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Investigation on the Influence of Temperature on Starting Torque of Magnetic Fluid Seal

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The widest application of magnetic fluid is in magnetic fluid seals. The starting torque varying with temperature of magnetic fluid seal has limited its application in special seal field such as military industry. This paper firstly measure the starting torque of magnetic fluid seals under different temperature conditions from −55 °C to 70 °C after holding for 2.5 hours in a closed environment with uniform temperature. And the law of starting torque with temperature change is studied experimentally. The results show that the starting torque of the magnetic fluid seal changes unobvious at 25 °C or higher temperature. The starting toque of magnetic fluid seal increases with the decrease of temperature, and the causes of which are analyzed. The results of this study provide experimental and theoretical reference for reducing the staring torque of magnetic fluid seal in low temperature environment.

Keywords : starting torque, magnetic fluid, temperature, rotating seal

1. Introduction

One of the most important applications of magnetic fluids as a new type of functional material is magnetic fluid seal with the advantages of long life, function without rubbing contact with the rotating shaft surface, and zero leakage rate. Magnetic fluid plays an irreplaceable role in military, chemical, vacuum, aerospace and energy industries [1]. Therefore, the development of sealing equipment can work seamlessly in harsh environment such as extremely high or low temperature, acidity and alkalinity, and radiation is urgently needed. The starting torque is one of the important parameters in the application of the rotating seal of the magnetic fluid, and its change may lead to undesirable results including incompetence of equipment and effect on normal use. In some military applications, the magnetic fluid rotary seal needs to start under different temperature conditions.

However, the experimental research and application theory of the starting torque of the magnetic fluid rotational seal at different temperatures are not mature enough and need to be further studied for providing theoretical and experimental references on expanding the application of magnetic fluid seals in special environments.

Previous experimental results [2-4] show that the starting torque is proportional to the number of seal stages, the injected quantity of magnetic fluid and the standing time at the normal temperature, and the viscosity is the key factor of affecting the change in the starting torque. Furthermore, shear thinning and agglomeration are the essential reasons leading to the change. In this letter, the influence of temperature on the starting torque of magnetic fluid rotating seal is analyzed based on the derivation of the viscous drag equation. This paper firstly measured the starting torque of magnetic fluid seals under different temperature conditions from −55 °C to 70 °C after holding for 2.5 hours in a closed environment with uniform temperature.

2. Analysis of Rotating Seal Staring Torque of Magnetic Liquid

In the magnetic fluid sealing device, the shaft is in contact with the magnetic fluid in the seal gap before it starts, the resistance moments that are encountered at startup include: the inertia moment and the viscous resistance moment of the magnetic fluid. Let the contact length of the rotating shaft with the magnetic liquid be l,

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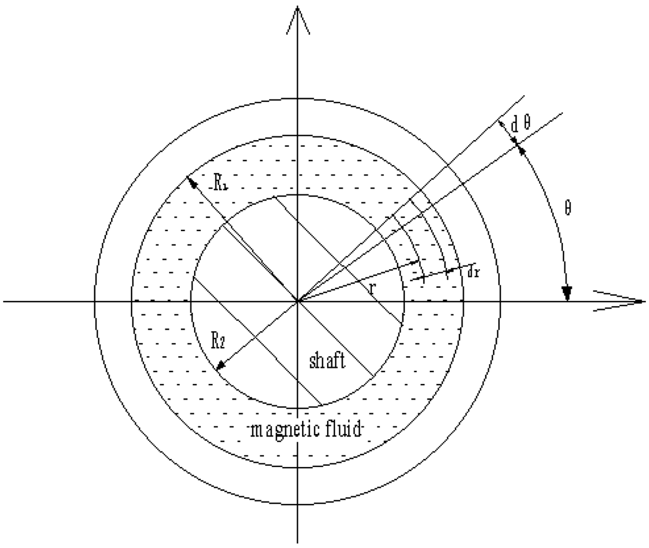


Fig. 1. Schematic diagram of two dimensional model.

the minimum radius which is the radius of the rotating shaft be R_1, and the maximum radius which is the inner diameter of the pole shoe be R_2. (shown in Fig. 1)

The inertia moment of mass element dm is

$$dM_g = -\varepsilon r^2 \mathrm{d}m$$

$$M_g = \int_m -\varepsilon r^2 dm = -\varepsilon \int_{\theta_1}^{\theta_2} d\theta \int_{R_1}^{R_2} \rho l r^3 dr = -\frac{\pi}{2}\varepsilon \rho l (R_2^4 - R_1^4)$$

