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Finite Element Analysis and Experimental Study on Magnetorheological Fluid Seal of the Hydraulic Cylinder

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In order to solve the leakage problem of the engineering mechanical hydraulic cylinder, a magnetorheological fluid (MRF) seal structure with a multistage source is designed. The magnetic field in the gap of the sealing structure is analyzed by ANSYS finite element analysis method, the influence about the number of magnetic sources and the length of pole teeth on the pressure capability of the MRF seal is studied, and the results are analyzed. The results show that the suitable number of magnetic sources is 10; The length of the pole teeth with the best magnetic concentrating effect is 0.7 mm. Then, the influence of the MRF injection volume, reciprocating speed, reciprocating distance and holding pressure time of the hydraulic cylinder on the MRF sealing pressure capability is studied. The experimental results show that the maximum pressure capacity can be achieved when the MRF injection volume is 12 ml. With the increase of reciprocating speed, the pressure capability of the MRF seal decreases obviously. With the increase of reciprocating distance and holding time, the sealing pressure capability has no obvious change. Through the finite element analysis and experimental study of the MRF seal, it is of great significance to develop a device with high sealing performance suitable for the hydraulic cylinders.

Keywords : MRF, reciprocating seal, finite element analysis, experimental study, hydraulic cylinder

1. Introduction

Magnetorheological fluid (MRF) is a kind of intelligent material, which is a suspension formed by micro or nano ferromagnetic particles immersed in non-magnetic carrier fluid [1, 2]. The volume fraction of ferromagnetic particles in MR materials is usually between 20 % and 40 %. It's rheological properties can be controlled by external magnetic field [3, 4]. The properties of MRF are different with different magnetic field strength. Based on the unique properties of MR materials and a large number of related basic research, MR technology is more and more used to solve practical engineering problems [5-7].

Hydraulic cylinder is a kind of reciprocating linear motion hydraulic device, which can convert hydraulic energy into mechanical energy and in well used the engineering machinery [8]. However, the hydraulic cylinder has the problem of hydraulic oil leakage, which is difficult to solve for a long time. Tian [9] Analyzed and studied the failure of O-ring, Yu [10] studied the contact stress characteristics of seal ring through ABAQUS, and Tang [11, 12] studied the test method standard of sealing performance of reciprocating parts of hydraulic cylinder. However, with the improvement of working technology of hydraulic cylinder in engineering machinery, the traditional sealing technology has great shortcomings, which cannot meet the requirements of sealing.

Magnetorheological fluid (MRF) sealing technology uses the response of highly saturated magnetic fluid to magnetic field to seal related equipment. At present, there are many researches on MRF rotary seal [13-15], Kubik *et al*. [16] designed the sealing experiment based on the pinch mode of MR fluid, and finally found that pinch MR fluid obtained lower friction torque than ordinary (standard) MR fluid and higher burst pressure than any ferrofluid seal (FFs). Cheng *et al.* [17] studied

MRF seal under different main shaft rotating speeds of the hydraulic turbine, and analyzed the seal pressure and friction heat under different rotational speed mutation conditions through experiments. Urreta *et al.* [18] analyzed the performance of ferrofluid and magnetorheological fluid seal, and proved that ferrofluid can meet the

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requirements of high-precision spindle seal by experiments. However, there is little research into the MRF reciprocating seal. Li and Ma [19-21] carried out the test of reciprocating shaft magnetic fluid seal and the formula of pressure capability for magnetic fluid reciprocating seal was deduced according to the theoretical analysis of magnetic fluid amount carried away by reciprocating shaft. Yang and Hao [22] designed a MRF reciprocating seal structure with four magnetic sources and studied the influence of key parameters on the pressure capability, but lack of the experimental research.

In this paper, the MRF reciprocating seal structure with multi-stage magnetic source is designed, and the influence of the number of magnetic sources and the length of pole teeth on the sealing capability is analyzed by finite element method, it is of great significance to develop a MRF sealing device suitable for the hydraulic cylinder. The influence of MRF injection volume, reciprocating speed, reciprocating distance and pressure holding time on sealing capability is studied by experiments, which proves the correctness of theoretical analysis.

