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Sealing Behavior Research on the Radial Ferrofluid Seal Structure with Oblique Teeth

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Considering various unstable factors when the large-diameter spindle operates at a high speed, such as eccentricity, centrifugal force, etc., the ordinary ferrofluid seal structures will show poor sealing performance. This paper proposes an axial-radial bidirectional ferrofluid seal structure with radial oblique teeth to improve the sealing performance. The pressure resistance of the radial ferrofluid seal structure in the magnetic circuit is theoretically analyzed. The magnetic flux distribution characteristic in the gap of the oblique teeth is studied by magnetic field simulation. According to the analysis results of the magnetic induction intensity, to obtain the larger theoretical pressure resistance, the optimal angle of oblique teeth is 77.87°, 64.28° and 62.81° under the radial seal structure with different gaps of 0.1 mm, 0.15 mm and 0.2 mm, respectively. In addition, simulation analysis is carried out to obtain the fluid pressure and velocity distribution of the radial ferrofluid seal structure with different oblique teeth angles. When the oblique teeth angle is small, the pressure drops and gas flow speeds in the ferrofluid area are all lower, and the pressure resistance is higher.

Keywords : ferrofluid seal, oblique tooth, magnetic field simulation, flow field simulation

1. Introduction

Magnetorheological fluid (MRF) and ferrofluid are all smart materials whose properties can be controlled by means of external magnetic field and all composed of carrier liquid, ferromagnetic particle and additive. There is a difference between them in size of ferromagnetic particle, known as MRF with micron-sized ferromagnetic particle and ferrofluid with nanometer-sized ferromagnetic particle, which makes them show different physical properties in the presence of external magnetic field, such as magnetorheological effect for MRF and magnetoviscous effect for ferrofluid [1]. Based on the magnetic response properties, MRF and MF can all be used as seal mediums of seal structures to solve some seal problems [2]. Compared with MRF, ferrofluid is more widely used. Ferrofluid sealing technology is a new sealing way with the advantages of simple design, zero leakage, low friction and less pollution, which is more suitable for the dynamic seal of rotating spindle with a high speed due to the small friction torque [3]. Compared with ferrofluid, MRF has high magnetic permeability, high chain strength, and relatively high-pressure resistance, but MRF will cause shaft wear, and its durability and stability are poor. The operating temperature range of dynamic sealing is relatively small, for the increased working temperature can reduce the viscosity of the MRF and ferrofluid, which reduces its pressure resistance.

For the dynamic seal of ferrofluid, the common sealing form is the axial seal. The ferrofluid is adsorbed in the gap between the dynamic spindle and the static pole boot as the sealing medium to play the role of the dynamic seal [3]. However, when this sealing form is applied to the high-speed rotating spindle, the sealing effect is not ideal due to the great influence of the high rotating speed of the spindle [4]. In the case of heavy machinery with a large diameter rotating spindle at a high speed, eccentricity and centrifugal force will increase the instability of the seal structure, and the traditional sealing method can cause mechanical wear and seal leakage. These unstable factors can cause the radial movement of the ferrofluid and reduce the axial section distance of the sealing ring formed by the ferrofluid on the spindle surface, which will lead to the decrease of the magnetic induction

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intensity difference between the two interfaces and its sealing performance [5]. Saurabh Parmar *et al.* [6] carried out static and dynamic tests on radial gap ferrofluid seal, which proved that radial gap has better pressure resistance. Therefore, to improve the sealing ability of the ferrofluid seal on the high-speed and large-diameter rotating spindle, the radial ferrofluid seal is added to the traditional axial seal to optimize its structure. This structure can reduce the influence of eccentricity and centrifugal force on sealing performance, and solve the problem of seal reliability of the high-speed and large-diameter rotating spindle.

2. Axial-radial Bidirectional Ferrofluid Seal Structure

As is shown in Fig. 1, the axial-radial bidirectional ferrofluid seal structure consists of permanent magnets, the axial seal and the radial seal, which are fulfilled through the series magnetic circuit. The radial seal structure is located between the permanent magnets and the axial seal part. Ferrofluid is usually filled in the gap as a sealing medium and like a liquid O-ring under the control of an external magnetic field. The inner surfaces of the first and the second static rings have been designed into rectangular teeth and form an axial seal with ferrofluids on the rotating spindle.

Permanent magnets are fixed between the first and the second moving rings, which are fixedly connected on the rotating spindle. The end surfaces of the static rings and the moving rings are designed into oblique pole teeth. They form two sets of radial seals, which are located on both sides of the permanent magnet and show a symmetrical structure. Chambers on both sides of the axial and radial seal gaps connect and form a tandem seal. The eccentricity will cause a decrease in the pressure tolerance of the axial seal. However, this type of tandem seal can effectively reduce the effect of eccentricity on the pressure resistance of the system. To a certain extent, the radial sealing structure can supplement the deficiency of axial sealing performance and ensure the stability of the sealing system.

