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Magnetic Circuit Design and Numerical Study of Diverging Stepped Magnetofluid Seal with Small Clearance

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In order to obtain the maximum magnetic energy product in the sealing clearance of magnetofluid seal and improve its critical pressure, a diverging stepped magnetofluid seal with small clearance was designed based on the magnetic circuit design theory and the magnetofluid seal theory. Magnetic distribution and its theoretical critical pressure were calculated by the finite element method, which could prove the reliability of design method in the magnetic circuit. The paper studies the effects of axial clearance, radial clearance and pole tooth number on the pressure capabilities of diverging stepped magnetofluid seal in specific values, which were analyzed and compared in details. The results show that the magnetic flux leakage at the junction of the pole piece and the permanent magnet in the diverging stepped magnetofluid seal leads the theoretical critical pressure calculated by the magnetic circuit method to be lower than that calculated by the finite element method. Moreover, when the pole tooth number in the axial clearance is not less than the pole tooth number in the radial clearance, and the width of axial clearance is smaller than the height of radial clearance, the critical pressure of diverging stepped magnetofluid seal is better than that of the ordinary magnetofluid seal.

Keywords : small clearance finite element stepped magnetofluid seal critical pressure

1. Introduction

Magnetofluid seal is a kind of sealing technology, which functions when magnetofluid is subjected to the external magnetic field, there will be a sealing ring in sealing clearance to resist the pressure difference between both sides of the sealing structure. Due to its advantages of zero leakage, long life and low friction, the technology is widely used in fields of aerospace, machinery, national defense, chemical industry and petroleum engineering [1-5].

At present, lots of literatures focus on the static and dynamic seal of ordinary magnetofluid with less than 0.4 mm small clearances [6-9]. Marcin Szczech *et al*. [10, 11] studied magnetofluid seal and found that tightness is an important factor. A magnetofluid should have mainly a hydrophobic carrier fluid. From the research, it can be concluded that for non-static seals in water environments, we can observe a slight and continuous loss of tightness. This is caused by the peripheral speed of the seal, water pressure and certain properties of the magnetofluid. The rate of water pressure decrease in the test chamber can be taken as the criterion of seal tightness for rotary magnetofluid seals and experimental results showed that higher viscosity of magnetofluid causes decrease of critical pressure to maximize the value of the critical pressure. So it is important to select a certain amount of magnetofluid and permanent magnet. Leszek *et al*. [12] analyzed properties of magnetic fluid seals installed in rotary sealing nodes which operate in the utility water environment. Seals of this type have been examined as a possible solution to the problem with ship manoeuvring propulsion sealing. There are some researches on stepped magnetofluid seal with large sealing clearance already. In 2014, Yang *et al.* carried out numerical analysis and experimental investigation on stepped magnetofluid seal with large sealing clearance, and came to the conclusion that the stepped magnetofluid seal is an effective method to improve the sealing performance with large clearance [13]. Yang *et al.* demonstrated that the pressure capabilities of the diverging and converging stepped magnetofluid seals with large clearance not only depend on the height of radial clearance but also on the width of axial clearance [14, 15]. However, there is no report on the research of

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the stepped magnetofluid seal with small sealing clearance.

In order to improve the critical pressure of magnetofluid seal with small clearance, a stepped structure of diverging magnetofluid seal is designed based on the theory of magnetic circuit design, with full consideration of structure parameters such as axial clearance, radial clearance and sealing structure. Moreover, these structure parameters on pressure capabilities are investigated in finite element method. The research results provide important theoretical guidance for designing a reliable stepped structure of diverging magnetofluid seal with small sealing clearance.