2. Theoretical Research

The physical model of magnetic fluid reciprocating seals is shown in Fig. 1 and the magnetic fluid film in the sealing gap moves from the beginning to a stable position according to the position shown by the dotted line in Fig. 1. The formula of pressure capability of magnetic fluid reciprocating seal [19, 20, 22] is

$$\Delta P = P_h - P_0 = [H(X_C) - H(X_B)]\mu_0 M_S$$
$$+ \eta 6V\{\frac{1}{h^2_{(x_C)}} x_C - \frac{1}{[0.66D(6V/\sigma)^{2/3}]^2} x_B\} \quad (1)$$

Where P_h is pressure at high pressure side, P_0 is pressure at atmospheric side, X_C is coordinate of point C, $H(X_B)$ and $H(X_C)$ are magnetic field strengths at X_B and X_C respectively, μ_0 is air permeability, M_S is saturated magnetization of magnetic fluid, η is dynamic viscosity of magnetic fluid, V is velocity of reciprocating shaft, $h(x_C)$ is film thickness of magnetic fluid corresponding to point x_C, D is gap between reciprocating shaft and pole teeth, σ is surface tension of magnetic fluids.

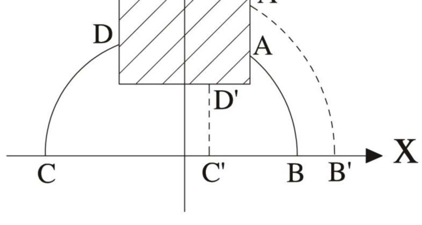


Fig. 1. Physical model of magnetic fluid reciprocating seals.

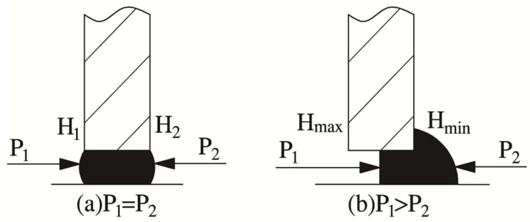


Fig. 2. Pressure capability process of one pole tooth.

Experiments show [19, 20] that when the amount of magnetic fluid is sufficient and the velocity of reciprocating shaft is not fast, the magnetic fluid film can return to the static position of reciprocating shaft after the velocity of reciprocating shaft is zero. Because the static capability state of magnetic fluid seals is studied, the effect of velocity on magnetic fluid seals can be neglected, and the effect of surface tension and viscosity of magnetic fluid seals can also be neglected. So the pressure capability of single pole teeth seals can be simplified as follows:

$$\Delta P = P_h - P_0 = [H_{(x_C)} - H_{(x_D)}]\mu_0 M \quad (2)$$

Therefore, the pressure capability process of the i pole teeth seal in the horizontal direction is shown in Fig. 2. The pressure capability formula of magnetic fluid seal of the i pole teeth is obtained, as shown in formula (3):

$$\Delta P_i = P_1 - P_2 = \int_{H_2}^{H_1} M_S dH \quad (3)$$

When $P_1 = P_2$, the pressure capability of reciprocating shaft seals is zero. When $P_1 > P_2$, under the new balance of the pressure capability, the magnetic fluid in the sealing gap will be pulled to the appropriate position along the direction of capability gradient difference. Considering that the saturation magnetization of the magnetic fluid is much less than external magnetic field, formula (3) can be simplified to formula (4):

$$\Delta P_i = P_1 - P_2 = \int_{H_{min}}^{H_{max}} M_S dH \quad (4)$$

According to the superposition principle [19], the total pressure capability of the reciprocating MRF seal with four magnetic sources is deduced as shown in equation (5):

$$\Delta P = \sum_{i=1}^{N} \sum_{j=1}^{M} \Delta P_{ij} \quad (5)$$

N is the number of pole teeth of a single pole piece; M is

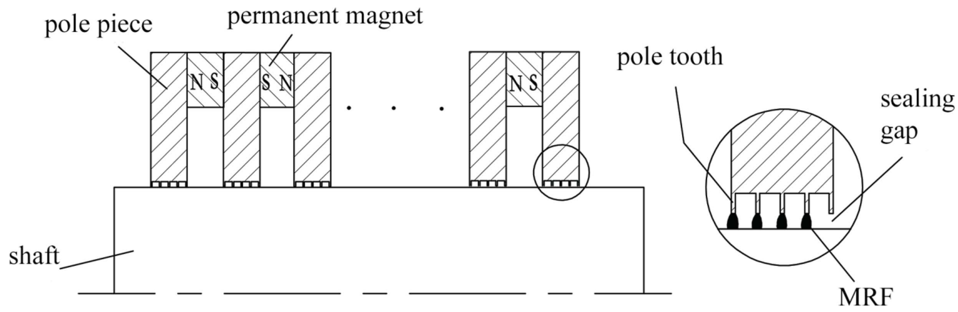


Fig. 3. Schematic diagram of two-dimensional physical model of MRF seal.

the number of pole pieces.