Centrifugal force makes the ferrofluid move radially, which has a great influence on the sealing capacity. To reduce the impact, the pole teeth at the two sets of radial seals are designed as oblique teeth. As can be seen from Fig. 1, the oblique teeth are arranged in a staggered pattern in the direction of the short edge. There are four pole pieces, the middle two pole pieces have 13 oblique teeth, the two side pole pieces have 7 rectangular teeth on the inner surface, and the end surface has 13 oblique teeth. The gap between each pair of oblique teeth is the

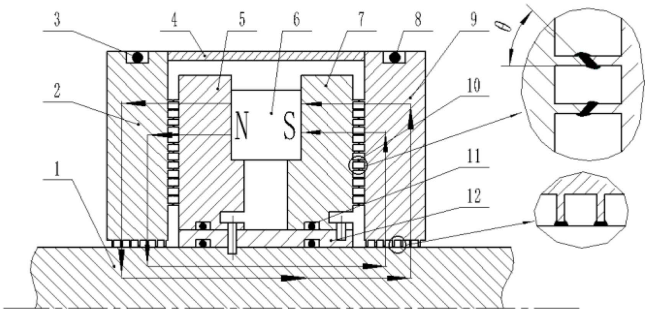


Fig. 1. Diagram of axial-radial bidirectional ferrofluid seal structure: 1. Rotating spindle 2. First static ring 3. Sealing ring 4. Positioning spacer ring 5. First moving ring 6. Permanent magnet 7. Second moving ring 8. Sealing ring 9. Second static ring 10. Ferrofluid 11. Sealing ring 12. Non-conductive magnetic shaft sleeve.

area of the ferrofluid. The gap height between the inner diameter of the rectangular teeth and the outer diameter of the rotating spindle is 0.3 mm. During the operation of the sealing structure, the first and second moving rings of the radial seal rotate together with the rotating spindle with the diameter of 55 mm.

According to the magnetic circuit in Fig. 1, it can be seen that the magnetic field produced by permanent magnets forms a closed loop in the seal structure, which passes through the radial and the axial gaps. Under the action of strong magnetic field, the ferrofluid in the gap forms an "O"-shaped sealing ring, which achieves the sealing effect.

3. Theory Analysis of the Ferrofluid Seal

The general form of the Bernoulli equation for ferrofluids is

$$p^* + \frac{1}{2}\rho_f V^2 + \rho_f gh - \mu_0 MH = const. \qquad (1)$$

Where p^* is the pressure, ρ_f is the fluid density, g is the gravitational acceleration, V is the velocity, μ_0 is the permeability of free space, M represents the magnetization of the suspension, H is the magnetic field, and h is the height above a reference plane.

The radial gap between the first static ring and the first moving ring is analyzed. Suppose that the magnetic field lines at the gap can be approximately replaced by arcs and that the isomagnetic field lines coincide with the magnetic field lines, ignoring the surface tension of the ferrofluid. Under the assumption of intrinsic property, the ferrofluid magnetization $\boldsymbol{M}$ is parallel to the external magnetic field $\boldsymbol{H}$. The normal component of the $\boldsymbol{M}$ does not exist on the symmetric middle plane in the gap, that is, the M_n is equal to zero. The ferrofluids are affected by the parallel magnetic field, and the gravitational potential energy is generated by radial deformation caused by the pressure difference between the two sides of the ferrofluid [7]. Based on the above assumptions, the Bernoulli equation is

$$p_1 + \rho_f g h_1 - \mu_0 \int_0^{H_1} MdH = p_2 + \rho_f g h_2 - \mu_0 \int_0^{H_2} MdH \quad (2)$$

$$\Delta p = p_1 - p_2 = \rho_f g(h_2 - h_1) + \mu_0 \int_{H_2}^{H_1} MdH = \rho_f g(h_2 - h_1) + M \cdot \Delta B \quad (3)$$

Where h_1 and h_2 are the heights of the fluid films on the high-pressure side and on the low-pressure side, respectively.

According to the above formula, the pressure resistance of multi-stage radial seals can be deduced [8], that is

$$\Delta P_{radial} = \sum_{i=1}^{n} \rho_f g(h_{2\max} - h_{1\max}) + \sum_{i=1}^{n} M_s \Delta B_{Ri} \quad (4)$$

Where M_s is the saturated magnetization strength of ferrofluids, ΔB_{Ri} is the magnetic induction intensity gradient on both sides of the ferrofluid at each oblique tooth of the radial seal, n is the number of oblique teeth on the side of the radial seal.

