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Influence of Particle Size Distribution of Magnetic Fluid on the Resistance Torque of Magnetic Fluid Seal

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Magnetic fluid seal is widely used in military and aerospace industry owing to its zero leakage property, long life and reliability. The resistance torque is often required to be small and stay within allowable scope with the standing time expanding and the working environment changing. In this paper, we discussed the influence of the particle size distribution of magnetic fluid on the resistance torque of magnetic fluid seal. Samples of magnetic fluid of different particle size distribution were processed by applying a magnetic field gradient. Afterwards, the rheological property of different samples was analyzed using rheometer. Besides, the resistance torque of magnetic fluid seal on different occasions was measured. We explained these results from the point of formation and destruction of magnetic aggregations based on the theory of magnetoviscous effect, thus provided feasible ways to improve the performance of magnetic fluid seal.

Keywords : magnetic fluid, magnetoviscous effect, magnetic fluid seal, resistance torque, rheology

1. Introduction

With the rapid development of military, aerospace and other fields, better performance of seals is demanded. Magnetic fluid seal (also called ferrofluid seal) with characteristics of zero leakage, long life and high reliability shows unique advantages and has been widely used in many devices, such as the tank panoramic mirror, missile launching system and radar waveguide component [1-3]. In these sealing cases, the resistance torque of the sealing structure is expected to be small and could maintain in a stable range with the standing time (time when the device is not running) expanding and the working environment changing. While in practical applications, some problems arise, which may lead to the decline of sealing performance and even the failure and destruction of the devices, thus limiting the application of magnetic fluid seal. This work focused on three typical and related problems. First, it is found that the resistance torque of magnetic fluid seal increases greatly with the expanding of standing time. Second, the resistance torque of magnetic fluid seal also increases greatly with the decrease of temperature. Third, the starting torque is always a little larger than the resistance torque of stable operation.

Considering the resistance torque, though there is no contact between solid fractions in magnetic fluid seal, a viscous resistance torque generated by the magnetic fluid in the sealing clearance still need to be overcome. There are many factors influencing the resistance torque of magnetic fluid seal, including viscosity of the magnetic fluid, sealing structure, quantity of the magnetic fluid injected and so on. Decai Li *et al.* [4] studied the starting torque of magnetic fluid seal of large diameter under low temperature experimentally, but there was no theoretical analysis of the observed phenomenon. Xinzhi He *et al.* [5] made further experimental study on the influence of yield stress of magnetic fluid on the starting torque. Although He made some assumptions based on the experimental results to explain the phenomenon, but the study was not thorough and the assumptions were not verified.

Since the sealing structure and the quantity of the magnetic fluid injected are invariant during use, the fundamental reason of the resistance torque change induced by the temperature change or standing time and the difference between the starting torque and the resistance torque of stable operation can be attributed to the change of viscosity of the magnetic fluid. Viscosity of magnetic fluid is correlated with many factors, including external factors such as magnetic field strength, shear rate, temper-

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ature and internal factors such as the type of the magnetic particles and the carrier liquid, the size distribution of magnetic particles and the volume fraction of magnetic particles. John P. McTague [6] published an article on the change of viscosity of the dilute suspensions of cobalt particles in magnetic fields. Hall and Busenberg [7] gave the theoretical explanation to the results of the experiments made by McTague, neglecting the interactions between particles. Later on, a theoretical model was proposed for magnetic fluid with high particle volume concentration by Andrey Zubarev [8]. In this model, the dipolar interactions between particles were taken into consideration, leading to the formation of chainlike aggregations, which had significant influence on the viscosity of the magnetic fluid. Since the external factors are usually specified or uncontrollable during use, this work focused on the size distribution of magnetic fluid, which is one of the easily controllable internal factors and also one of the key factors of magnetoviscous effect.

Thus, the purpose of this paper was to figure out the influence of the particle size distribution of magnetic particles in magnetic fluid on the resistance torque of magnetic fluid seal. Magnetic fluid was processed by a permanent magnet to get samples of different particle size distribution (especially the fraction of large particles). Then, the rheological property was studied experimentally to figure out the magnetoviscous effect of magnetic fluid with different particle size distribution, including the influence of magnetic field strength, shear rate, and temperature on the viscosity of magnetic fluid. Afterwards, experiments on resistance torque of magnetic fluid seal were carried out. By analyzing the results, the micro-mechanism of the change of resistance torque was studied based on the theory of magnetoviscous effect.