3. Structure Design of MRF Reciprocating Seal with Muti-stage Magnetic Sources

As shown in Fig. 3, the MRF reciprocating seal structure with multi-stage magnetic source is designed to study the influence of key parameters of the seal structure on the pressure capability of MRF reciprocating seal, the structural parameters are shown in Table 1. The permanent magnet materials are selected as NdFeB, its remanence Br = 1.13T, coercive force HC = 1.356×10^6 A/m. Magnetic fluid is selected as MRF and saturation magnetization is 307 KA/m, it's magnetization curve (M-H curve) is shown in Fig. 4(a). Pole pieces and shaft materials are the same 2Cr13, and the magnetization curve (B-H curve) is shown in Fig. 4(b). The method of intelligent mesh is selected and the mesh precision is applied. The boundary condition is that magnetic field lines is parallel to physical model boundary. The magnetic flux density in the sealing gap can be obtained by the solver. In the process of finite element analysis, the single variable control method is used to study the influence of the number of magnetic sources and the length of pole teeth on the sealing pressure capability.

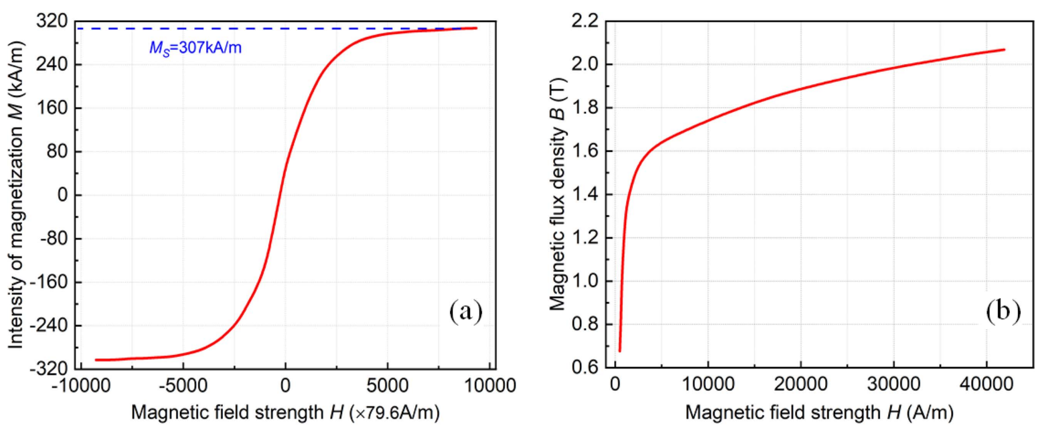
Table 1. Parameters of the MRF reciprocating seal structure.

Item	Value
Inner radius of the pole piece (mm)	25.1
Outer radius of the pole piece (mm)	45
Axial length of the pole piece (mm)	5
Permanent magnets length	5
Inner radius of each permanent magnets	24
Outer radius of each permanent magnets	30
Number of permanent magnet	8/9/10/11/12
Width of pole teeth (mm)	0.2
Length of pole teeth (mm)	0.3/0.5/0.7/0.9
Radial sealing gap height (mm)	0.1
Slot of teeth width (mm)	0.8

4. Finite Element Analysis and Discussion of Results

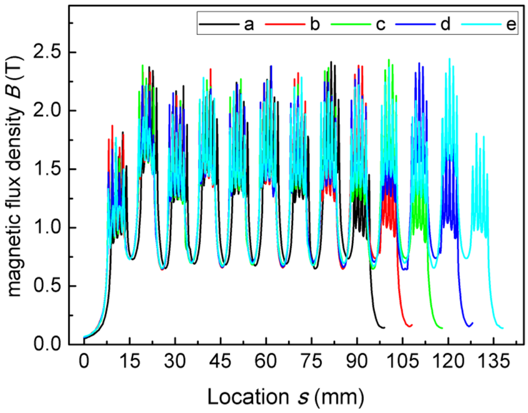
4.1. Effect of number of magnetic sources on sealing performance

The magnetic source provides the magnetic energy for



(a) is the magnetization curve (M-H curve) of MRF; (b) is the magnetization curve (B-H curve) of 2Cr13

Fig. 4. (Color online) The magnetization curves of MRF and 2Cr13.



(a), (b), (c), (d), (e) denote magnetic distribution with 8, 9, 10, 11, 12 magnetic sources respectively.