Using cylindrical coordinates and rotating shaft seals, the axis z is directed along shaft axis, and the plane perpendicular to the z-axis is a polar coordinate plane. According to the Navier-Stokes equation and $V_z = 0$, $V_r = 0$, $V_\theta = 0$, the viscous resistance on per unit length is expressed by

$$\tau_{r\theta} = \eta\left(\frac{\partial V}{\partial r} - \frac{V}{r}\right) = \frac{2\eta\omega R_2^2}{R_2^2 - R_1^2} \tag{1}$$

So the viscous resistance torque acting on the shaft is defined by the expression

$$M = 2\pi R_1 \cdot l \cdot \tau_{r\theta} \cdot R_1 = 4\pi \frac{\eta l \omega R_1^2 R_2^2}{R_2^2 - R_1^2} \tag{2}$$

Where η is the viscosity of magnetic fluid, ω is the angular velocity of shaft, l denotes The length of the magnetic fluid in contact with the shaft, R_1 is the rotary shaft radius, R_2 denotes inner diameter of pole piece.

Based on equation (1) and equation (2), we can obtain the starting torque of magnetic fluid seal T_0 as follows:

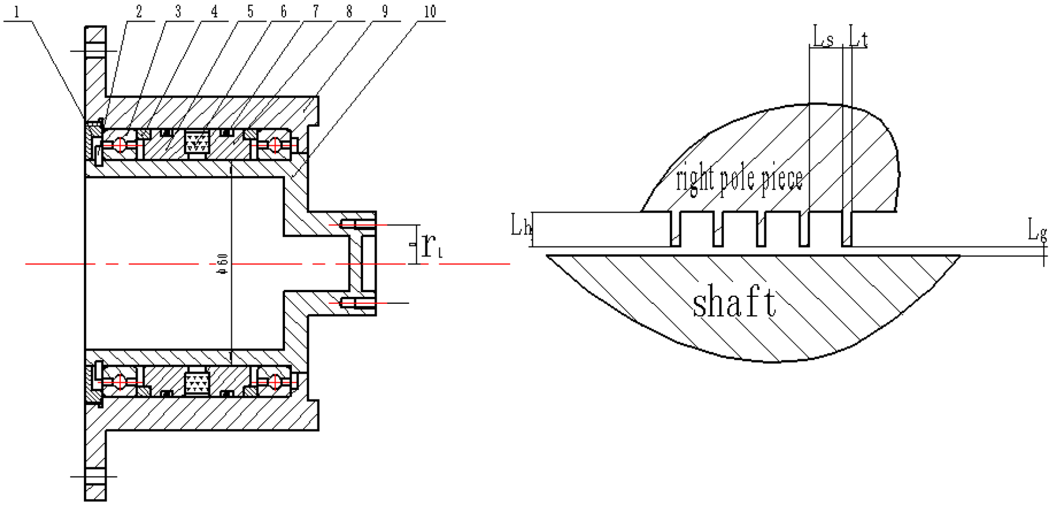
$$T_0 = M + M_g = -\frac{\pi}{2}\varepsilon \rho l (R_2^4 - R_1^4) + 4\pi \frac{\eta l \omega R_1^2 R_2^2}{R_2^2 - R_1^2} \tag{3}$$

Equation (3) assumes that there are two main factors that affect the starting torque: the viscosity of the magnetic fluid and the contact length of the magnetic fluid and the shaft. The larger the number of pole teeth is, or the more the amount of magnetic fluid injection is, the greater the magnetic fluid seal starting torque will be. The viscosity of the magnetic fluid is affected by many factors, among which the temperature has a great influence. As a result, the temperature has a greater influence on the starting torque of the magnetic fluid seal. The temperature also influences the starting torque of the magnetic fluid seal through affecting the frictional torque of the bearing, because of the increasing of viscosity of the lubricating oil. And bearing retainer of different materials have different shrinkage coefficients at low temperature, this may affect the frictional moment of bearing at low temperature. Therefore, this article will study the effect of temperature on magnetic fluid seal starting torque.

3. Experimental Study

The magnetic fluid sealing device used in the experiment is shown in Fig. 2. The left and right pole pieces, permanent magnets and shaft form a closed magnetic circuit. 13 polar teeth are manufactured on each pole piece. The height of a tooth is $L_h = 0.7$ mm, the width of a tooth $L_t = 0.2$ mm, the width of a tooth groove $L_s = 0.8$ mm, the width of a groove $L_g = 0.1$ mm.Ring permanent magnet produces a circular magnetic field distribution at the shaft sealed parts. By using of magnetic conductivity of pole piece magnetic fluid is constrained in the magnetic field to form the O-ring of magnetic fluids.