The total pressure resistance of the radial seals on both sides can be written as

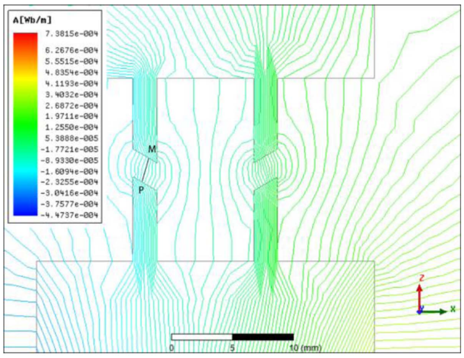
$$\Delta P = 2\sum_{i=1}^{n_2} M_s \Delta B_{Ri} \quad (5)$$

4. Effect of Oblique Teeth Angle on the Sealing Performance

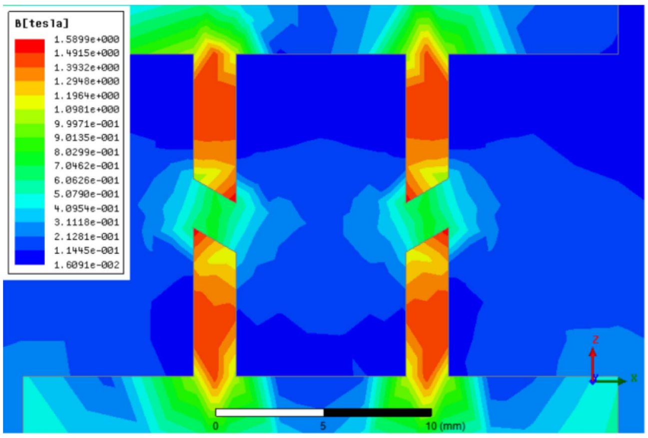
4.1. Magnetic field simulation analysis

It is known that the seal structure is an axisymmetric model, which can be converted into a two-dimensional model for simulation analysis. When the external magnetic field intensity is strong enough, the ferrofluid in the gap can be approximately considered as medium with saturation. In addition, to explore the distribution of magnetic induction intensity within the gap, the ferrofluid can be treated as an air item, and the hysteresis phenomenon of the pole boots can be ignored [9]. The higher the saturation magnetization of ferrofluid, the stronger the ability resisting the centrifugal force and the more stable the sealing performance [10]. Therefore, perfluoropolyether oil (PFPE-oil) based ferrofluid with higher saturation magnetization of 334Gs is used in the gap. The material properties of each part in the seal structure are shown in Table 1.

Based on the parameters, the magnetic field analysis of the oblique teeth in the radial seal is carried out. The corresponding simulation results, including the distribution of magnetic field lines and the cloud map of the magnetic induction intensity in the gap, are shown in Fig. 2. The



(a) Distribution of magnetic field lines at oblique teeth and the line M-P



(b) Cloud map of the magnetic induction intensity at oblique teeth

Fig. 2. (Color online) Distribution of magnetic field lines, the cloud map of the magnetic induction intensity at the gap between the oblique teeth at the radial seal.

Table 1. Material properties.

Parts	Spindle	Pole pieces	Permanent magnet	Nonmagnetic shaft sleeve	Isolation ring	Ferrofluid
Materials	2Cr13	2Cr13	NdFeB	304 stainless steels	304 stainless steels	Perfluoropolyether oil (PFPE-oil) based ferrofluid

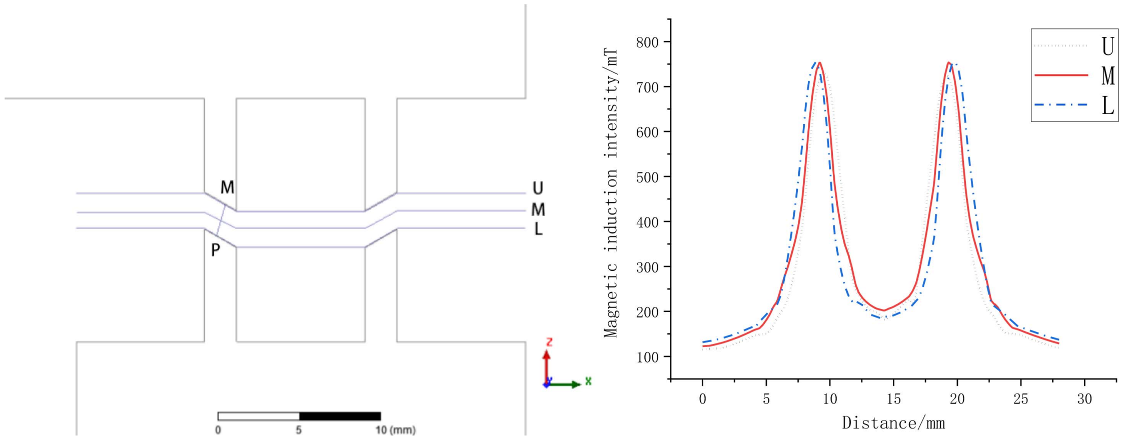


Fig. 3. (Color online) Change curve of the magnetic induction intensity at the three positions in the gap, U-line near the static ring polar tooth (top side), L-line near the polar tooth side (bottom side), M-line at the center position within the gap.

line M-P in the gap is perpendicular to the short side of the oblique tooth. It can be seen from Fig. 2(a) that the direction of the magnetic field lines in the gap is perpendicular to the short side of the oblique tooth, and the magnetic flux inside the pole tooth all almost converges in the gap. The accumulation of magnetic flux increases the magnetic induction intensity in the gap to improve the pressure resistance and the using life of the ferrofluid seal.