2. Experimental Method

2.1. Materials

A container filled with magnetic fluid was placed on a permanent magnet to obtain magnetic fluid with different particle size distribution. Schematic sketch of the magnetic separation device is shown in Fig. 1 and the average magnetic field strength of the surface of the permanent magnet was 0.45 T. After 14 days, we took 8 ml magnetic fluid from the upper part and the bottom part of the container respectively as samples and numbered them as No.1 and No.2. In magnetic fluid, only magnetic particles with a diameter smaller than the critical diameter could stay stable under the influence of gravity and magnetic field, while the larger magnetic particles would turn into sediment [9]. Thus the particle size distribution would change after the separation process. Sample No.1 (the sample from the upper part of the container) contained a reduced amount of large particles, while sample No.2 (the sample from the bottom part of the container) was enriched with large particles.

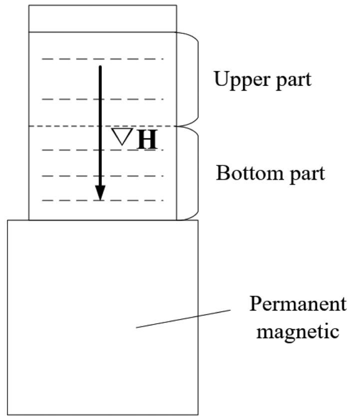

Fig. 1. Schematic sketch of the magnetic separation device.

2.2. Measurement of the rheological properties of magnetic fluid

In this study, an Anton Paar MCR302 rheometer was used to study the temperature-viscosity characteristics and the magnetoviscous effect of the magnetic fluid, *i.e.* the influence of magnetic field strength and shear rate on the viscosity of magnetic fluid. To obtain more accurate results, a cone-plate measuring system was chosen. The temperature of the measuring system was controlled during the measurements with a precision of 0.01 ^{o}C.

2.3. Measurement of the resistance torque of magnetic fluid seal

The resistance torque of magnetic fluid seal was measured by a torque spanner. On one side of the shaft of the magnetic fluid sealing device, a threaded hole was made and a hexagon screw was installed and tightened in it. The shaft of magnetic fluid sealing device was driven to rotate by the torque spanner through the hexagon screw. The set value of the torque spanner could be modified in the range of 5~60 cN·m with a precision of 0.5 cN·m. The diameter of the shaft was 20 mm and the type of torque spanner was N6LTDK produced by KANON.

3. Results

3.1. Result for magnetoviscous effect of magnetic fluid

Figure 2 shows the dependence of the viscosity of magnetic fluid on the magnetic field strength of No.1 (the sample contains less large particles) and No.2 (the sample

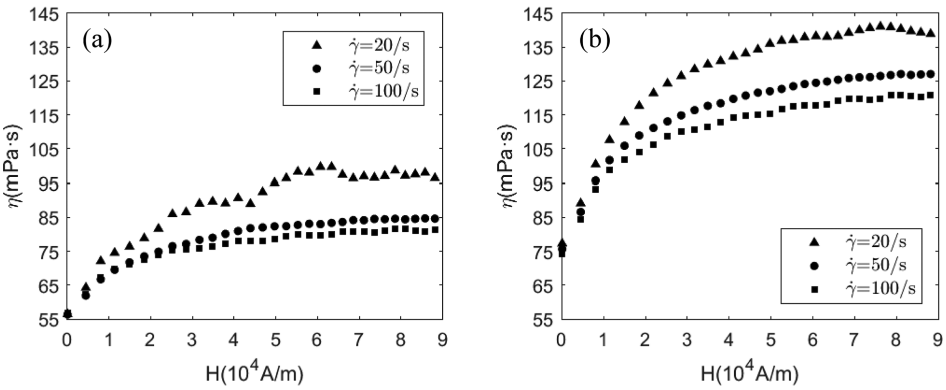

Fig. 2. The dependence of the viscosity of magnetic fluid on the magnetic field strength of No.1 magnetic fluid (a) and No.2 magnetic fluid (b) at the temperature of 20 °C when the shear rate is 20 /s, 50 /s, 100 /s, respectively.

contains more large particles) magnetic fluid samples at the temperature of 20 °C when the shear rate is 20 /s, 50 /s, 100 /s, respectively. It was observed that the viscosity of magnetic fluid increased with the increasing strength of magnetic field and gradually saturated. Also, the viscosity decreased with the increasing of shear rate. According to the experimental results, the viscosity of No.2 magnetic fluid was higher than No.1 magnetic fluid. Furthermore, the relative increase of the viscosity of No.2 magnetic fluid was also greater than No.1 magnetic fluid. It showed that the magnetoviscous effect was stronger when the proportion of large particles of magnetic fluid was higher.

