly affected by temperature, is another important performance evaluation index and can be measured using a SV-10 vibration viscometer. In order to obtain the viscosity-temperature properties of the MR fluid, the viscosity is measured at different temperatures (from 20 ºC to 200 ºC, an interval of 20 ºC).

The observation method is adopted to evaluate the sedimentation stability, whose principle is that the light density of the base liquid will be squeezed into the upper layer after the high density of solid particles in the

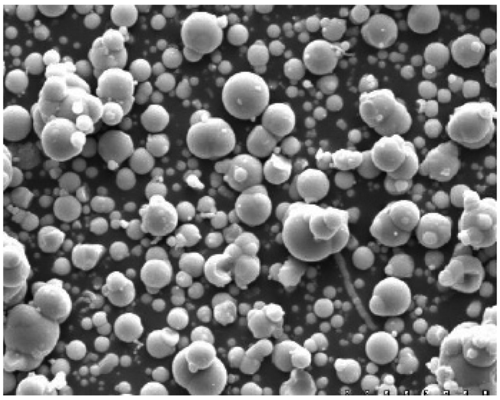


Fig. 1. Microstructure of CIP by SEM.

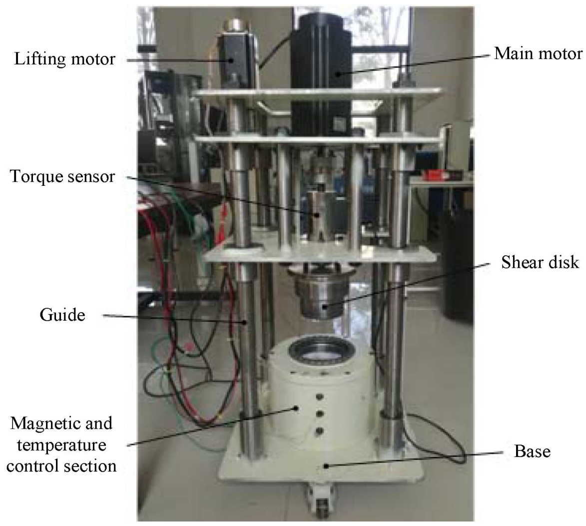


Fig. 2. (Color online) Shear yield stress tester.

magnetorheological fluid settle down, namely the so-called segregation phenomenon. Then the interface layer will appear between clear liquid and sediment. The sedimentation stability can be expressed by sedimentation rate, which is defined as the clear liquid volume *a* relative to the total MR fluid volume *b*.

3. Results and Discussions

3.1. Content of components

The experimental scheme of orthogonal test is adopted. The experimental indexes are sedimentation rate and apparent viscosity. The orthogonal table $L_{16}(4^5)$ is selected, namely 16 sets of experiments, taking into account 5 factors, each factor is divided into 4 levels. The influencing factors are several kinds of additives, including Povidone K30, Tween 80, Glycerin, SDBS, and Diatomite. Levels are the mass fraction of additives. The active agent are divided into four levels: 0.5 wt%, 1.0 wt%, 1.5 wt%, 2.0 wt%. The thixotropic agents are also divided into four levels: 1.0 wt%, 1.5 wt%, 2.0 wt%, 2.5 wt%. The content of carbonyl iron powder is 60 wt%, and nano Fe_3O_4 additive is taken 5 wt%. The modification effect of coupling agent is stronger than that of active agent, thus making a greater impact on the sedimentation and viscosity so that other factors will bring a greater error when single factor effect is larger in orthogonal test, so in order to reduce the experimental error, the coupling agent is not used in the orthogonal experiment, but it will continue in the next independent experiment. The settlement rate is calculated according to the time of resting for one week and the apparent viscosity is measured by the viscometer at 25 °C.

Table 1 is the results of $L_{16}(4^5)$ orthogonal test, the first target is sedimentation rate of MRF, and the second target is apparent viscosity. In orthogonal tables, each influencing factor is divided into four levels, and the values in brackets are the actual mass fraction of additives. We refer to the result that the sum of all sedimentation rates of a given additive whose list belongs to the rank 1 is divided by the level number as the average of the first level. And so on, we can get the average of 2, 3 and 4 levels. According to this method, the average value of each additive under different levels can be concluded to plot the effect diagram of single factor under a certain index. Figure 3 shows the effect line chart under the