Fig. 5. (Color online) Magnetic flux densities corresponding to different number of magnetic sources.

the whole sealing device. Therefore, it is of great significance to study the effect of number of magnetic sources on the pressure capability of MRF seal to develop the hydraulic cylinder seal device with high sealing performance. Magnetic flux density distribution under different number of magnetic sources is shown in Fig. 5.

It can be seen in the Fig. 5 that with the increase of the number of magnetic sources, the magnetic flux density under the sealing gap increases uniformly. The main reason is that permanent magnet as a magnetic source provides magnetic energy for the whole magnetic circuit. In theory, the more magnetic sources, the greater the corresponding magnetic field strength. According to the magnetic fluid reciprocating seal pressure capability formula and the magnetic flux density in Fig. 5, the pressure capability of the MRF reciprocating seal can be calculated, as shown in Fig. 6.

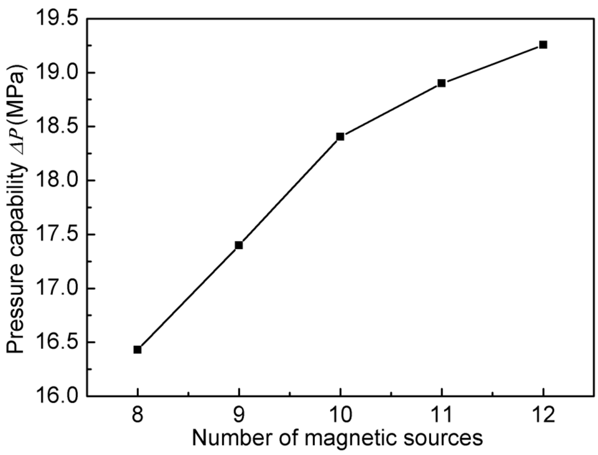


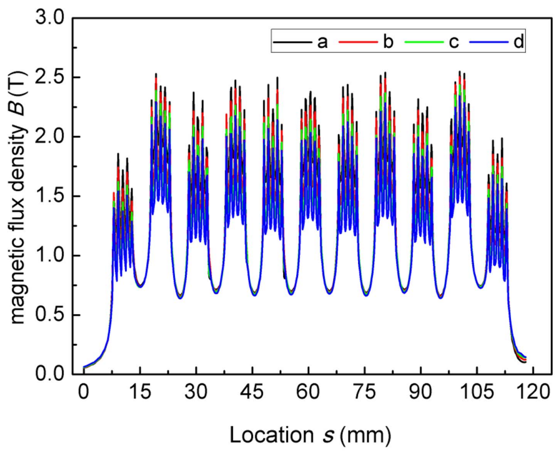
Fig. 6. Effect of number of magnetic sources on pressure capability.

It can be seen from Fig. 6 that with the increase of the number of magnetic sources, the pressure capability of MRF seal increases, but when the number of magnetic sources is more than 10, the value of pressure capability increases slowly. This is because the magnetic source provides magnetic energy for the whole magnetic circuit, with the increase of the number of magnetic sources, the magnetic flux through the whole sealing structure will increase, therefore, the sealing pressure capability is also increased. When the number of magnetic sources is more than 10, the magnetic source cannot provide the best magnetic energy product for the whole circuit, which should be due to the whole magnetic circuit saturation.

4.2. Effect of length of pole teeth on sealing performance

The length of the pole teeth is a key parameter affecting the MRF seal of the hydraulic cylinder. Therefore, the research on the influence about the length of the pole teeth on the seal performance can provide a theoretical basis for the MRF seal experiment of the hydraulic cylinder. When the number of magnetic sources is 10, magnetic flux density distribution under different length of pole teeth is shown in Fig. 7.

It can be clearly seen in Fig. 7 that when the length of the pole teeth is 0.9 mm, the corresponding magnetic flux density is the weakest, while when the length of the pole teeth is 0.3 mm, the corresponding magnetic flux density is the strongest. The main reason is that when the magnetic energy provided by the magnetic source is constant, the longer the length of the pole teeth is, the greater its magnetic resistance will be. Therefore, the magnetic



(a) is 0.3mm; (b) is 0.5mm; (c) is 0.7mm; (d) is 0.9mm

Fig. 7. (Color online) Magnetic flux densities corresponding to different length of pole teeth.

