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Design and simulation of horizontal large shaft diameter seal based on magnetic fluid

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ABSTRACT

As high-end equipment requires a higher and higher sealing effect, sealing forms such as packing seals expose problems such as considerable wear and high heat generated by friction. Based on the theoretical analysis of the instability at the liquid-liquid interface and the pressure resistance of the seal structure, considering the rotating speed of the rotating shaft, this paper reconstructs the formula for calculating the pressure resistance value of the seal structure. On this basis, a magnetic fluid seal structure is designed for a large horizontal shaft diameter in liquid. Based on the magnetic field analysis software Maxwell, the magnetic field of the magnetic fluid seal is analyzed, and the mapping relationship between the different tooth widths of the pole teeth, the size of the permanent magnet, and the difference in the magnetic induction intensity of the seal gap is obtained. Built in the ring seal test system, the pressure test of the horizontal large shaft diameter seal structure under different rotating speeds was carried out to verify the effectiveness of the seal structure. The results have specific theoretical research significance and engineering application value for designing and applying magnetic fluid seal structures.

Keywords: Magnetic fluid; Sealing; Large shaft diameter; Magnetic field; Pressure test.

1. INTRODUCTION

There are different degrees of leakage problems in various mechanical equipment. For the dynamic seal in industrial applications, the traditional seal forms mainly include packing seal, double-layer flat seal, gasket seal and other seal forms. The purpose of sealing depends on the pressure between rotating parts and fixed parts. Due to the defects of the sealing principle, significant friction wear and high friction heat are caused large leakage and other problems [1–3]. Magnetic fluid sealing technology is a new type of sealing technology, mainly using new magnetic nano-fluid materials to achieve the purpose of sealing, this form of sealing can not only overcome the friction loss problem, but also has the advantage of achieving "zero" leakage [4]. While magnetic fluid technology is becoming more sophisticated in sealing gases, it is still lacking in sealing liquids. When operating in a liquid environment, the magnetic fluid sealing structure involves very complex physical processes; when sealing liquids, the interfacial instability between the sealed medium and the magnetic fluid results in poor magnetic fluid sealing performance, lower pressure resistance compared to traditional sealing structures, and shorter sealing life. This paper will systematically analyze the magnetic fluid seal structure of a large shaft diameter rotating shaft. It mainly includes the principle of magnetic fluid seal, the pressure resistance value of magnetic fluid seal structure and the theoretical analysis of two kinds of liquid velocities, the influence of different tooth widths and permanent magnet sizes on the magnetic induction strength at the seal gap, the establishment of an experimental platform and the rotation speed of the rotating shaft as a factor affecting the pressure resistance value of the seal structure. According to the experimental results, a new formula for calculating the pressure resistance of magnetic fluid seal structure is obtained. Based on the above, it is expected that the improved magnetic fluid seal structure will significantly improve the sealing performance when sealing liquids.

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2. PRINCIPLE OF MAGNETIC FLUID SEAL

Magnetic fluid is a very typical composite material. It is mainly composed of a solid-liquid mixed colloidal solution [5] of nanometer-sized solid magnetic particles that can be distributed uniformly in the base carrier solution under the action of different interfacial active agents. Its composition is shown in Figure 1 [6]. The colloidal solution can remain stable without precipitation under the external magnetic and gravity fields [7].

The application of magnetic fluid in the sealing field is a relatively mature application of magnetic fluid at present [8]. After a long period of application research, design, and application, the magnetic fluid seal technology has matured. The magnetic fluid seal structure is mainly composed of four parts: permanent magnet, shaft, magnetic fluid and pole shoe. Its structure diagram is shown in Figure 2 [9]. The pole shoe is provided with multi-level pole teeth. The magnetic field generated by the permanent magnet passes through the pole shoe, the magnetic fluid, and the shaft to form a complete magnetic circuit. The magnetic fluid existing in the sealing gap forms a liquid "O" shaped seal ring under the action of the magnetic field to achieve the sealing effect [10–11].