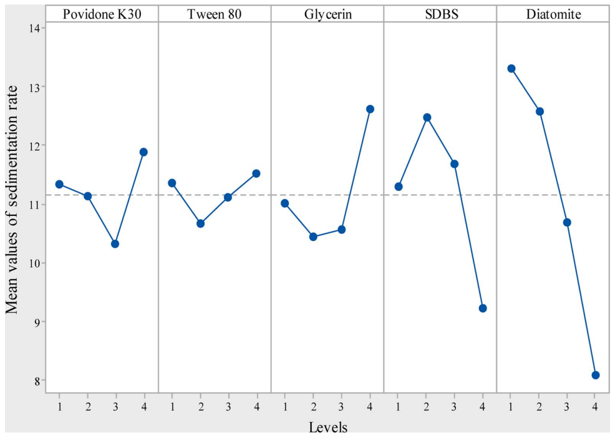


Fig. 3. (Color online) Orthogonal test results (sedimentation stability).

Table 1. Orthogonal test data.

$L_{16}(4^5)$	Povidon (wt%)	Tween (wt%)	Glycerin (wt%)	SDBS (wt%)	Diatomite (wt%)	Sedimentation rate (%)	viscosity (Pa·s)
Exp.1	1(0.5)	1(0.5)	1(0.5)	1(0.5)	1(1.0)	13.64	0.48
Exp.2	1(0.5)	2(1.0)	2(1.0)	2(1.0)	2(1.5)	12.81	0.55
Exp.3	1(0.5)	3(1.5)	3(1.5)	3(1.5)	3(2.0)	10.71	0.69
Exp.4	1(0.5)	4(2.0)	4(2.0)	4(2.0)	4(2.5)	8.13	1.50
Exp.5	2(1.0)	1(0.5)	2(1.0)	3(1.5)	4(2.5)	8.04	1.34
Exp.6	2(1.0)	2(1.0)	1(0.5)	4(2.0)	3(2.0)	8.04	0.71
Exp.7	2(1.0)	3(1.5)	4(2.0)	1(0.5)	2(1.5)	14.07	0.79
Exp.8	2(1.0)	4(2.0)	3(1.5)	2(1.0)	1(0.5)	14.34	0.66
Exp.9	3(1.5)	1(0.5)	3(1.5)	4(2.0)	2(1.5)	9.38	0.73
Exp.10	3(1.5)	2(1.0)	4(2.0)	3(1.5)	1(0.5)	13.92	0.90
Exp.11	3(1.5)	3(1.5)	1(0.5)	2(1.0)	4(2.5)	8.34	0.91
Exp.12	3(1.5)	4(2.0)	2(1.0)	1(0.5)	3(2.0)	9.60	0.55
Exp.13	4(2.0)	1(0.5)	4(2.0)	2(1.0)	3(2.0)	14.36	0.79
Exp.14	4(2.0)	2(1.0)	3(1.5)	1(0.5)	4(2.5)	7.85	0.88
Exp.15	4(2.0)	3(1.5)	2(1.0)	4(2.0)	1(0.5)	11.30	0.50
Exp.16	4(2.0)	4(2.0)	1(0.5)	3(1.5)	2(1.5)	14.01	0.46

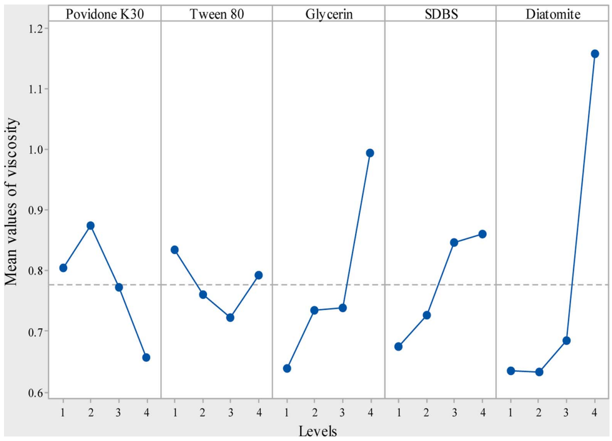


Fig. 4. (Color online) Orthogonal est results (viscosity characteristics).