2. Magnetic Circuit Design of Diverging Stepped Magnetofluid Seal

Figure 1 is a diverging stepped magnetofluid seal structure, and its magnetic circuit is shown in Fig. 2. In Fig. 1, the magnetic circuit is mainly composed of permanent magnet, pole piece magnetofluid and stepped shaft. The permanent magnet generates magnetic field

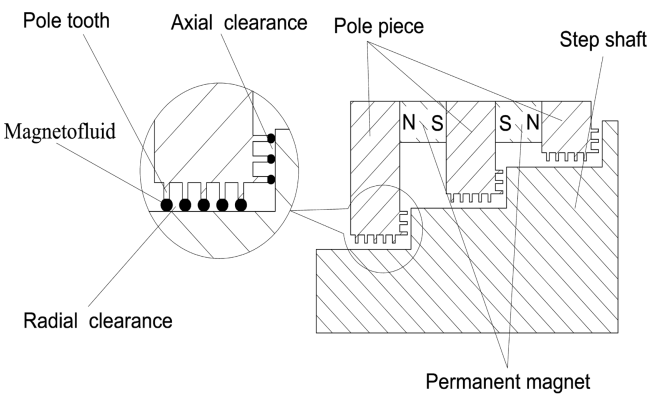


Fig. 1. 2-Ddiagram of diverging stepped magnetofluid seal.

which binds the magnetofluid in the radial and axial clearance between the stepped shaft and the pole piece. The magnetic force on the magnetofluid resists the pressure difference between two sides of the seal structure, and then blocks the leakage channel. The influence of gravity can be ignored, since the gravity of magnetofluid is much less than magnetic force. If the surface tension of magnetofluid is ignored, the pressure formula for the static seal of ordinary magnetofluid is

$$\Delta P = \mu_0 M_s \sum_{i=1}^{N} (H_{\max}^i - H_{\min}^i) = M_s \sum_{i=1}^{N} (B_{\max}^i - B_{\min}^i) \tag{1}$$

In the formula, μ_0 and M_s are the vacuum permeability and saturation magnetization of the magnetofluid respectively; N is the total sealing series; $H_{\max}^i$ and $H_{\min}^i$ are the maximum and minimum magnetic field strength under the first polar tooth in the sealing clearance; $B_{\max}^i$ and $B_{\min}^i$ are the maximum and minimum magnetic induction intensity under the second polar tooth respectively.

The formula for theoretical critical pressure of diverging stepped magnetofluid seal [13] is:

$$\Delta P = \sum_{i}^{N} (P_{ia} + \lambda P_{ir}) \tag{2}$$

In the formula, P_{ia} and P_{ir} are the magnetofluid sealing critical pressures in the axial and radial clearance formed by the i pole piece and the stepped shaft. If P_{ia} is less than P_{ir}, then lambda is 1, otherwise 0, P_{ia} and P_{ir} can be calculated by formula (1).

Additionally in this study, magnetic leakage and edge effect are not concerned in the magnetic circuit design of diverging magnetofluid seal. According to Kirchhoff's first law of magnetic circuit,

$$\sum \phi_i = 0 \tag{3}$$

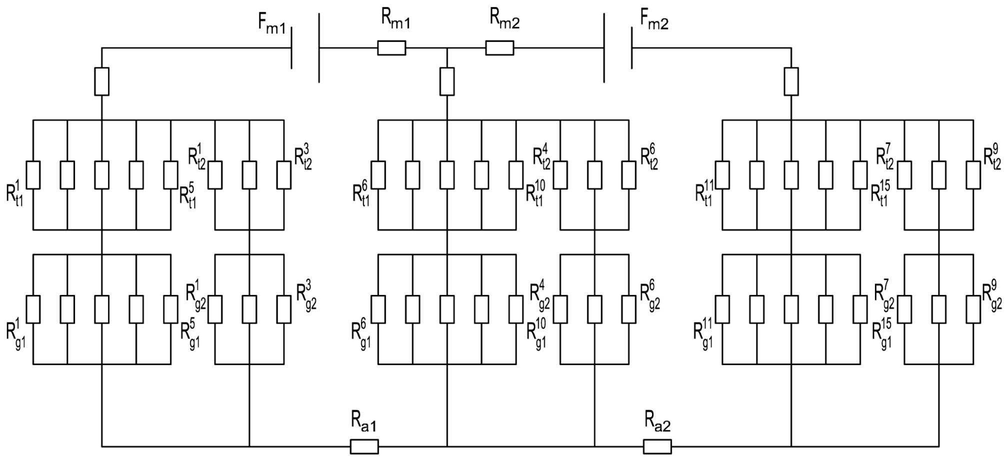


Fig. 2. Equivalent magnetic circuit diagram of diverging stepped magnetofluid seal.