The approximate formula for calculating the pressure difference between a pair of oblique teeth is $\Delta P(\approx M_s \Delta B_{Ri})$, $\Delta B_{Ri}(= B_{\max} - B_{\min})$ represents the maximum difference in magnetic induction intensity of the ferrofluid, namely the numerical difference between peaks and valleys on the change curve [11]. As can be seen from Fig. 2(b), the magnetic induction intensity at the sharp corner is much higher due to the sharp angle effect of the magnetic field.

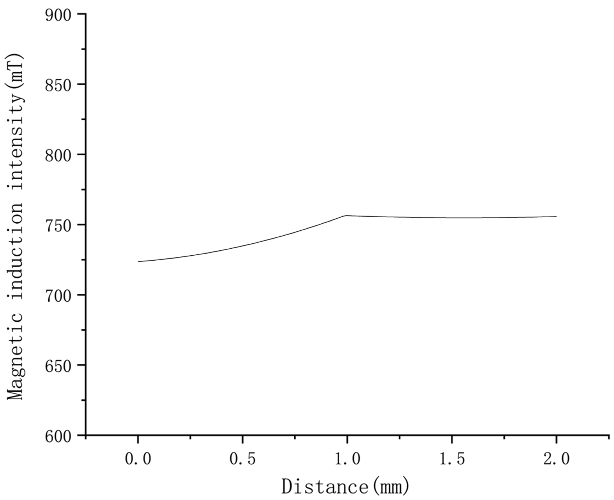
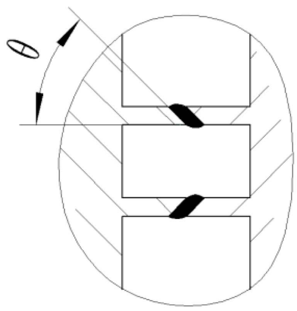


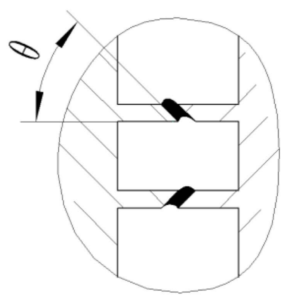
Fig. 4. Magnetic induction intensity distribution at the M-P line.

Figure 3 shows the variation curve at the three different positions, with the maximum values of 0.54T, 0.56T and 0.55T for U-line, L-line and M-line, respectively. The values are approximately equal, which shows that the ferrofluid in the gap has a consistent magnetic induction strength gradient, and this unique magnetic flux characteristic in the gap can ensure that ferrofluids in the gap are not prone to seal failure, so the sealing performance of the oblique tooth structure is stable.

As can be seen from Fig. 4 that the magnetic induction



(a) in the static state



(b) under the action of centrifugal force

Fig. 5. Diagram of the shape of a ferrofluid in the gap between the oblique teeth at the radial seal.

intensity on the M-P line is higher near the moving ring than that near the static ring, and it decreases from the middle position to the two sides along the short edge of the oblique tooth. Fig. 5 shows the shapes of the ferrofluid films in the static state and under the action of centrifugal force. It can be seen that the high-speed rotating spindle makes the ferrofluid move radially. Under the action of centrifugal force, the ferrofluid moves in the same direction as the increasing direction of the flux density. If the fluid boundary at the lower end of the ferrofluid does not exceed the middle of the gap, the magnetic induction intensity gradient and the pressure resistance value of the ferrofluid remain unchanged. Therefore, the magnetic flux distribution characteristic of the oblique tooth can help the ferrofluid overcome the effects of centrifugal forces.

4.2. Effect of oblique teeth with different angles on radial seal

Taking radial sealing as the research object, the sealing performance of the oblique teeth of different angles is distinct. Therefore, it is necessary to explore the influence of oblique teeth with various edges and gaps on radial sealing performance. Firstly, the data for these two factors are analyzed. The angle of the oblique tooth is set in the range of 20° to 90°. The dimensions of the gap are 0.1 mm, 0.15 mm, and 0.2 mm, respectively. Secondly, the magnetic induction strength gradient and theoretical pressure resistance value of the radial seal are calculated with the help of magnetic field simulation.

For multi-stage radial oblique teeth sealing structures, the theoretical pressure resistance value is positively correlated with the magnetic induction intensity gradient of Eq. (5). As can be seen from Fig. 6, the smaller the gaps between each pair of oblique teeth, the greater the magnetic induction intensity gradient and the theoretical pressure resistance value. The simulation results show that the curve is close to the parabolic. According to the theoretical pressure peaks at different gap sizes and angles of the oblique teeth, the optimal parameters of the oblique tooth angle can be determined. The analysis results of the peaks are shown in Table 2, which can be seen that the optimal angle is 77.87°, 64.28° and 62.81° for the corresponding gaps of 0.1 mm, 0.15 mm and 0.2 mm, respectively.