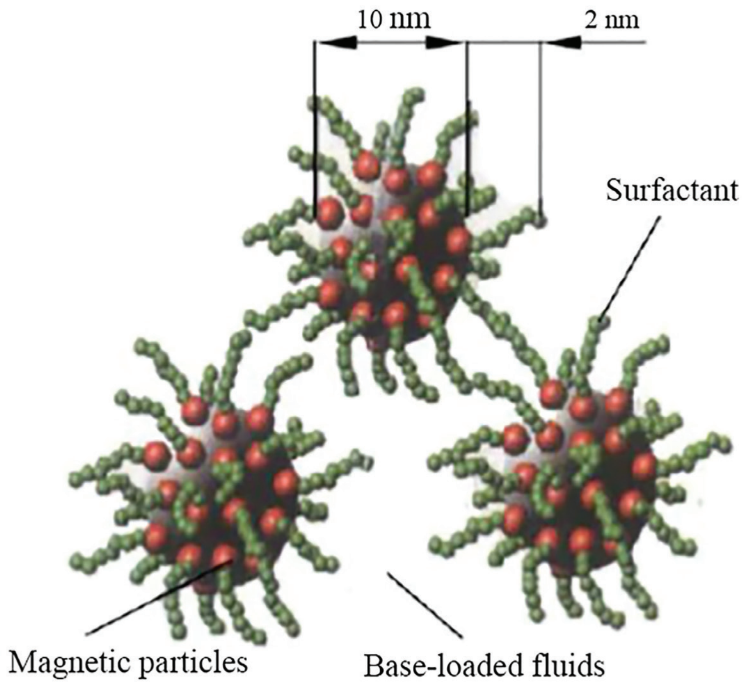
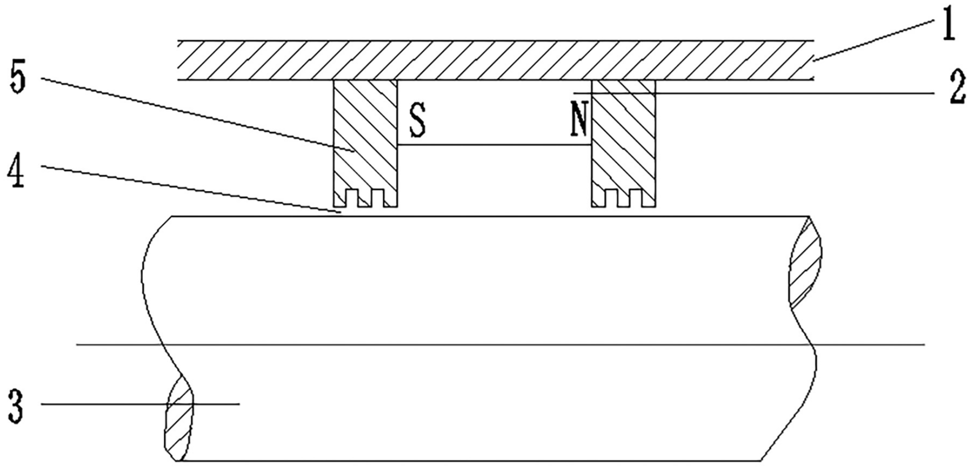


Figure 1: Composition of magnetic fluid.



1. Shell 2. Permanent magnet 3. Rotating shaft 4. Magnetic fluid 5. Pole shoe

Figure 2: Structure diagram of magnetic fluid seal.

3. THEORETICAL ANALYSIS

In the magnetic fluid sealing liquid structure, there is a relative movement between the magnetic fluid at the sealing gap and the liquid to be sealed. This relative movement causes the instability at the interface between the two liquids to expand [12]. In addition, in the large shaft diameter magnetic fluid seal structure, the size of the seal gap is far smaller than the size of the rotating shaft. At this time, the magnetic fluid motion at the seal gap is assumed to be pure shear motion. Only circumferential motion is available, meeting the Kuette flow model between two cylinders, generally moving and stationary [13–14]. The movement of the sealed liquid in the sealing chamber is also treated according to this model.

Figure 3 shows the structural diagram of the magnetic fluid seal when it is used to seal liquid medium, where R1 is the radius of the shaft, R2 is the inner diameter of the pole shoe, and R3 is the inner diameter of the seal chamber. The sealed liquid in the large shaft diameter sealing structure is a common fluid, and the motion equation of the common fluid is:

$$\rho \frac{\partial v}{\partial t} + \rho V.\nabla V = \rho g - \nabla p + \eta \nabla^2 V \tag{1}$$

Where: ρ—density of the ordinary fluid

V—Velocity of ordinary fluid

g—Gravitational constant

η—Dynamic viscosity coefficient of ordinary fluid

∇p—Pressure gradient

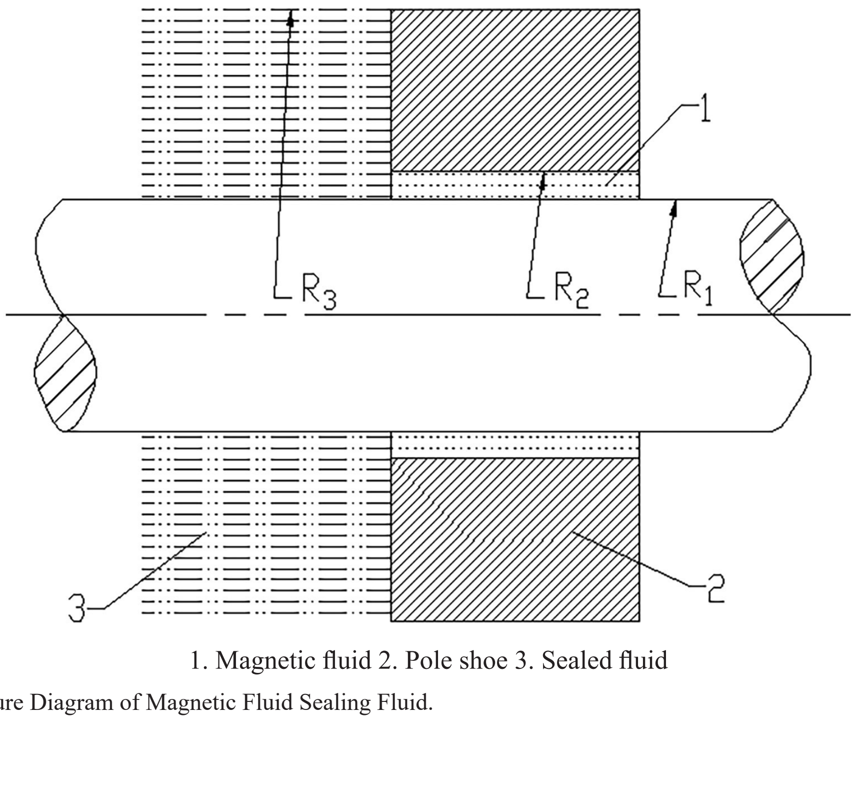
The radial size of the sealed liquid is small, so the flow of the sealed liquid can be regarded as one-dimensional laminar flow along the tangential direction, and the sealed liquid is incompressible, ignoring the gravity and axial and radial velocity components of the sealed liquid. According to the above characteristics:

$$\rho = const, v_r = v_z = 0, \frac{\partial v\theta}{\partial t} = 0, \frac{\partial v\theta}{\partial t} = 0$$

Where: v_r—The radial component of the velocity of the liquid to be sealed

v_z—The radial component of the movement speed of the sealed liquid

v_θ—Circumferential component of the movement speed of the sealed liquid



1. Magnetic fluid 2. Pole shoe 3. Sealed fluid

Figure 3: Structure Diagram of Magnetic Fluid Sealing Fluid.

The velocity formula of the liquid to be sealed is:

$$v_{\theta 1} = \frac{\omega R_1^2}{R_1^2 - R_3^2}\left(r - \frac{R_3^2}{r}\right) \tag{2}$$

Assuming that the magnetic particles in the magnetic fluid are uniformly distributed, the motion equation of the magnetic fluid is:

$$\rho\frac{\partial v}{\partial t} + \rho V.\nabla V = f_b + f_s \tag{3}$$

Where: f_b—volume force on the fluid

f_s—Surface force on the fluid

The velocity formula of the magnetic fluid is:

$$v_{\theta 2} = \frac{\omega R_1^2}{R_1^2 - R_3^2}\left(r - \frac{R_2^2}{r}\right) \tag{4}$$

According to the above conclusion, the velocity difference function at the interface between the magnetic fluid and the sealed liquid is:

$$\begin{aligned}\Delta v = v_{\theta 1} - v_{\theta 2} &= \frac{\omega R_1^2}{R_1^2 - R_3^2}\left(r - \frac{R_3^2}{r}\right) - \frac{\omega R_1^2}{R_1^2 - R_2^2}\left(r - \frac{R_2^2}{r}\right) \\ &= \omega R_1^2\left[\begin{array}{l}\left(\frac{1}{R_1^2 - R_3^2} - \frac{1}{R_1^2 - R_3^2}\right)r \\ +\left(\frac{R_2^2}{R_1^2 - R_2^2} - \frac{R_3^2}{R_1^2 - R_3^2}\right)\frac{1}{r}\end{array}\right]\end{aligned} \tag{5}$$

It can be seen from the above formula that the rotating speed of the shaft is related to the relative speed at the interface between the two liquids. The higher the rotating speed of the shaft is, the more significant the velocity difference at the interface is, and the interface stability is reduced [15], resulting in a reduction in the pressure resistance value of the seal structure.

According to the literature [16], the simplified Bernoulli equation of magnetic fluid is:

$$p^* + \frac{1}{2}\rho_m V^2 + \rho_m gh - \mu_0\int_0^H MdH = \mathrm{C} \tag{6}$$

Including:

$$p^* = p + p_m + p_s$$

$$p_m = \mu_0\int_0^H MdH$$

$$p_s = \mu_0\int_0^H \rho_m\frac{\partial M}{\partial \rho_m}dH$$

Where: C—Constant

p_m—Magnetization pressure of the magnetic fluid

p_s—Magnetostrictive pressure of the magnetic fluid

The general formula for calculating the withstand voltage value of the magnetic fluid seal structure is as follows:

$$\Delta p = NM_s \left(B_{\max} - B_{\min} \right) \tag{7}$$

According to the derivation of the velocity difference function at the interface, the rotating speed of the shaft has a certain influence on the withstand voltage value of the seal structure. However, the above withstand voltage formula does not consider the influence of the rotating speed on the withstand voltage value of the multistage magnetic fluid seal structure. Now, a modified formula for calculating the withstand voltage value is proposed:

$$\Delta p = NM_s \left(B_{\max} - B_{\min} + f\left(\omega\right) \right) \tag{8}$$

Where: *f(ω)*—the function of shaft speed, with a negative value

It can be seen from the above functional relationship that the pressure resistance value of the seal structure decreases with the increase in rotating speed, and the specific expression is fitted according to the following experimental data.