At any point in the magnetic circuit, the sum of flux algebras entering the place is equal to the sum of flux algebras leaving the place.

According to the symmetry of the magnetic circuit structure,

$$\phi_2 = \phi_1 + \phi_3 \tag{4}$$

ϕ_1, ϕ_2 and ϕ_3 respectively indicate the magnetic flux in high pressure side-pole pieces, middle-pole pieces and atmospheric side-pole pieces in formula (5).

$$\phi_1 = 5B_{g1}^1 S_{g1}^1 + 3B_{g2}^1 S_{g2}^1 \tag{5}$$

B_{g1}^1 indicates the magnetic induction intensity in the first radial clearance, which locates under first pole piece of the first pole tooth on the high pole side, and B_{g2}^1 refers to the magnetic induction intensity in the first axial clearance under the first pole tooth of the first pole piece; S_{g1}^1 indicates the annular area of the first radial clearance, which locates in the first pole tooth of the pole piece on high-voltage side, and S_{g2}^1 refers to the annular area of the first axial clearance under the first pole tooth.

$$\phi_2 = 5B_{g1}^6 S_{g1}^6 + 3B_{g2}^4 S_{g2}^4 \tag{6}$$

B_{g1}^6 indicates the magnetic induction intensity in the sixth radial clearance, which locates under the sixth pole tooth of the second pole piece, and B_{g2}^4 refers to the magnetic induction intensity in the fourth axial clearance under the fourth pole tooth of the second pole piece; S_{g1}^6 indicates the annular area of the sixth radial clearance which locates in the sixth pole tooth of the second pole piece, and S_{g2}^4 refers to the annular area of the fourth axial clearance under the fourth pole tooth.

$$\phi_3 = 5B_{g1}^{11} S_{g1}^{11} + 3B_{g2}^7 S_{g2}^7 \tag{7}$$

B_{g1}^{11} indicates the magnetic induction intensity in the eleventh radial clearance which locates under the eleventh pole tooth of the atmospheric side pole piece, and B_{g2}^7 refers to the magnetic induction intensity in the seventh axial clearance under the seventh pole tooth of the atmospheric side pole piece; S_{g1}^{11} indicates the annular area of the eleventh radial clearance, which locates in the eleventh pole tooth of the pole piece on atmospheric side, and S_{g2}^7 refers to the annular area of the seventh axial clearance under the seventh pole tooth.

$$\phi_{m2} = B_{m2} S_{m2} = \phi_3 = 5B_{g1}^{11} S_{g1}^{11} + 3B_{g2}^7 S_{g2}^7 \tag{8}$$

ϕ_{m2}, B_{m2} and S_{m2} represent the magnetic flux, magnetic induction intensity and annular area of the second permanent magnet on the atmospheric side respectively.

According to Kirchhoff's second law, $\sum H_i L_i = \sum N_i i$, and then there are

$$\begin{aligned} F_2 = H_{m2} L_{m2} = (5B_{g1}^6 S_{g1}^6 + 3B_{g2}^4 S_{g2}^4)\left[\frac{R_{P2} + (R_{t1}^6 + R_{g1}^6)(R_{t2}^4 + R_{g2}^4)}{5(R_{t2}^4 + R_{g2}^4) + 3(R_{t1}^6 + R_{g1}^6)}\right] \\ + (5B_{g1}^{11} S_{g1}^{11} + 3B_{g2}^7 S_{g2}^7)\left[\frac{R_{P3} + R_{a2} + R_{m2} + (R_{t1}^{11} + R_{g1}^{11})(R_{t2}^7 + R_{g2}^7)}{5(R_{t2}^7 + R_{g2}^7) + 3(R_{t1}^{11} + R_{g1}^{11})}\right] \end{aligned} \tag{9}$$