The experimental device for measuring the starting torque of the magnetic fluid seal is shown in Fig. 3. The magnetic fluid seal with two screws at the shaft end is mounted on special fixture. The special fixture is used to fix the magnetic fluid seal. The special fixture with magnetic fluid seal is placed in an 8-cubic high-low temperature chamber, which can change the experimental temperature and keep the temperature to be nearly constant during the experiment. The experimenter can enter into the chamber to measure the starting torque. And this way can forbid change of temperature or frosting. When the starting torque need to be measured, experimenter enter into the chamber and hang some suitable weights (10 to 100 grams) on the screw gently one by one. The total mass of the weight is recorded at the moment when the shaft starts to rotate, which is used to calculate the staring torque of the magnetic fluid seal, while the starting torque is $T = mgr_\mathrm{L}$, lever arm $r_\mathrm{L} = 11.5$ mm (shown in Fig. 2), The total mass of the weight m.



1—End cover；2—Circlip；3—Bearing；4—No magnetic ring；5—Left pole piece；6—Permanent magnet；7—Seal ring；8—Right pole piece；9—Outer sleeve；10—shaft

Fig. 2. (Color online) Schematic diagram of magnetic fluid seal device.

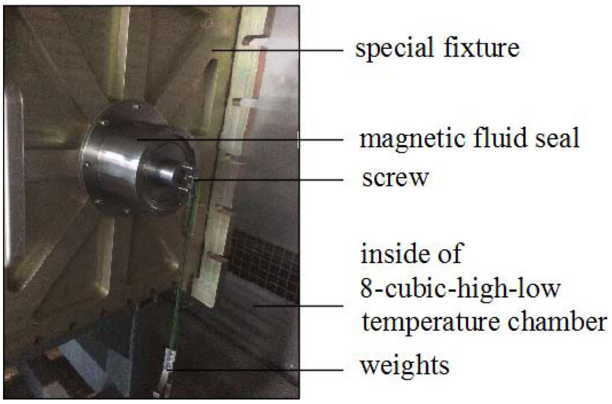


Fig. 3. (Color online) Experimental device for starting torque of magnetic fluid seals.

Two magnetic fluids are used in the experiment to measure the starting torque of the magnetic fluid seal in the temperature range of –55 °C to 70 °C. Parameters of the two kinds of magnetic fluids are shown in Table 1. In the range of –55 °C to 0 °C, measure the starting torque of magnetic fluid seals at various experimental temperatures of 0 °C, –10 °C, –20 °C, –30 °C, –40 °C and –55 °C. In the range of 0 °C to 70 °C, the starting torque of magnetic fluid seals at 25 °C, 40 °C, and 70 °C are measured. During the experiment, the special fixture with magnetic fluid seal is placed in the high-low temperature chamber and is kept under certain temperature for 2.5 hours, after which the experimenter will enter the chamber to measure the staring torque by hanging weights.

Table 1. Parameters of magnetic fluids in the experiment.

Magnetic fluid	Base carrier liquid	Mean particle diameter d/nm
1	Machine oil	10.1
2	Diester	10.1

Figure 4 illustrates the relationship between temperature and starting torque of different kinds of magnetic fluids, and the quantity of magnetic fluid is 0.4 ml. Variation of temperature with starting torque of different quantities of magnetic fluid is shown in Fig. 5.

It can be seen from the results in Fig. 4 and Fig. 5:

(1) In the temperature range of 25 °C~70 °C, the

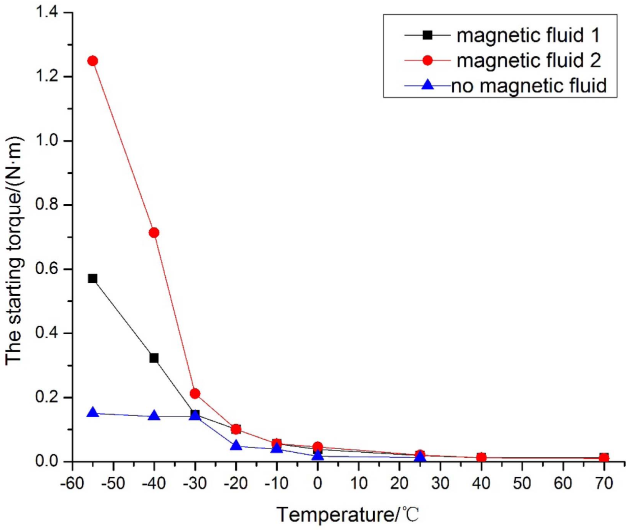


Fig. 4. (Color online) The relationship between temperature and starting torque of different kinds of magnetic fluids.