4. MAGNETIC FIELD SIMULATION

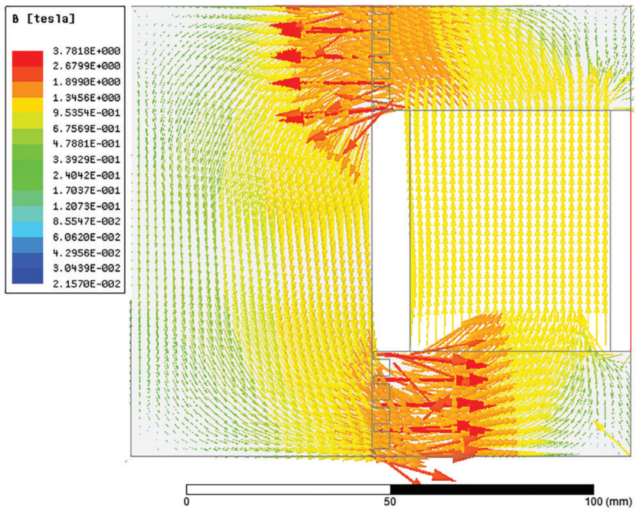
Aiming at the question of whether the size of the large-shaft diameter magnetic fluid seal structure is reasonable, Maxwell is used to simulate and analyze the static magnetic field. Compared with other software of the same type, Maxwell has higher simulation accuracy for three-dimensional and two-dimensional magnetic fields, while the simulation is less computationally intensive and more responsive, and can use parametric design functions to create different dimensions and analyze the effects of different parameters on electromagnetic forces. In this paper, Maxwell is used to model the tooth widths of different sizes of pole teeth and permanent magnets, to visually judge the rationality of the magnetic circuit of the seal structure by the distribution of magnetic induction lines in the large shaft diameter seal structure, and to plot the distribution curve of magnetic induction intensity at the seal gap.

4.1. Influence of tooth width on magnetic induction strength at seal clearance

In order to explore the influence of the tooth's width of the polar gear on the magnetic induction strength at the seal gap, when the size of the permanent magnet is unchanged, models with the tooth width of the polar gear of 2 mm, 3 mm and 4 mm are established in Maxwell. The magnitude and direction of magnetic field intensity at different positions in the large shaft diameter seal structure can be viewed through the magnetic flux density vector diagram. When the sealing gap is 0.5 mm, the magnetic flux density vector diagram for different tooth widths is shown in Figure 4. The direction of the arrow in the figure represents the direction of the magnetic field, and the color shades represent the magnitude of the magnetic field strength. It can be seen from the figure that the magnetic flux density at the pole teeth is the largest and uniformly distributed, and the magnetic field in the pole boots on both sides of the permanent magnet is in opposite directions, forming a closed magnetic circuit, which verifies the rationality of the large axis diameter magnetic fluid seal structure.

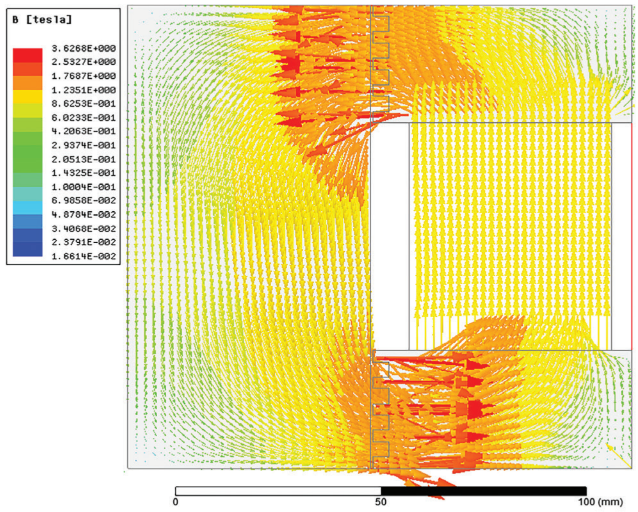
The magnetic induction intensity distribution cloud expresses the magnitude of the magnetic induction intensity mode at different locations in the model. Figure 5 shows the magnetic induction intensity distribution cloud for different tooth widths. The figure shows that the magnetic field intensity at different locations in the model with different tooth widths is constantly changing. The overall magnetic induction intensity at the pole tooth is obviously higher than that at the tooth groove. The magnetic induction intensity at the pole tooth is the largest, and the local location can reach 2.5. The magnetic induction intensity at the pole tooth is the highest, and the magnetic induction intensity at different pole teeth is close to each other, and the overall magnetic circuit shows a symmetric distribution. From this figure, it can be seen that the boundary of each different magnetic induction intensity is smoother, which indicates that the mesh division quality is good in this simulation pre-processing process and meets the requirements of static magnetic field simulation calculation. In addition, there is a more obvious distribution of magnetic induction gradient in the axial direction, which is the premise that the magnetic fluid seal structure has a certain pressure resistance value, the magnetic fluid under the action of the magnetic field in the polar teeth to form a liquid "O" seal, to play a sealing effect.