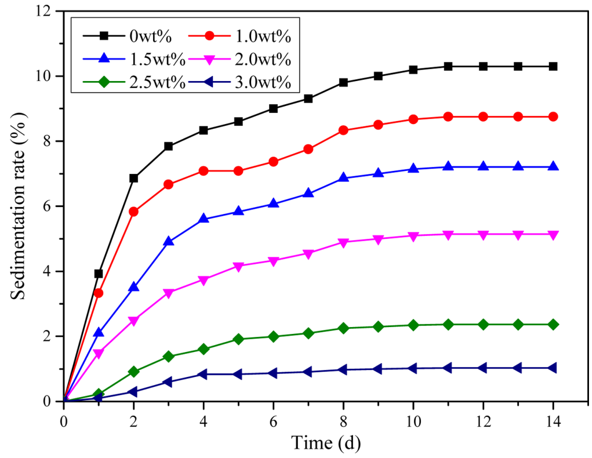


Fig. 5. (Color online) Effect of Titanate content on the sedimentation stability.

settlement rate index and Fig. 4 shows the effect line diagram under the viscosity index, which both abscissa is the level number (content) and the ordinate is the average value.

From Fig. 3 and Fig. 4, we can observe that the sedimentation rate and apparent viscosity of the sixth group's experiments and the fourteenth experiments are both low, so the final proportioning scheme need refer to these two experiments. It can also be seen that the content of SDBS and diatomite have great influence on the sedimentation rate and apparent viscosity. Furthermore, the additive of glycerin does not work well when used in combination, which the sedimentation rate and the apparent viscosity all increase when the content is more than 1.0 wt%. When the content of povidone is more than 1.0 wt%, the effect of apparent viscosity will decrease and the sedimentation rate is minimum when taking 1.5 wt%. The sedimentation rate is minimum when Tween takes 1.0 wt%. Considering synthetically the settlement rate and apparent viscosity (preferential settlement rate), the material of each component is determined as follows: povidone 1.5 wt%, Tween 1.0 wt%, SDBS 2.0 wt%, diatomite 2.0 wt%. The whole proportioning scheme is close to the sixth experiment.

Titanate coupling agent with 1 %, 1.5 %, 2 %, 2.5 %, 3 % mass fraction are added to the prepared MRF for coupling processing to get the settlement curve as shown in Fig. 5.

As can be seen from Fig. 5, the settling effect can be expected well when the mass fraction of coupling agent is 2.5 %. Further increase the mass fraction of the settlement has little effect instead increase apparent viscosity greatly, thus the titanate coupling agent with mass fraction of 2.5 % will be the most reasonable choice. Therefore, the prepared parameter of transmission MRF is as follows: the contents of CIP, nano Fe_3O_4, Tween 80, SDBS, Diatomite and Titanate coupling agent is 60 wt%, 5 wt%, 1.0 wt%, 2.0 wt%, 2.0 wt% and 2.5 wt%, respectively. Finally, the apparent viscosity of the prepared MRF is 2.15 Pa·s and the stability settlement is less than 3 % after 2 weeks.

3.2. Performance test of prepared MRF

3.2.1. Shear yield stress

The shear yield stress of two kinds of MRF (chain oil base and silicone oil base) of iron powder with mass fraction of 60 % at field strength of 0.5T was tested. The results are shown in Fig. 6.

As can be seen from Fig. 6, the shear yield stress can reach to 36 kPa as the magnetic field is 0.5T. Furthermore, with the increase of temperature, the shear yield stress of two kinds of MRF decreases, the shear stress of

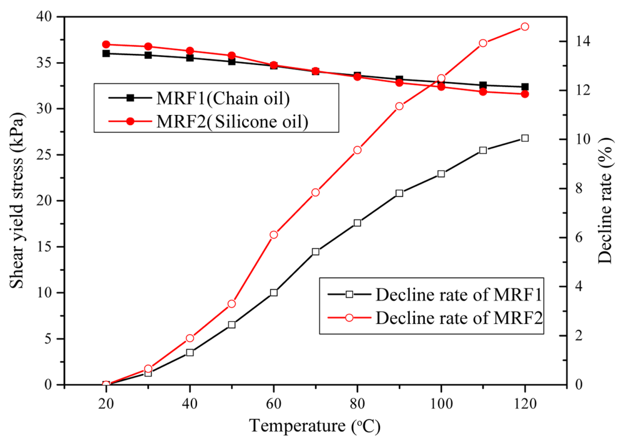


Fig. 6. (Color online) Relationship between shear yield stress and temperature.