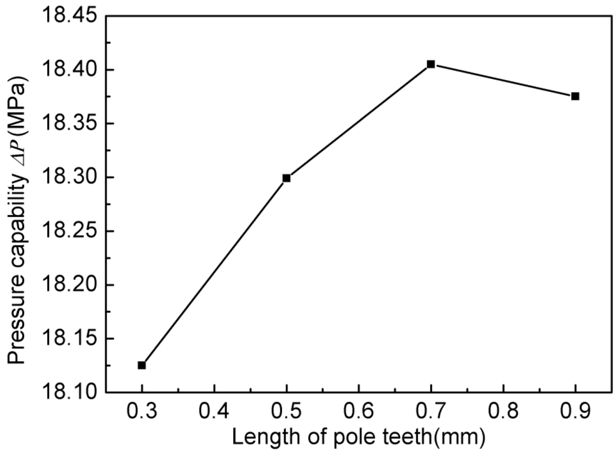


Fig. 8. Effect of length of pole teeth on pressure capability.

resistance when the pole teeth length is 0.9 mm is larger than that when the pole teeth length is 0.3 mm, which leads to the maximum magnetic flux density when the pole teeth length is 0.3 mm. According to the magnetic fluid reciprocating seal pressure capability formula and the magnetic flux density in Fig. 7, the pressure capability of the MRF reciprocating seal can be calculated, as shown in Fig. 8.

It can be clearly seen from the Fig. 8 that when the length of the pole teeth increases, the sealing pressure capability increases firstly and then decreases. When the length of the pole teeth is 0.7 mm, the sealing pressure capability is the largest, because with the increase of the length of the pole teeth, the magnetic field gradient in the sealing gap between the pole teeth and the shaft will also increase, and the magnetic field gradient difference will also increase, the pressure capability will be even greater. And when the length of the pole teeth is 0.7 mm, the maximum magnetic energy product of the whole magnetic circuit is just obtained.

5. Experimental Study on MRF Seal of Hydraulic Cylinder

According to the results of finite element analysis, the MRF sealing device with 10 magnetic sources and 0.7 mm pole teeth length is used in the experiment. In the preparation process, the designed and processed permanent magnet is assembled into the groove of the end face of the pole piece, and then the sealing ring is installed into the groove of the outer circular face of the pole piece. Put the shell of the seal into the high and low temperature test box as shown in Fig. 9, heat it for 20 minutes, and then install the seal assembly into the shell. In the process of assembly, a layer of lubricating oil is applied on the outer surface of the sealing component and the inner surface of the shell to reduce the friction, so as to effectively ensure the reliability of assembly. The MRF seal structure is installed on the hydraulic cylinder test bench as shown in Fig. 10, and the maximum output load of the oil pump is 17 MPa. When conducting the reciprocating seal experiment of hydraulic cylinder, start the oil pump. After the indicator light of the oil pump sensor is on, click automatic start, and the piston rod of hydraulic cylinder can reciprocate. The reciprocating distance and speed of the piston rod of the hydraulic cylinder can be adjusted through the control bench.

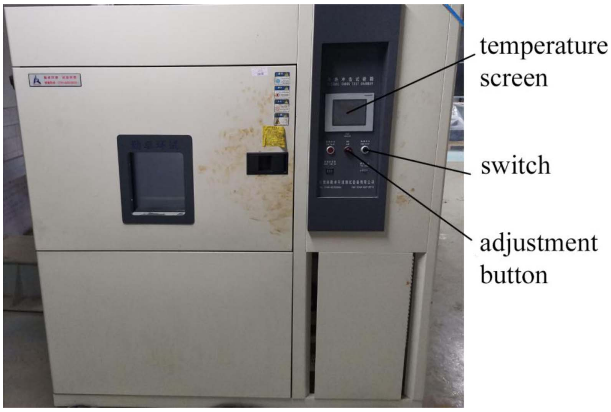
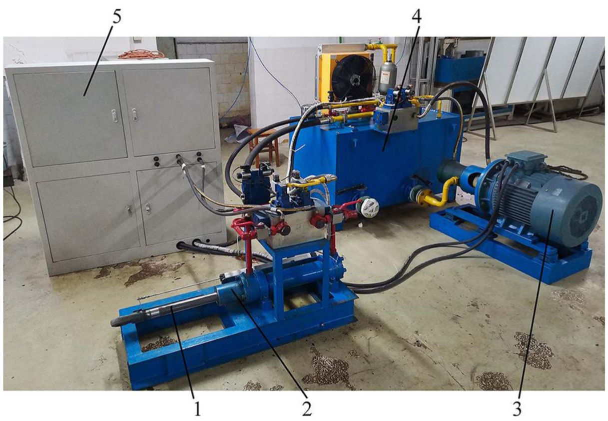


Fig. 9. (Color online) High and low temperature test box.