(a)



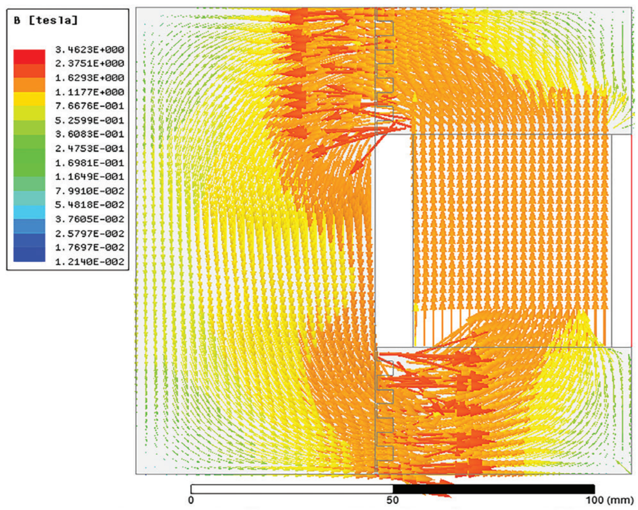
Tooth width is 2mm

(b)



Tooth width is 3mm

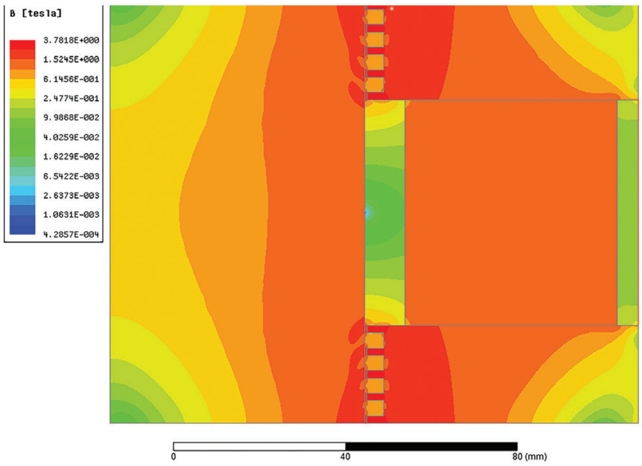
(c)



Tooth width is 4mm

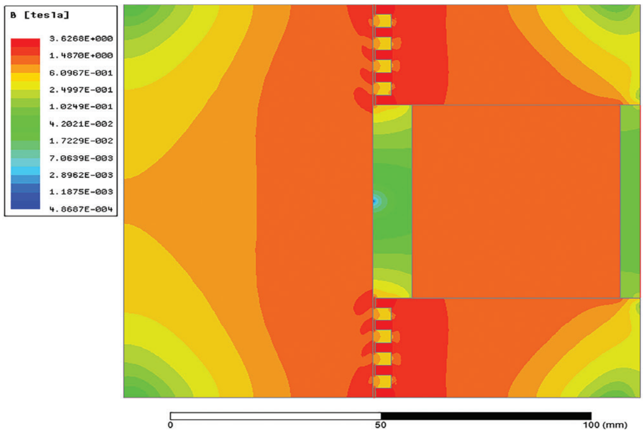
Figure 4: Vector diagram of magnetic flux density for different tooth widths:(a) Tooth width is 2 mm, (b) Tooth width is 3 mm, (c) Tooth width is 4 mm.

(a)



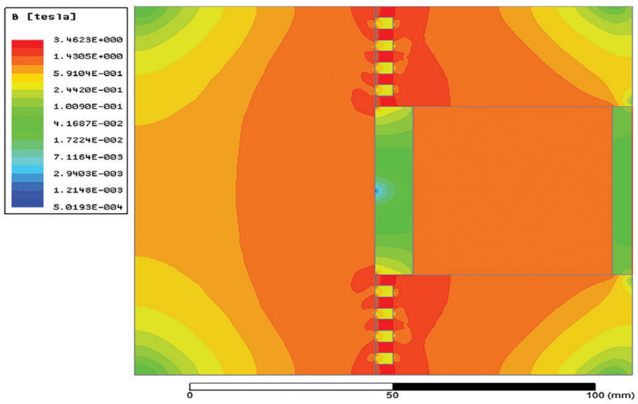
Tooth width is 2mm

(b)



Tooth width is 3mm

(c)



Tooth width is 4mm

Figure 5: Cloud map of magnetic induction intensity distribution for different tooth widths:(a) Tooth width is 2 mm, (b) Tooth width is 3 mm, (c) Tooth width is 4 mm.

According to the formula of the pressure resistance value of magnetic fluid seal structure in equation (7), if we want to get the pressure resistance value, we need to get the specific value of magnetic induction intensity at each pole tooth at the seal gap. We derive the magnetic induction intensity graphs at the seal gap under different tooth width sizes according to the simulation results, as shown in Figures 6, 7 and 8. It can be seen from these three figures: the magnetic induction intensity is the largest on the outermost side of the pole shoe, and the maximum magnetic induction intensity value can reach 3.58T when the tooth width is 2mm. Based on the coordinates of the positions of the peaks and troughs appearing in the image, it can be concluded that the magnetic