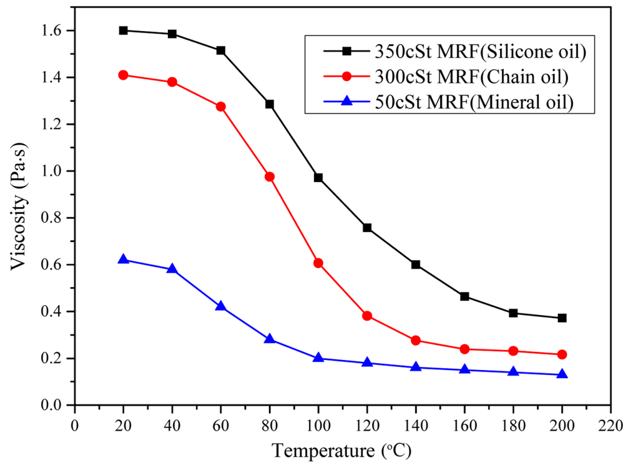


Fig. 7. (Color online) Viscosity temperature characteristics of MRF.

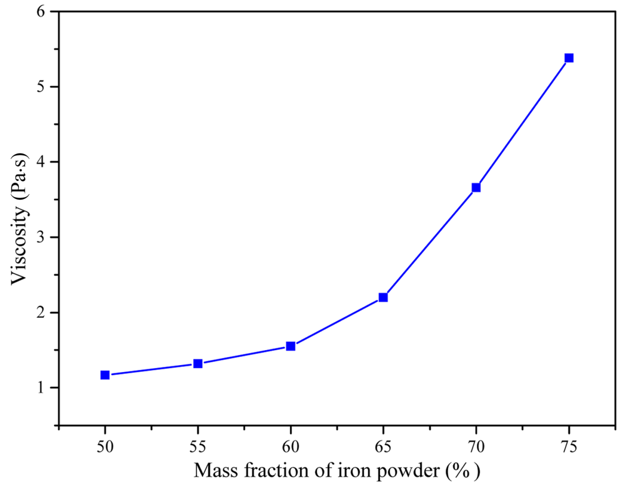


Fig. 8. (Color online) Relationship between the viscosity of MRF and the mass fraction of iron powder.

silicone based MRF decreases by about 15 % while the chain oil base decreases by about 10 % at 120 °C, and the reduction of shear yield stress of chain oil based MRF is smaller with the decrease of temperature. Factors affecting the decrease of yield stress: the increase of temperature leads to the decrease of base liquid viscosity, the decrease of magnetization of iron powder and the thinning of MRF caused by thermal expansion.

3.2.2. Apparent viscosity

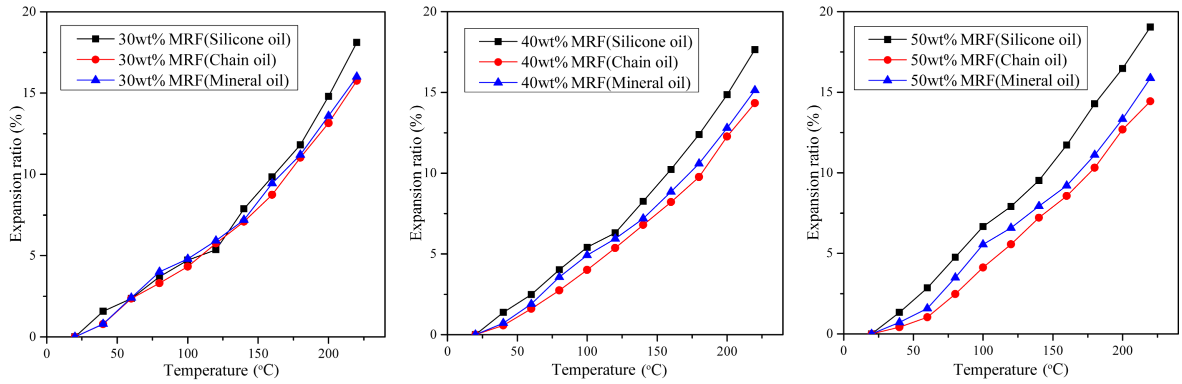
The apparent viscosity of MRF is measured and the viscosity-temperature characteristic curve is obtained, as shown in Fig. 7. Furthermore, the effect of particles content on apparent viscosity is also tested, as shown in Fig. 8.

As can be seen from Fig. 7, no matter what type of oil base fluid is used, the viscosity of MRF decreases greatly with the increase of temperature, and tends to be stable at 200 °C. The viscosity of silicone oil base, chain oil base and mineral oil based MRF decreased by 78 %, 85 % and 81 % respectively. The decrease of viscosity of MRF is mainly due to the decrease of viscosity of base fluid, which is also the general characteristic of oil.