3.2. Result for viscosity-temperature characteristics of magnetic fluid

Figure 3 shows the viscosity-temperature characteristic of magnetic fluid when the strength of magnetic field is 3 × 10^4 A/m and the shear rate is 50 /s. It could be seen that the viscosity of magnetic fluid decreased with the temperature. The rate of decline was fast below 10 °C, while it slowed down and gradually stabilized when the temperature was above 10 °C.

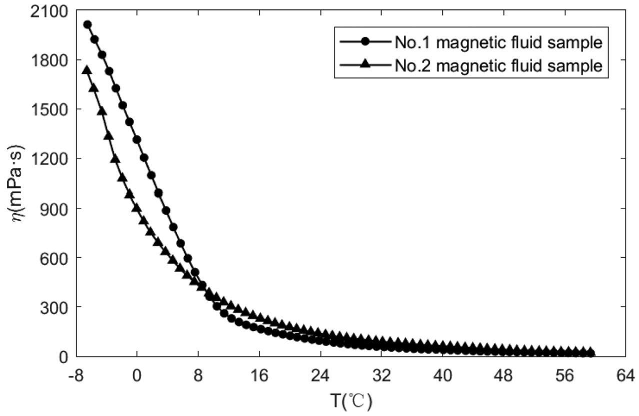

Fig. 3. The viscosity-temperature curve of No.1 and No.2 magnetic fluid when the magnetic field strength is 3 × 10^4 A/m and the shear rate is 50 /s, respectively.

3.3. Result for resistance torque of magnetic fluid seal

The resistance torque of the magnetic fluid seal using the ferrofluid with different particle size distribution is shown in Table 1. The result presented that the starting torque of magnetic fluid seal was larger than the resistance torque of stable operation. Furthermore, the starting torque of magnetic fluid seal using No.2 ferrofluid with a higher proportion of large particles was larger than using No.1 ferrofluid.

Table 1. The resistance torque of magnetic fluid with different particle size distribution.

Magnetic fluid number	Starting torque/ mN·m	Resistance torque of stable operation/mN·m
No.1 magnetic fluid	150	130
No.2 magnetic fluid	175	130

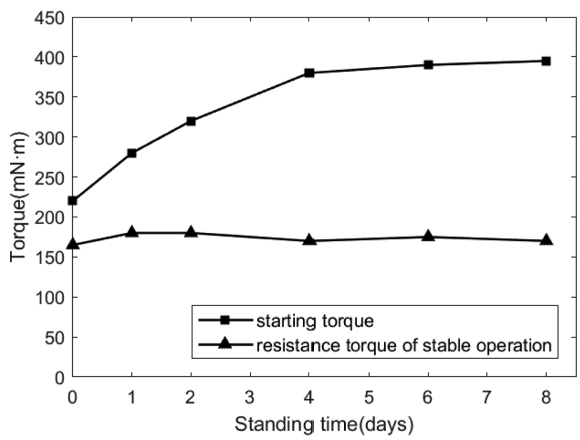

Fig. 4. The relationship between the resistance torque of magnetic fluid seal and standing time (using No.1 magnetic fluid).

Figure 4 displays the dependence of the resistance torque on the standing time for the No.1 magnetic fluid. As seen from Fig. 4, the starting torque of No.1 magnetic fluid seal increased significantly with the increase of standing time. When the standing time reached a certain value, the starting torque gradually stabilized. However, the resistance torque of stable operation was basically unchanged.

4. Discussion

4.1. The discussion of the magnetoviscous effect of magnetic fluid

From the established theories [9], the magnetic particles of large size could form chains under the influence of magnetic field. These particles are only a small part of the suspended magnetic particles. While the influence of these chains and their interaction with external fields are the dominant factor of the magnetoviscous effect.