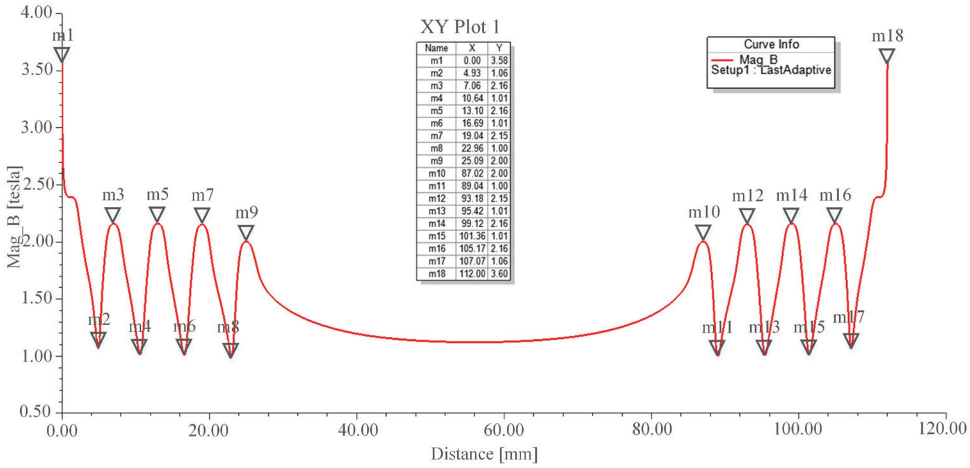


Figure 6: Magnetic induction intensity curve at the seal gap of 2 mm tooth width.

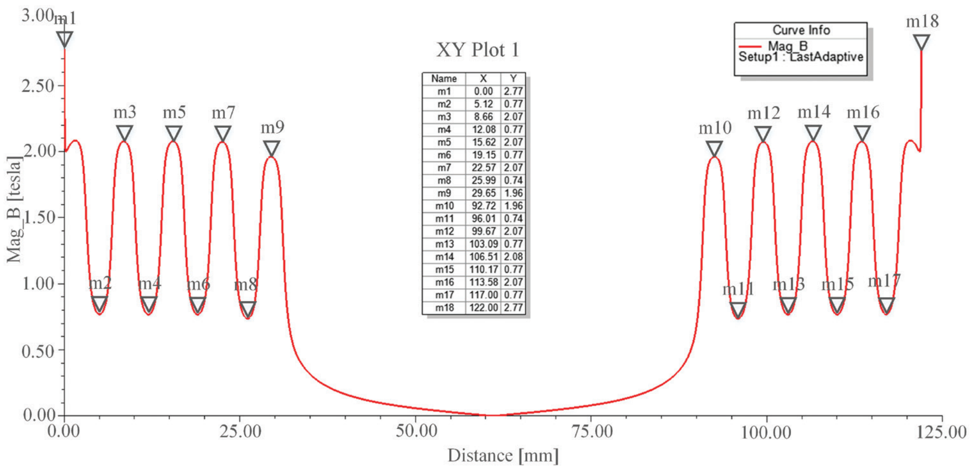


Figure 7: Magnetic induction intensity curve at the seal gap of 3 mm tooth width.

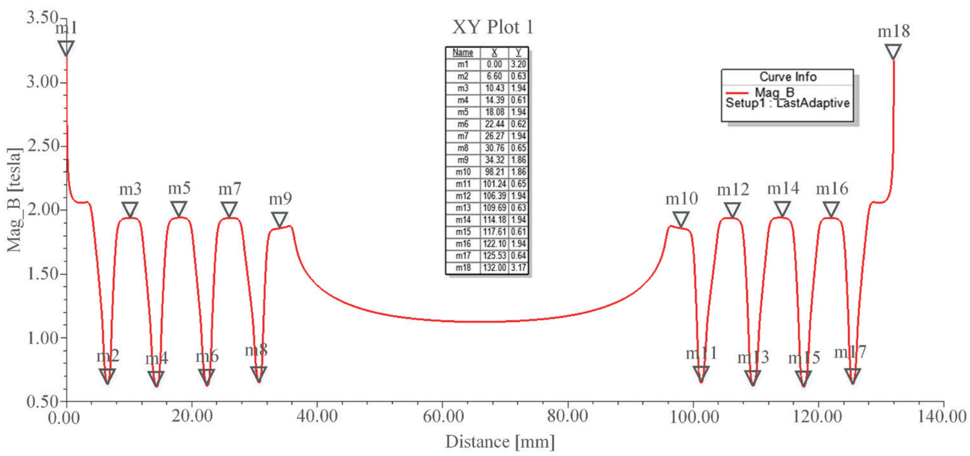


Figure 8: Magnetic induction intensity curve at the seal gap of 4 mm tooth width.

induction intensity is maximum at the polar teeth and minimum at the tooth grooves. When the tooth width is 2 mm, the magnetic induction intensity at the position without the pole tooth is larger compared with other tooth width dimensions, so the pole tooth width dimension is finally determined as 2 mm.

4.2. Effect of permanent magnet size on magnetic induction intensity at the sealing gap

In order to investigate the effect of permanent magnet size on the magnetic induction intensity at the sealing gap, when the tooth width is 2 mm, and the inner diameter of the permanent magnet is 320 mm, the models of permanent magnet outer diameter of 420 mm, 400 mm and 380 mm are established in Maxwell. According to the simulation results obtained, the effect of permanent magnet size on the magnitude of magnetic induction at the sealing gap is analyzed. The magnetic induction curves for different permanent magnet outer diameter sizes are shown in Figures 9, 10 and 11. From the above data, it can be seen that the maximum value of magnetic induction at the gap decreases gradually as the outer diameter of the permanent magnet decreases. The difference in magnetic induction near the pole tooth is an important factor affecting the pressure resistance value of the seal structure. When the difference of magnetic induction near the pole tooth is smaller, the pressure resistance value of the seal structure is smaller at this time, which is not conducive to the application of the seal structure. In summary, the width of the pole tooth teeth is 2 mm, the inner diameter of the permanent magnet is 320 mm, and the outer diameter is 420 mm, which can ensure the pressure resistance value of the sealing structure to the greatest extent.