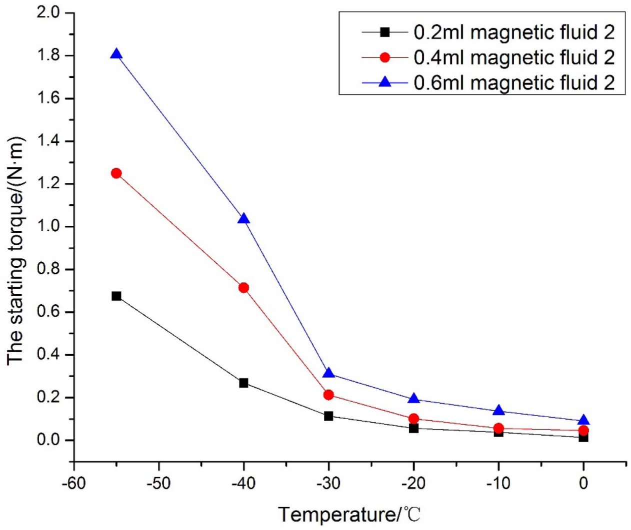


Fig. 5. (Color online) Variation of temperature with starting torque of different quantities of magnetic fluid.

starting torque of the two kinds of magnetic fluids doesn't change obviously with the increase of temperature, and the maximum variation is 0.011 N·m.

(2) In the temperature range of −55 °C~25 °C, the starting torque of the two kinds of magnetic fluid seals increases with the temperature decreases, and the degree of change in the starting torque wouldn't necessarily be the same. To be more specific, the starting torque of the magnetic fluid seal injected magnetic fluid 1 at −55 °C is 30 times that of the magnetic fluid seal injected magnetic fluid 1 at 25 °C. The starting torque of the magnetic fluid seal injected magnetic fluid 2 at −55 °C is 60 times that of 25 °C. The starting torque of the two magnetic fluid seals is almost the same at 25 °C and the difference is 0.002 N·m. However, the starting torque of the magnetic fluid seal injected magnetic fluid 2 at −55 °C is 2.2 times greater than that of the magnetic fluid seal injected magnetic fluid 1.

(3) Under the same conditions, the larger the injection volume of the magnetic fluid is, the greater the starting torque of the magnetic fluid seal will be.

(4) As the temperature decreases, the frictional torque of the bearing increases, and the frictional moment of the bearing at −55 °C is about 10 times that of 25 °C.

4. Results and Analysis

In [5-11], magnetic fluids are polydisperse systems and always contain magnetic particles which are large enough to agglomerate and form various chain-like heterogeneous aggregates when subjected to a magnetic field. For example, it is well known that magnetic fluids demonstrate an abrupt viscosity increase when subjected to a magnetic field, while by increasing the shear rate, the viscosity gets reduced as a result of chain-like aggregation destruction. Frictional moment is small for magnetic fluid seals of rotating shafts because shaft rotation actively mixes the magnetic fluid and homogenizes it. However, the concentration of magnetic particles in a magnetic field can lead to chain-like aggregation for a static magnetic fluid, thus preventing rotation of the shaft.

The inter-particle interaction, which causes the formation of chain-like structures, blocks the flow of the magnetic fluid and increases the viscosity of the magnetic fluid. These chain-like structures must be destroyed before the shaft rotates, which results in an increase in the starting torque of a magnetic fluid seal.

There are a great many of magnetic particles in magnetic fluids. The magnetic fluids do not have magnetic properties in the absence of a magnetic field because magnetic particles are in Brownian diffusion. Brownian diffusion, a random movement which makes magnetic particles scattered randomly, leads to the vector of the magnetic moment being zero in the macroscopic properties of magnetic fluids. When a magnetic field is applied, the magnetic field produces a magnetic moment on the magnetic particles, which tries to make the magnetic moment direction of the magnetic particles align along with the direction of the magnetic field. The magnetic moment exerted on the magnetic particles overcomes the Brownian motion of them to make them chain in order. The condition of equilibrium is determined by the degree of balance between the strength of the applied magnetic field and the intensity of Brownian thermal motion.