During the magnetic separation process, the large particles concentrate in the lower part, while the small particles still maintain good uniformity. Therefore, the fraction of the large particles of No.2 sample is larger than that of No.1 sample. However, during this process, the total fraction of magnetic particles has also changed, which may also affect the magnetoviscous effect. But the fraction of large particles is so small that the total fraction of magnetic particles would not change much even if all the large particles concentrate in the lower part. Thus, in the following discussion, we focus on the difference in the fraction of large magnetic particles and neglect the difference in the total fraction of magnetic particles, since the effect of the formation of aggregations is more decisive.

Large particles form aggregations in the magnetic field which hinder the rotation of the particles in the flow, leading to the increase of the viscosity. Thus the viscosity of the magnetic fluid increases with the magnetic field strength, as seen from Fig. 2.

The aggregate structures of magnetic particles would be destroyed under a shear flow. As a result, the viscosity of the magnetic fluid decreases, which is called the shear thinning effect. Furthermore, when the shear rate is high enough, the aggregate structures are thoroughly destroyed and no longer exist. Then the viscosity of magnetic fluid no longer reduces and remains stable.

According to the results shown in Fig. 2, the reason that the magnetic fluid with a higher proportion of large particles has a more significant magnetoviscous effect can be attribute to the aggregation among magnetic particles. The No.2 magnetic fluid with a higher proportion of large magnetic particles is more likely to form aggregations and thus exhibit a more obvious magnetoviscous effect.

4.2. The discussion of the viscosity-temperature characteristics of magnetic fluid

Accordingly, we can also explain the experimental results of Fig. 3 from the point of formation and destruction of magnetic aggregations. As the temperature rising, the thermal energy of magnetic particles increases and the magnetic structures are more likely to break up, causing the viscosity of the magnetic fluid to decrease, thus leading to the reduction of resistance torque of magnetic fluid seal.

4.3. The discussion of the resistance torque experiment results

As seen from Table 1, the starting torque of the magnetic fluid seal using No.2 magnetic fluid sample is higher than No.1 magnetic fluid sample, basically because of the viscosity difference. Therefore, to reduce the resistance torque of magnetic fluid seal, magnetic fluid with lower viscosity is expected. However, the choice varies for different temperature ranges, since the two temperature-viscosity lines have an intersection. For the typical occasion that the magnetic fluid seal works at room temperature (20 °C), magnetic fluid which has less large particles is preferable. As for the phenomenon that the starting torque is greater than the resistance torque of stable operation observed in Table 1, it could be explained by the shear thinning effect of magnetic fluid. The shear rate increases from zero to the stable speed during the starting process, destroying the aggregations, causing the decrease of the viscosity, so the torque gradually reduces until constant.

The reason of the increase of starting torque with the expanding standing time in Fig. 4 could be explained by the separation of large particles in strong magnetic field. The large particles concentrate in the area with a relatively higher magnetic field strength gradually during the standing time and thus form chainlike magnetic structures, even complicated drop-like structures. The process keeps going with time expanding and finally stabilize, thus cause the starting torque change in the same pattern. Therefore, to keep the starting torque stable, the standing time need to be reduced. The magnetic fluid seal need to be rotated regularly when it is not running.

5. Conclusion

This paper studied the influence of the particle size distribution of magnetic fluid on the resistance torque of magnetic fluid seal by experiments on rheological properties of magnetic fluid and measurement of magnetic fluid seal resistance torque. A theoretical analysis was presented and leaded to the following conclusions.

(1) Magnetic fluid with higher concentration of large particles exhibits more obvious magnetoviscous effect since it is more easily to form aggregations.

(2) As the temperature decreases, the aggregations get longer and tougher, thus the viscosity of magnetic fluid increases significantly and leads to the increase of resistance torque of magnetic fluid seal.

(3) The starting torque of the magnetic fluid seal increases with the standing time expanding, because the large particles concentrate in the area of high magnetic field strength and form aggregations. Accordingly, the magnetic fluid sealing devices should be activated regularly.

(4) Owing to the shear thinning effect of magnetic fluid under a magnetic field, starting torque is greater than the resistance torque of stable operation for magnetic fluid seal. It's unavoidable, but the difference could be reduced by applying magnetic fluid containing less large particles.

(5) For sealing devices working in different range of temperature, different kinds of magnetic fluid may be chosen to reduce the resistance torque. For example, if the sealing device often work at room temperature (20 ^oC), magnetic fluid with lower proportion of large particles is better since its viscosity is lower.

Acknowledgement

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