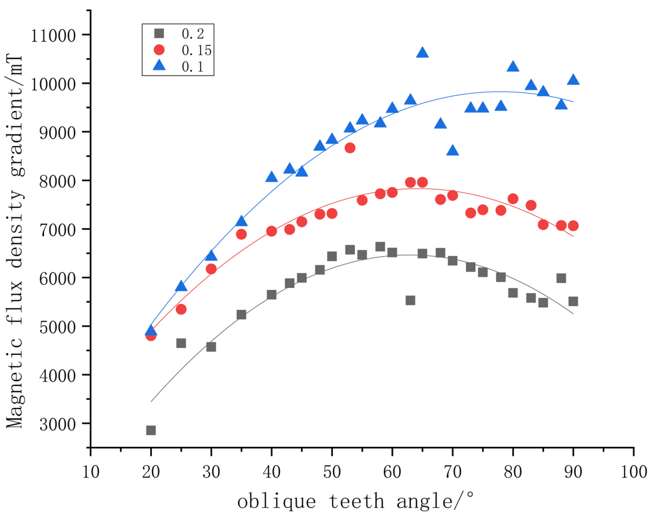


Fig. 6. (Color online) The change trend of magnetic induction intensity gradient under different angle and gap of oblique teeth.

Table 2. Peak value analysis of magnetic induction intensity gradient.

Size of gap/mm	0.1	0.15	0.2
Angle of oblique teeth/°	77.87	64.28	62.81
magnetic induction intensity gradient/mT	9824.73	7830.12	6464.04
Theoretical Pressure Resistance value/Mpa	0.261	0.208	0.172

5. Fluid Analysis of Radial Ferrofluid Seal

5.1. Establishment of numerical analysis model

Under the action of a strong magnetic field, the ferrofluid is magnetized into an anisotropic solid-like structure, which can be regarded as a porous medium. Aggregates of magnetic particles form chain-like or complex reticular skeleton structures along the direction of the magnetic field, and small holes appear inside the medium. Leakage will occur when the sealing medium enters the connected pores. Fig. 2 shows that magnetic field aggregation occurs in the gap of oblique teeth. The following assumptions are made for the ferrofluid numerical analysis: 1) Ignoring the deformation of ferrofluid in the gap under pressure; 2) Ignoring the fracture of magnetic particle chain structure due to external pressure; 3) Ignoring the influence of the base carrier.

The fluid area of the structure includes the lower inlet fluid area, the middle gas area, the ferrofluid area (porous media) and the upper outlet fluid area, and the other areas are ordinary air [12]. The ferrofluid shape between the oblique teeth is closely related to the external magnetic field. The outer contour of the ferrofluid can be described as its boundary in pressure analysis based on the distribution of magnetic field lines in the seal structure. The ferrofluid region (porous media region) is the primary analysis region, in which the mesh is appropriately encrypted in

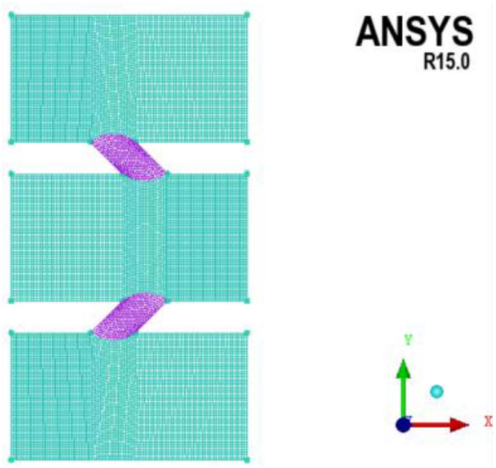


Fig. 7. (Color online) The meshing result of radial ferrofluid seal.

the mesh segmentation to ensure the quality of the mesh. The meshing result of radial ferrofluid seal is shown in Fig. 7.

FLUENT software is used to simulate and analyze the flow field of the radial ferrofluid seal structure. Here, the viscosity resistance coefficient α and inertial resistance coefficient β of porous medium should be given. Based on Ergun's experiments, a more famous Ergun equation is proposed for the unidirectional flow in porous medium with spherical particle accumulation, as shown in Eq. (6) [13].

$$-\frac{dp}{dx}=\frac{\mu}{K}J+\frac{\rho}{\eta}J^2=\frac{150(1-\varepsilon)^2\mu}{d^2\varepsilon^3}J+\frac{1.75(1-\varepsilon)\rho}{d\varepsilon^3}J^2 \quad (6)$$