From the Fig. 8, it can be found that when the iron content is greater than 65 wt% (including nano Fe_3O_4 of 5 wt%), the viscosity of MRF increases rapidly. During the experiment, it is found that when the apparent viscosity was greater than 3.5 Pa·s, the MRF had poor fluidity. Therefore, in order to guarantee the fluidity of MRF, it is reasonable to determine the content of iron powder as 65 wt%.

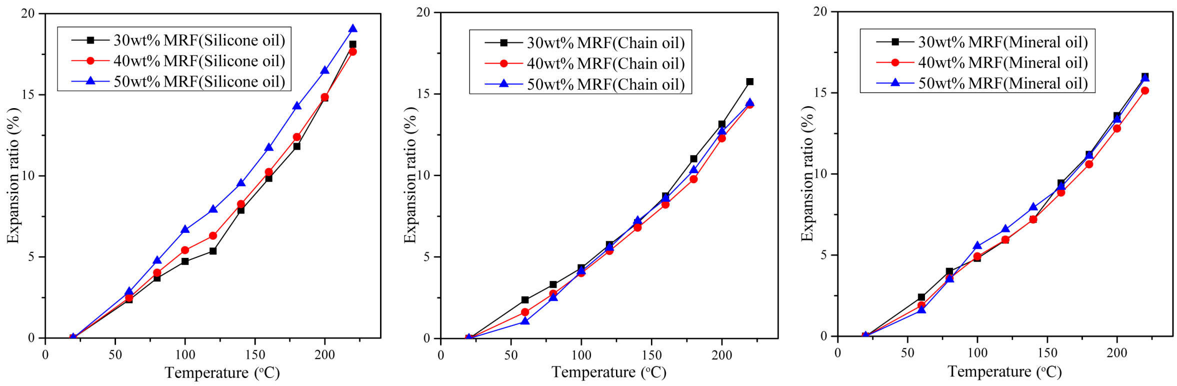
3.2.3. Thermal expansion characteristics

9 groups of MRF with iron content of 30 %, 40 % and 50 % are prepared by using two methyl silicone oil, synthetic ester chain oil and mineral oil as base carrier fluid. the thermal expansion rates are measured in the



(a) 30wt% iron powder (b) 40wt % iron powder (c) 50wt % iron powder

Fig. 9. (Color online) Thermal expansion characteristics of MRF with different base carrier fluids.



(a) Silicone oil base fluid (b) Chain oil base fluid (c) Mineral oil base fluid

Fig. 10. (Color online) Thermal expansion characteristics of MRF with different mass fraction of iron powder.

range of 20-220 °C, as shown in Fig. 9 and Fig. 10.

From Fig. 9 and Fig. 10, we can find that, in the same iron content conditions, the largest expansion rate is silicone oil MRF, and the expansion rate of three kinds of mass fraction is 18.1 %, 17.6 %, 19 % at 220 °C respectively, while the mineral oil is 16.0 %, 15.1 %, 15.9 %, and the chain oil is 15.7 %, 14.3 %, 14.4 %, the greater the mass fraction of iron powder, the larger the difference of thermal expansion rate of MRF. Furthermore, the silicon oil based MRF thermal expansion rate is affected obviously by iron content, and therefore, the chain oil is suitable to use as carrier fluid in high power transmission.

4. Conclusions

(1) With orthogonal test, a MRF with high temperature chain oil as base carrier was prepared with apparent viscosity and settlement stability as index. The influence of single additive on sedimentation rate and viscosity was analyzed when additives were used in combination. The content is determined as follows: Povidone K30 1.5 wt%, Tween 80 1.0 wt%, SDBS 2.0 wt%, Diatomite, 2.0 wt%. In order to further reduce the sedimentation rate, experimental on the coupling effect of titanate is carried out and determine the amount of 2.5 wt%. Finally, the prepared MRF has a sedimentation of less than 3 % and a apparent viscosity of 2.15 Pa·s after two weeks.

(2) The shear yield stress of the prepared MRF was tested. It was found that the shear yield stress can reach 36 kPa when the content of iron powder is 60 % and the magnetic field strength is 0.5T. When the temperature increased from 20 °C to 120 °C, the yield stress of MRF decreased by about 10 %, while that of silicone oil decreased by 15 %. Viscosity of MRF decreased greatly at high temperature (80 % at 200 °C). The Decline rates of several oil-based MRF are basically same.

(3) The thermal expansion property of the chain oil based MRF was tested and compared with that of silicone oil and mineral oil-based MRF. The experimental results show that the thermal expansion rate of MRF prepared by high temperature chain oil is the lowest, and it is also affected little by the content of iron powder.

Acknowledgment

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