The condition of a magnetic particle in the magnetic field:

$$m\boldsymbol{a} = \boldsymbol{F}_{\mathrm{m}} + \boldsymbol{F}_d$$

Where m is the mass of a magnetic particle, $\boldsymbol{a}$ the acceleration of a magnetic particle, $\boldsymbol{F}_m$ the magnetic force acting on a magnetic particle, and $\boldsymbol{F}_d$ denotes the viscous resistance of the carrier fluid to a magnetic particle. One-dimensional form of the equation of motion is given by

$$m\frac{\mathrm{d}u}{\mathrm{d}t} = -C_{\mathrm{d}}u + \mu_0 M_p V_{p1}\frac{\partial H}{\partial x} \tag{4}$$

Where C_d is the drag coefficient, μ_0 the Vacuum permeability, M_p denoting the magnetization of the magnetic particle, and V_{p1} is the volume of a spherical particle. The magnetic particles driving by the force of the magnetic field move toward the place where the potential energy is lower. Diffusion rate u is given by the following expression

$$u = \frac{1}{C_d}\mu_0 M_p V_{p1}\frac{\partial H}{\partial x}\left[1-\exp\left(-\frac{C_d}{m_1}t\right)\right] \tag{5}$$

and the difference in concentration makes the magnetic particles diffuse from a region of greater to one of less concentration. The thermal diffusion rate u_d opposite to u is defined from the expression

$$\rho_p u_d = -D_p\frac{\partial \rho_p}{\partial x} \tag{6}$$

By comparison, the concentration diffusion coefficient can be obtained [12]

$$D_p = \frac{k_0 T}{C_d} = \frac{k_0 T}{3\pi\eta_c d_p} \tag{7}$$

Where η_c is the viscosity of carrier liquid, d_p the diameter of a magnetic particle, k_0 the Boltzmann constant, and T denotes the temperature.

It can be concluded that the lower the temperature is, the greater the viscosity of the carrier liquid is, or the larger the diameter of the magnetic particles is, the smaller the diffusion coefficient would be, and then the slower the diffusion process proceeds, and magnetic particles in magnetic fluid are more likely to aggregate and form chain-like structures.

The magnetic particles driving by the force of the magnetic field move toward the place where the magnetic field is larger. Then, the concentration of particles gradually increases to generate high concentration areas, where particles are more likely to attract each other to form various chain-like structures. Difference in concentration makes the magnetic particles diffuse from a region of greater to one of less concentration. When the two opposite movements reach equilibrium, the distribution of the magnetic particles in the magnetic fluid reach a steady state. This thermal movement is influenced by the temperature. As the temperature decreases, thermal diffusion becomes slower and slower. The decline in temperature increases the viscosity of the carrier fluid resulting in the numerator in equation (7) being smaller and the denominator getting larger. So the lower the temperature is, the slower the diffusion process will be.

Moreover, since particles are in intense thermal motion at high temperatures, the chain-like structures will not form to make the starting torque nearly the same as the frictional torque of the magnetic fluid seal with no magnetic fluid injected. Compared with the high temperature, low temperature make the thermal motion slow down. As a result, more particles aggregate at the region where the concentration of magnetic particles is high, and they are more likely to form more and bigger chain-like aggregates causing the fluidity of the magnetic fluid deteriorated and the starting torque increased. The starting moments of the two magnetic fluid seals increase with decreasing temperature, which are consistent with the experimental results.

The carrier fluids of the two magnetic fluids are different. At low temperatures, the fluidity of carrier fluid of magnetic fluid 2 is not as good as magnetic fluid 1. According to equation (7), it can be concluded that the larger the base fluid viscosity is, the smaller the concentration diffusion coefficient will be, the larger the staring torque would be. The result is consistent with experimental result (2): magnetic particles in the magnetic fluid 2 are more likely to aggregate and form chain-like structures, resulting in the low-temperature starting torque of magnetic fluid 2 being larger than magnetic fluid 1.

5. Conclusion

(1) If the temperature drops between 25 °C~70 °C, the change of temperature makes little effect on the magnetic fluid seal starting torque and the maximum value of difference is 0.011 N·m. When the temperature drops between −55 °C~25 °C, the change of temperature has great influence on the magnetic fluid seal starting torque, and the magnetic fluid seal starting torque changes in the reversed direction with the temperature. And different kinds of magnetic fluid seal change in different degrees.

(2) The starting torque can be reduced by restraining aggregation of magnetic particles. For example, the big particles should be removed before using the magnetic fluid. What's more, a micro-vibration structure could be added to the sealed structure to suppress the aggregation of magnetic particles.

(3) The fluid with low viscosity at low temperature can be used as the base carrier liquid to reduce the starting torque of the magnetic fluid seal at low temperature.

(4) Selecting a suitable bearing could be considered to reduce the starting torque of the magnetic fluid seal.

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