5. EXPERIMENTAL DATA ANALYSIS

The experimental method in this paper has been verified and analyzed in other projects, and proved to be feasible and reliable. Therefore, this paper has carried out relevant simulation experiments based on existing research. From the theoretical analysis in Section 3, it is known that the rotating shaft speed is a factor affecting the pressure resistance value. In order to investigate the relationship between the rotational speed of the rotating shaft

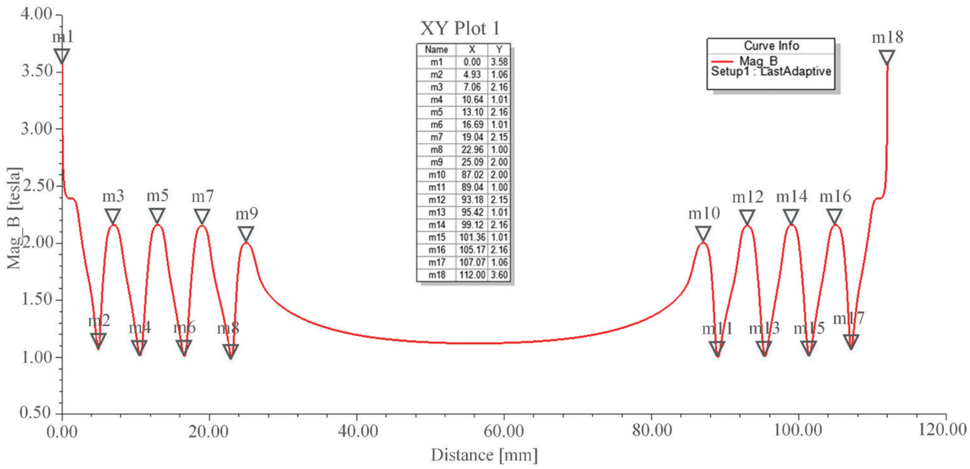


Figure 9: Magnetic induction intensity curve at the sealing gap of 420 mm outside diameter of permanent magnet.

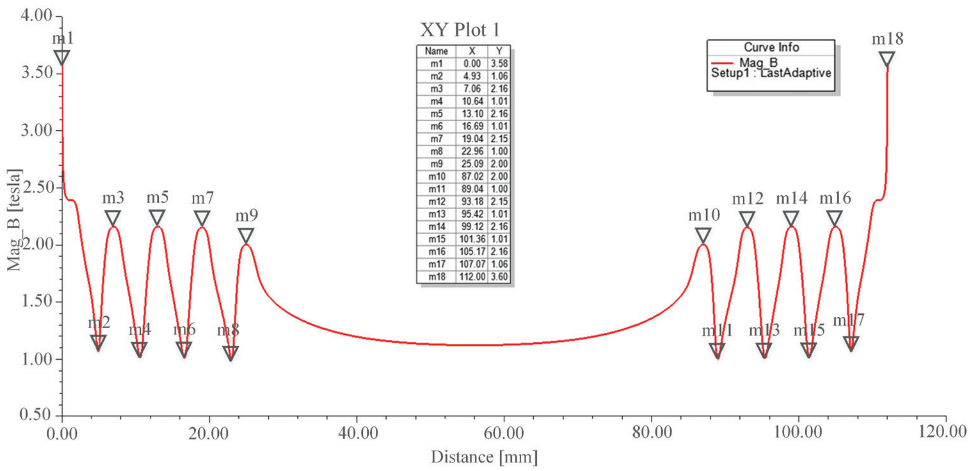


Figure 10: Magnetic induction intensity curve at the sealing gap of 400 mm outside diameter of permanent magnet.

and the pressure resistance value of the sealing structure, experiments on the rotational speed of the shaft and the pressure resistance capacity of the seal structure were designed, and the pressure resistance values of the seal structure at different rotational speeds of 100 r/min, 200 r/min and 300 r/min were studied in comparison. The experiment is mainly composed of the power, water supply, control, and sealing units. After setting up the experimental table, after injecting the magnetic fluid into the seal gap, the governor was used to control different rotational speeds of the rotating shaft. When the rotational speed of the spindle reaches the experimental requirements, the water supply device starts to supply pressurized water to the sealing device, and observe the pressure value of water when the seal fails in case of leakage, at which time the pressure of water is the maximum pressure resistance value of the seal structure. After completing one experiment, refill the magnetic fluid and conduct the next set of experiments. The experimental results are shown in Table 1.