5.1. MR fluid sample preparation

Considering the problem that MRF will be miscible with hydraulic oil. Therefore, we need to find a liquid that is incompatible with these two liquid for separation, so as to avoid the direct contact between MRF and hydraulic oil and effectively prevent the hydraulic oil from being



(1) is the reciprocating shaft; (2) is the sealing components; (3) is the oil pump; (4) is the oil tank; (5) is the control bench;

Fig. 10. (Color online) Hydraulic cylinder seal test bench.

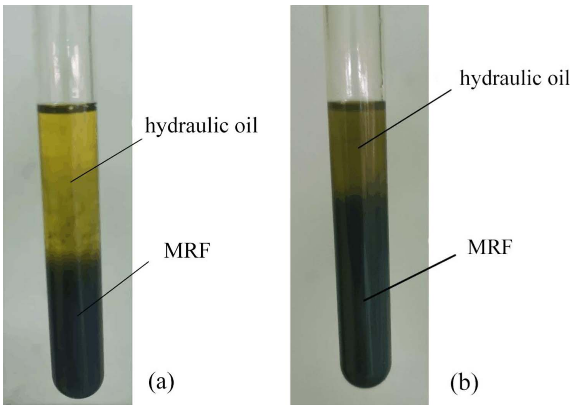


Fig. 11. (Color online) Solubility test of hydraulic oil and MRF.

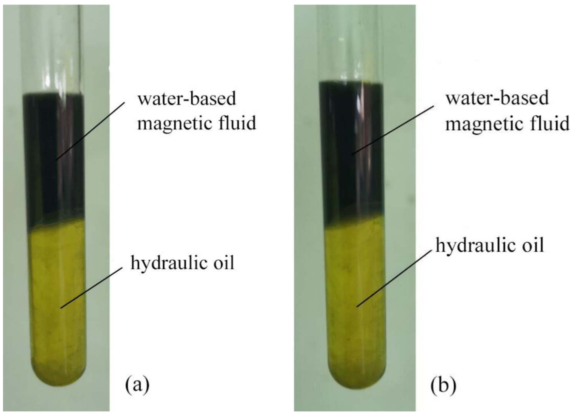


Fig. 12. (Color online) Solubility test of water-based magnetic fluid and hydraulic oil.

polluted. Through consulting the data, the water-based magnetic fluid is selected to separate the MRF from the hydraulic oil in this paper.

Take three 5 ml transparent glass test tubes, wash and dry them. In the first tube, 1 ml of MRF and 1 ml of hydraulic oil are injected; In the second tube, 1 ml of hydraulic oil and 1 ml of water-based magnetic fluid are injected; In the third tube, 1 ml of MRF and 1ml of water-based magnetic fluid are injected. The results are observed after 20 minutes, as shown in Fig. 11, Fig. 12 and Fig. 13.

It can be seen from Fig. 11(a) and (b) that the hydraulic oil and MRF have obviously dissolved after 20 minutes. This is because the carrier of MRF is oleyl. According to the principle of similar solubility, the intermolecular force is very small for the two liquids with the same solute, so both liquids have strong solubility.

It is not difficult to see from Fig. 12(a) and (b) that there is almost no change after 20 minutes of contact between water-based magnetic fluid and hydraulic oil, so it is proved that they are immiscible. This is because the hydraulic oil is mostly refined mineral oil without anti-oxidant, while the carrier liquid of water-based magnetic fluid is water-based. Therefore, according to the principle of similar solubility, it is difficult to dissolve.

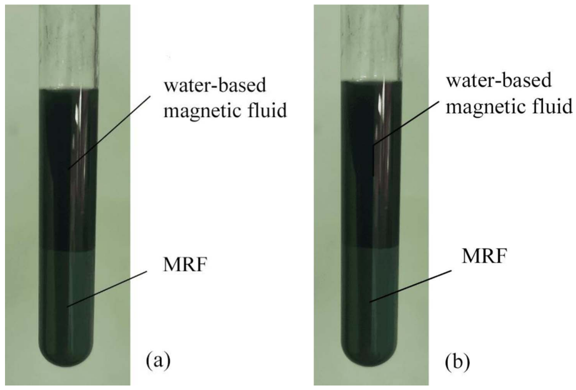


Fig. 13. (Color online) Solubility test of water-based magnetic fluid and MRF.