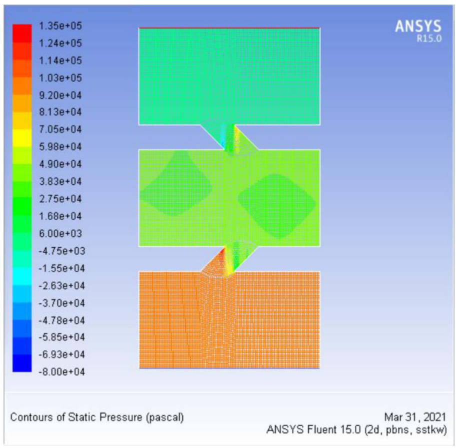
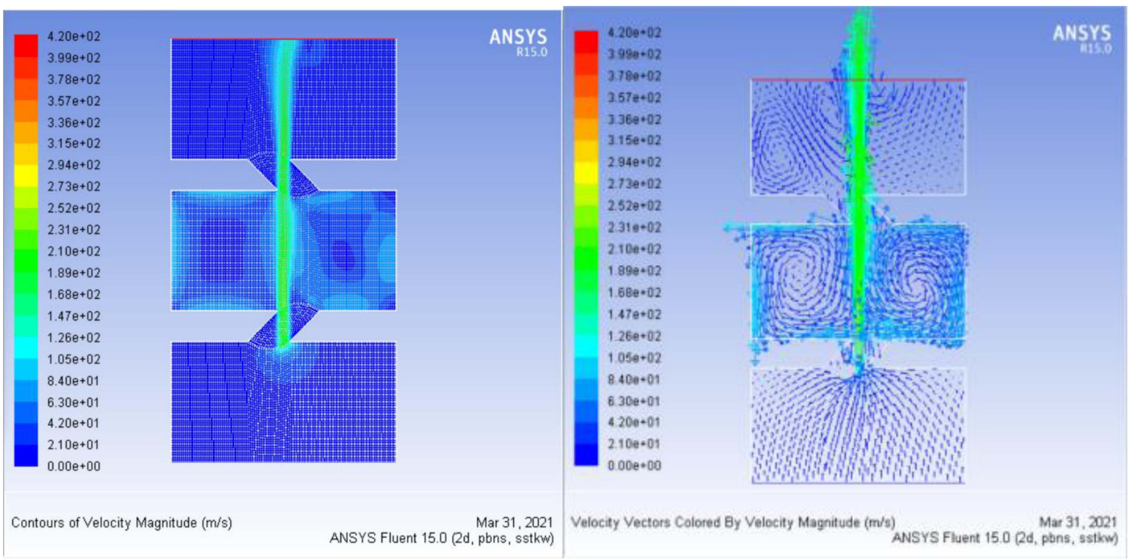


Fig. 8. (Color online) Contours of static pressure.

where the ε is the porosity of the porous medium, d is the effective diameter of the particles that make up the porous medium, ρ is the density, μ is the hydrodynamic viscosity, and J is the specific velocity of the fluid in the porous medium. Values of 150 and 1.75 are empirical constants based on experiments and are called Ergun constants. Therefore, the expressions of viscosity and inertial resistance coefficient in the process of ferrofluid seal can be obtained as follows:

$$\alpha=\frac{150(1-\varepsilon)^2}{d^2\varepsilon^3} \quad (7)$$

$$\beta=\frac{3.5(1-\varepsilon)}{d\varepsilon^3} \quad (8)$$

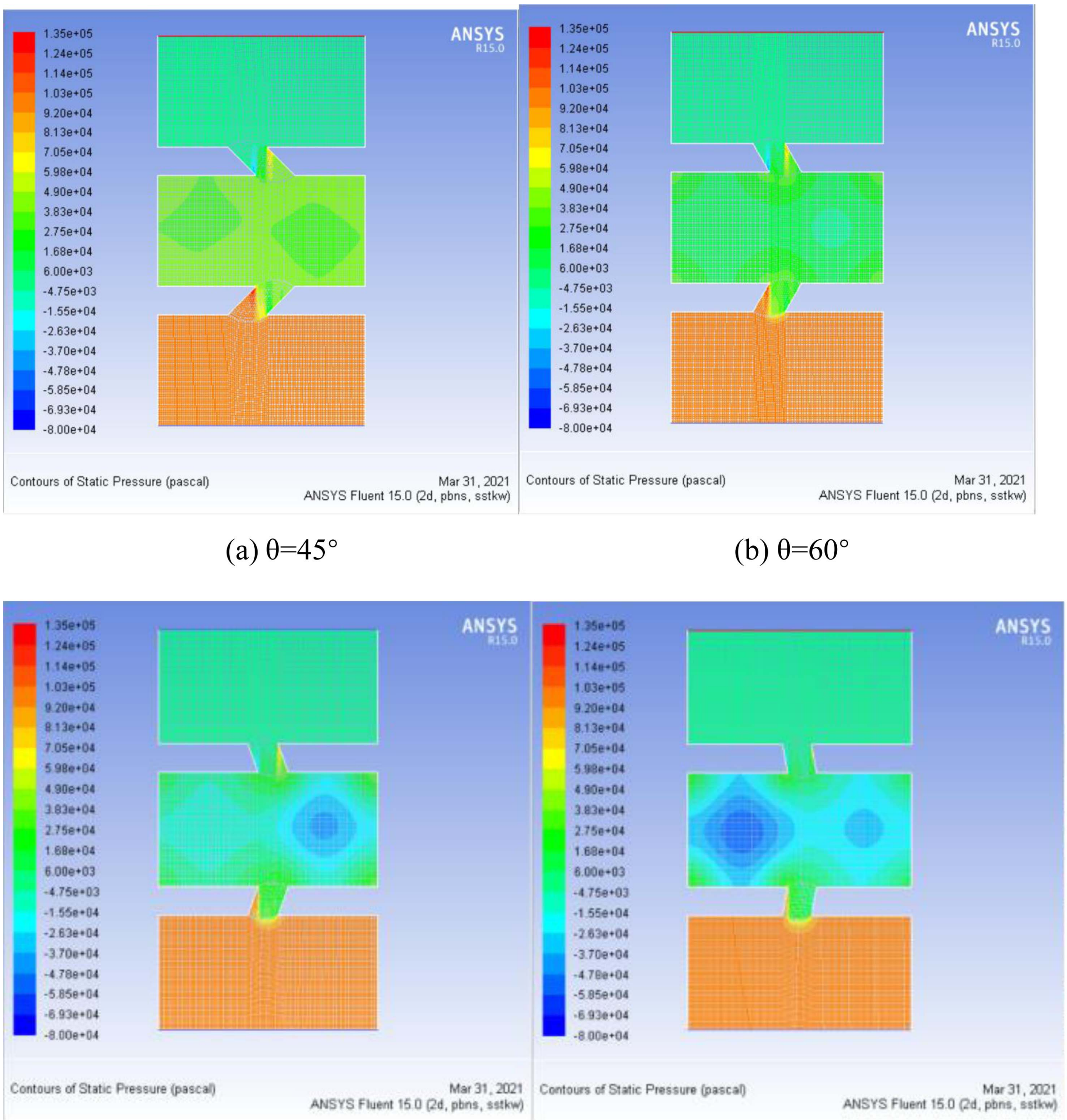


(a) Contours of velocity (b) Vector of velocity

Fig. 9. (Color online) Velocity distribution of ferrofluid seals.

According to the preparation of ferrofluids, the average diameter of magnetic particles is 30 nm, and the porosity of porous media formed by ferrofluids is in the range of 0.05 to 0.15. Here, the ferrofluid can be regarded as a porous medium with a particle size of 30 nm and an equivalent porosity of 0.12. The viscosity resistivity coefficient is 7.4×10^{19}, and the inertia resistance coefficient is 5.94×10^{10}, which can be obtained in Eq. (7) and Eq. (8).

The sealing medium in the sealing chamber can be considered as an ideal compressible gas, and the lower pressure storage area of the structure is set as the initial pressure inlet with a pressure value of 0.1 MPa. The upper region is connected to the atmosphere and considered as an outlet with a pressure value of 0 MPa. The contact surface between the ferrofluid and the bevel is set to the anti-slip wall boundary, and the outer contour of the ferrofluid is set in the inner boundary. The ferrofluid sealing structure with a bevel tooth angle of 45° is simulated to obtain its static pressure contour, shown in Fig. 8, and the pressure gradually decreases along the direction of the gas flow. In the sealing structure, the porous media area formed by the ferrofluid in the gap is the main factor in the pressure drop.