Figure 12 shows a scatter plot based on the experimental data, and the curve in the figure is a logarithmic function image fitted to the experimental data, from which it can be seen that the seal structure pressure

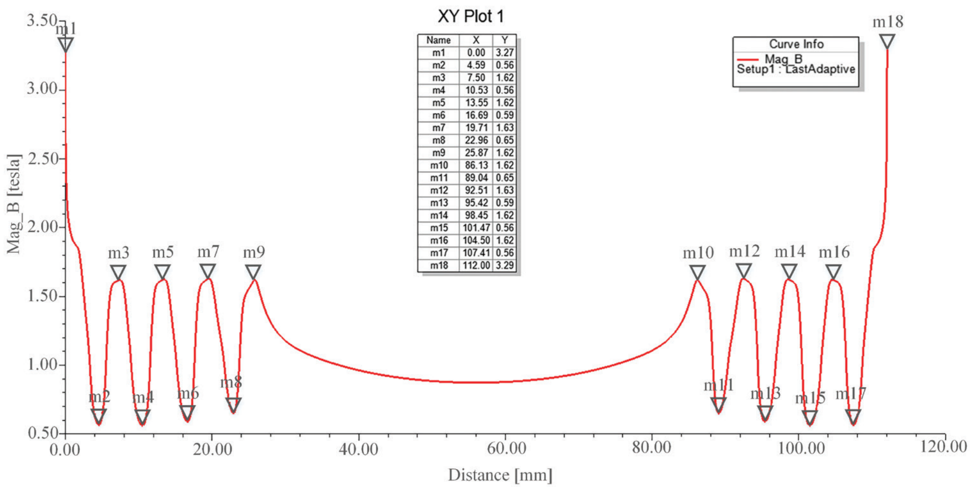


Figure 11: Magnetic induction intensity curve at the sealing gap of 380 mm outside diameter of permanent magnet.

Table 1: Record table of experimental results.

SPINDLE SPEED/(r/min)	PRESSURE RESISTANCE VALUE/(Mpa)
100	0.61
200	0.45
300	0.34
400	0.23
500	0.16
600	0.11

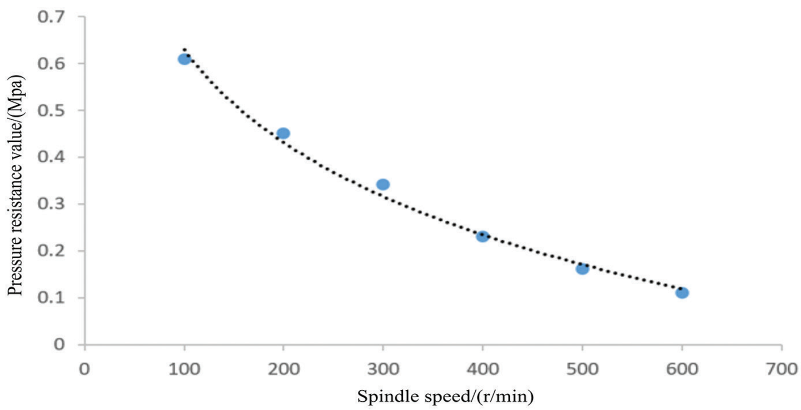


Figure 12: Relationship between the pressure resistance value of sealing structure and rotating shaft speed.

resistance value decreases more rapidly when the rotating shaft speed increases from 100 r/min to 400 r/min. When the speed exceeds 500 r/min, the pressure resistance value of the seal structure is lower. On the one hand, this phenomenon is due to that the velocity difference between the magnetic fluid and the liquid medium to be sealed gradually increases with the increase of the rotational speed of the rotating shaft, at this time, the instability at the interface increases, resulting in a continuous decrease in the pressure resistance value of the seal structure. On the other hand, with the increase of the rotating speed of the shaft, the flow mode of the sealed liquid and the magnetic fluid at the seal gap changes. When the rotating speed is low, the pressure resistance values of the two liquids are calculated using the laminar flow model. With the increase of the rotating speed, the flow mode of the two liquids changes from laminar flow to turbulent flow, causing the pressure resistance value of the seal structure to decrease.

According to the fitted logarithmic function image [17], a new type of magnetic fluid seal device pressure resistance value calculation formula is obtained.

$$\Delta p = -0.248\ ln\ \omega + 1.9386 \tag{9}$$

The formula can be used to estimate the pressure resistance of the rotating shaft at a certain speed when the seal clearance is 0.5 mm, which can be helpful to the practical problems encountered in engineering applications.

6. RESULTS

Aiming at the problems of large wear and leakage of traditional seals, the structure of magnetic fluid seal with large shaft diameter is systematically analyzed in this paper. Based on the equations of general fluid dynamics and the theory of magnetic fluid dynamics, the relationship between the rotational speed of the rotating shaft and the velocity distribution of the sealed fluid, and the relationship between the rotational speed of the rotating shaft and the velocity distribution of the magnetic fluid are derived. Analyzes the interface stability and pressure resistance value calculation formula through theoretical analysis, and proposes a new pressure resistance value calculation formula for the problems existing in the pressure resistance value calculation formula. In order to discuss the influence of the tooth width of the polar gear and the size of the permanent magnet on the magnetic induction strength at the seal gap, models of different sizes are established in the simulation software Maxwell for numerical simulation, and the reasonable size of the tooth width and the permanent magnet is determined; According to the experimental results, a new formula for calculating the withstand voltage value is fitted, which provides a theoretical basis for the problems encountered in engineering applications.

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