It can be clearly seen from Fig. 13(a) and (b) that there is no obvious change between water-based magnetic fluid and MRF after 20 minutes, which means that they are almost immiscible. This is because the carrier of MRF is silicone oil or hydrocarbon oil, while the carrier of water-based magnetic fluid is deionized water with additives. According to the principle of similar solubility, the interaction between water and oil molecules is very strong, so it is not dissolved.

5.2. Effect of MRF injection volume on sealing performance

In this experiment, the injection volume of MRF is 4 ml, 6 ml, 8 ml, 10 ml, 12 ml and 14 ml respectively. The result of the effects from different MRF injection volumes

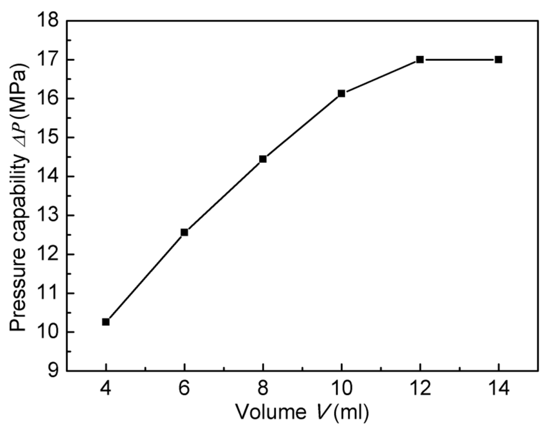


Fig. 14. Effect of MRF injection volume on pressure capability.

on the pressure capability is shown in Fig. 14.

It can be clearly seen from Fig. 14 that with the MRF injection volume from 4 ml to 12 ml, the sealing pressure capability increases significantly, but when the MRF injection volumes is from 12 ml to 14 ml, the sealing pressure capability value has no change. Therefore, it can be considered that the saturation state is reached when the injection volume of MRF is 12 ml. This is because in the experiment, MRF will not only fill the sealing gap between the pole teeth and the shaft, but also a part of MRF will stay in the slot of the pole teeth and not participate in the sealing function.

5.3. Effect of reciprocating speed on sealing performance

In the sealing experiment of hydraulic cylinder, the reciprocating speed has a great influence on the pressure capability of MRF reciprocating seal. In the design of hydraulic cylinder, the shock absorber is not considered. Therefore, when the reciprocating shaft moves at medium and high speed, there will be strong vibration at the end of the stroke, which will affect the precision of the result. In this sealing experiment, the reciprocating distance is fixed at 100 mm, and the effect of reciprocating speed of 0, 0.5 mm/s, 1 mm/s, 1.5 mm/s, 2 mm/s, 2.5 mm/s and 5 mm/s on pressure capability of MRF seal is studied. The results are shown in Fig. 15.

It can be clearly seen from Fig. 15 that when the reciprocating speed is zero, the MRF sealing pressure capability is 17 MPa, when the speed is 5 mm/s, the pressure capability is reduced to about 16.35 MPa. This is because when the reciprocating distance is constant, the greater the reciprocating speed, the more MRF is pulled out, and less MRF is involved in the sealing. When the reciprocating speed increases, deformation of MRF in the sealing gap could also increase sharply, resulting in the lack of self-refreshing ability of MRF, which leads to the reduction of the sealing pressure capability.

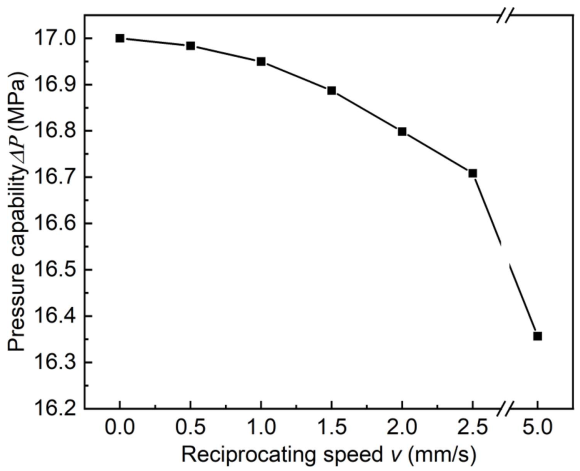


Fig. 15. Effect of reciprocating speed on pressure capability.

5.4. Effect of reciprocating distance on sealing performance

Reciprocating distance is a key parameter that affects the pressure capability of MRF seal. In this paper, the reciprocating speed is fixed at 1 mm/s and the reciprocating distance of 50 mm, 100 mm, 150 mm, 200 mm, 250 mm and 300 mm on the pressure capability of MRF seal was studied. The results are shown in Fig. 16.