(a) θ=45° (b) θ=60°

(c) θ=70° (d) θ=80°

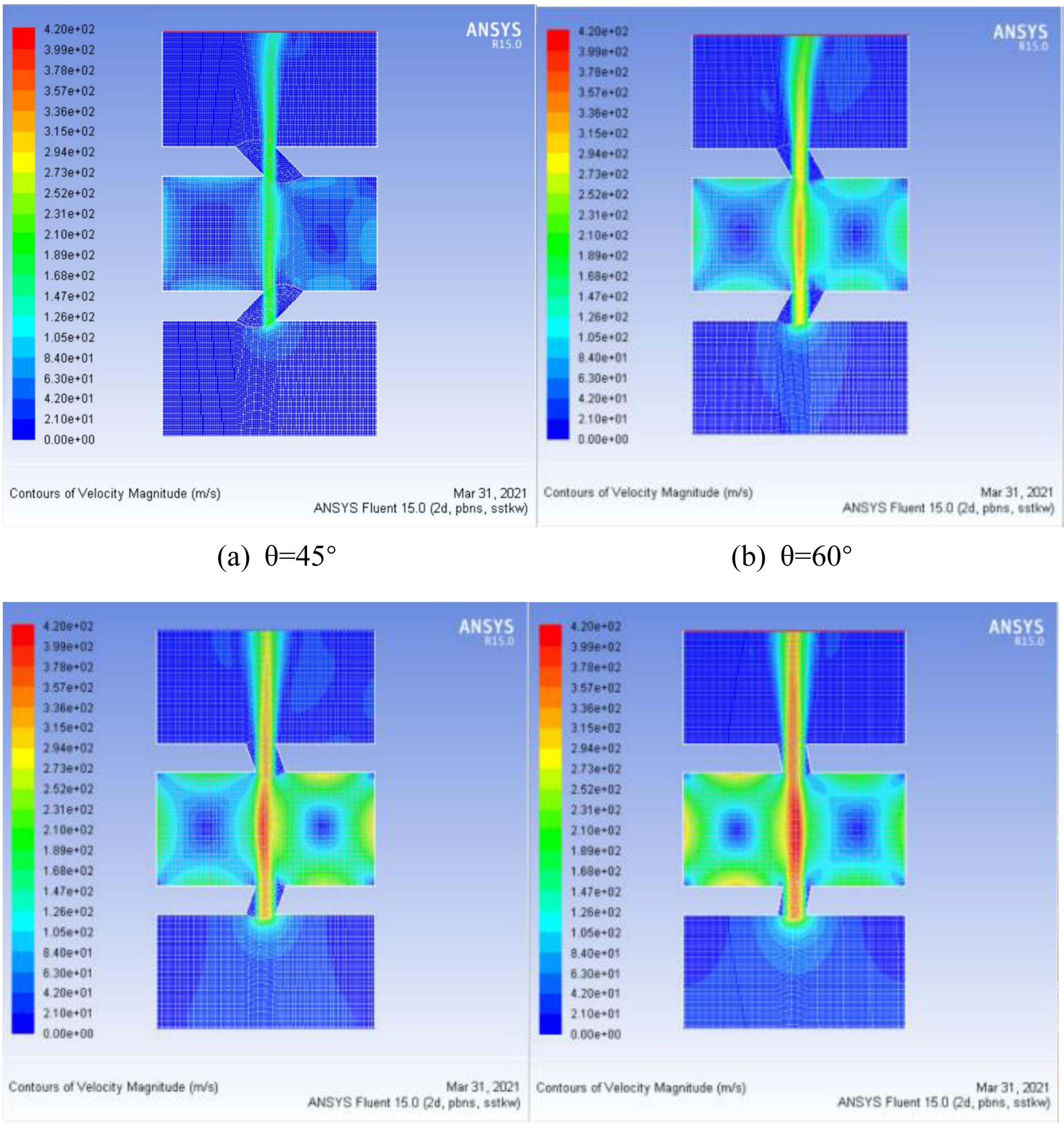
Fig. 10. (Color online) Contours of static pressure.

To further investigate the flow state of the fluid in the sealing structure, the profile and vector of velocity can be obtained using FLUENT software. It can be seen from Fig. 9(a) that the closer the radial distance of the oblique tooth, the higher the gas flow velocity in the intermediate gas region. The porous media in the gap has large viscous and inertial resistance, which impedes the gas flow. As can be seen from Fig. 9(b), the gas forms reflux, for eddy currents are generated in the middle gas region.

5.2. Sealing performance of oblique teeth with different angles

Two pairs of oblique teeth are used as research objects to explore the influence of different angles of oblique teeth on sealing performance. The angle values of 45°, 60°, 70° and 80° are chosen for the oblique teeth. Their static pressures and velocity contours are shown in Fig. 10 and Fig. 11, respectively.

According to the change of gas pressure at four angles, it can be seen that there are two trends in the gas pressure difference and velocity difference of the intermediate sealing chamber. When the angle is less than 70°, the pressure difference in the middle region gradually increases with the increase of the oblique angle. When it is greater



(a) θ=45° (b) θ=60°

(c) θ=70° (d) θ=80°

Fig. 11. (Color online) Contours of velocity.

than 70°, the trend of change in the left half of the sealing chamber increases, but the trend in the right half decreases. The angle increases lead to changing of the flow direction of the gas, and then make the pressure difference and the velocity difference on both sides of the intermediate gas area change. In addition, when the angle is small, the pressure drop velocity and gas flow velocity in the porous medium region is small, and the pressure resistance is high. Therefore, the oblique teeth should be designed at a smaller angle to achieve better sealing performance.

6. Conclusions

In the paper, the axial-radial bidirectional ferrofluid seal structure is proposed and designed to reduce the influence of various unstable factors caused by large diameter spindle with a high speed on the sealing performance of the ordinary ferrofluid seal. Oblique teeth can produce unique magnetic flux characteristics, so the ferrofluid located in the gap can effectively overcome the influence of centrifugal force generated at high speed under the action of the magnetic field. According to the analysis results of the magnetic induction intensity, to obtain the greater theoretical pressure resistance, the optimal angle of oblique teeth is 77.87°, 64.28° and 62.81° under the radial seal structure with different gaps of 0.1 mm, 0.15 mm and 0.2 mm, respectively. Based on the results of fluid simulation, if the oblique teeth with a smaller angle are chosen in the radial ferrofluid seal, the pressure drop velocity and gas flow velocity of the ferrofluid in the gap are smaller, and the sealing performance is excellent. The unique characteristics of the oblique tooth structure can effectively solve the sealing problems related to the high-speed mechanical equipment.

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