The experimental results show in Fig. 16 that the effect of reciprocating distance on the pressure capability of MRF seal can be ignored. This is because when the reciprocating speed of the hydraulic cylinder is fixed, increasing the distance can reduce the amount of MRF in the sealing gap to a certain extent, but it has little effect

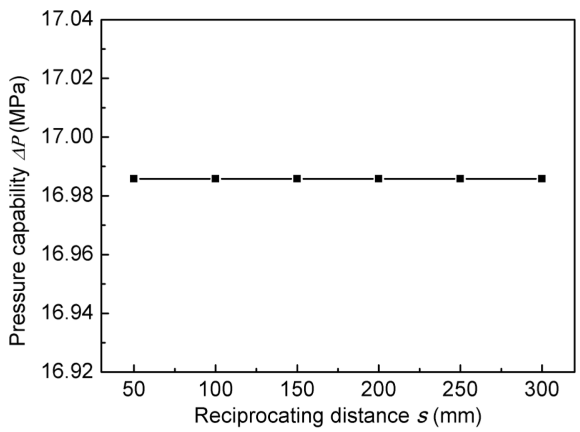
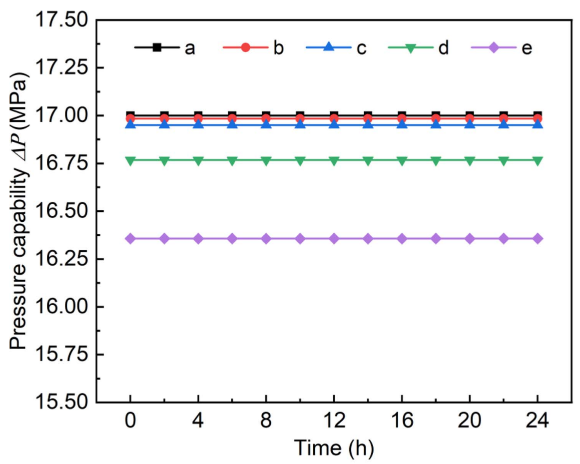


Fig. 16. Effect of reciprocating distance on pressure capability.



(a), (b), (c), (d), (e) represent the speeds of 0 mm/s, 0.5 mm/s, 1 mm/s, 2 mm/s, 5 mm/s respectively.

Fig. 17. (Color online) Effect of holding pressure time on pressure capability.

on the deformation of the MRF in sealing gap and the thickness of the liquid film adhered to the shaft, so the sealing pressure capability is almost unchanged.

5.5. Effect of holding pressure time on sealing performance

Holding pressure time plays a key role in the MRF sealing of hydraulic cylinder. In this experiment, the effect of holding time of 0 h to 24 h on the pressure capability of MRF seal has been studied under the static and dynamic state. The results are shown in Fig. 17.

According to the data in the Fig. 17, when the reciprocating speed is zero, the pressure capability still remains 17 MPa after 24 hours. When the speed of reciprocating shaft is 0.5 mm/s, 1 mm/s, 2 mm/s and 5 mm/s, the corresponding MRF sealing pressure capability is always 16.983 MPa, 16.941 MPa, 16.768 MPa and 16.356 MPa. Therefore, through static and dynamic experiment of hydraulic cylinder, the 10-stage MRF seal structure can maintain the pressure well, which proves the sealing reliability of the hydraulic cylinder.

6. Conclusion

Based on the leakage problem of hydraulic cylinders, the influence of number of magnetic sources and the length of pole teeth on the pressure capability of MRF seal is analyzed by finite element method in this paper. The results show that when the number of magnetic sources is 10, the most suitable magnetic energy product can be provided for the whole magnetic circuit. When the length of the pole teeth is 0.7 mm, the effect of magnetic concentration is the best. It is of great significance to develop MRF sealing device suitable for the hydraulic cylinder through the finite element analysis.

The effects of the MRF injection volume, the reciprocating speed, the reciprocating distance and the holding pressure time on the sealing capability of MRF are analyzed by experiments. The results show that the MRF sealing capability decreases with the increase of the reciprocating speed, and the MRF seal pressure capability of hydraulic cylinder has almost no change with the increase of reciprocating distance and pressure holding time. Through the static and dynamic experimental research, it is proved that the 10-stage MRF sealing structure can solve the leakage problem of hydraulic cylinder well.

Acknowledgments

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