F_2 represents the magnetic potential of the permanent magnet at atmospheric pressure side; H_{m2}, L_{m2} represent the magnetic field strength and length of the permanent magnet; R_{p3}, R_{a2} and R_{m2} indicate the reluctance of the third pole piece ,the second stepped shaft and the second permanent magnet; R_{t1}^6 and R_{g1}^6 respectively indicate the reluctance of the sixth radial pole tooth on the middle pole piece and the sixth radial clearance under the sixth pole tooth; R_{t2}^4 and R_{g2}^4 refer to the reluctance of the fourth axial pole tooth on the middle pole piece and the fourth axial clearance under the fourth pole tooth.

Formula (8) multiply Formula (9) yields

$$V_{m2} = S_{m2} L_{m2} = \frac{F_2 \phi_{m2}}{B_{m2} H_{m2}} \tag{10}$$

In order to reduce the volume and weight of permanent magnet and improve the utilization rate of permanent magnet, the permanent magnet should be operated at its maximum magnetic energy product, therefore,

$$V_{m2} = S_{m2} L_{m2} = \frac{F_2 \phi_{m2}}{(BH)_{\max}} \tag{11}$$

Divide Formula (8) by Formula (9)

$$\frac{S_{m2}}{L_{m2}} = \frac{(3B_{g1}^7 S_{g1}^7 + 5B_{g2}^{11} s_{g2}^{11}) H_{m2}}{F_2 B_{m2}} \tag{12}$$

Formula (11) multiply Formula (12)

$$S_{m2} = (3B_{g1}^7 S_{g1}^7 + 5B_{g2}^{11} S_{g2}^{11})\sqrt{\frac{H_{m2}}{(BH)_{\max} B_{m2}}} \tag{13}$$

Divide Formula (11) by Formula (12)

$$L_{m2} = F_2 \sqrt{\frac{B_{m2}}{(BH)_{\max} H_{m2}}} \tag{14}$$

Because the magnetic permeability of the material in the pole piece and rotating shaft is much higher than that of air and permanent magnet, the length of permanent magnet is calculated without the consideration of the resistance of the pole piece and rotating shaft, that is

$$\begin{aligned} L_{m2} = \Bigg\{ (3B_{g1}^4 S_{g1}^4 + 5B_{g2}^6 S_{g2}^6)\left[\frac{R_{g1}^4 R_{g2}^6}{3R_{g2}^6 + 5R_{g1}^4}\right] + \\ (3B_{g1}^7 S_{g1}^7 + 5B_{g2}^{11} S_{g2}^{11})\left[R_{m2} + \frac{R_{g1}^7 R_{g2}^{11}}{3R_{g2}^{11} + 5R_{g1}^7}\right]\Bigg\} \sqrt{\frac{H_{m2}}{(BH)_{\max} B_{m2}}} \end{aligned} \tag{15}$$

Table 1. Structure parameters of the diverging stepped magnetofluid seal.

Parameter	Parameter Value	Parameter	Parameter Value
inner radius of the first pole piece/mm	13	radial clearance height/mm	0.1
Outer radius of the first pole piece/mm	30	axial clearance width/mm	0.4
axial length of the first pole piece/mm	5.3	pole tooth width/mm	0.3
inner radius of the second pole piece/mm	17	groove depth/mm	0.8
outer radius of the second pole piece/mm	30	tooth width/mm	0.7
axial length of the second pole piece/mm	5.3	pole tooth in the radial clearance number	5
inner radius of the third pole piece/mm	21	pole tooth in the axial clearance number	3

According to the known demagnetizing curve and magnetic circuit parameters of permanent magnet, the length and cross-section area of permanent magnet can be calculated, in order to get the maximum magnetic energy product in the sealing clearance and improve the utilization rate of permanent magnet.

3. Finite Element Method of Magnetic Field

The dimensions of each part in the magnetic circuit are shown in Table 1. If the critical pressure of the diverging stepped magnetofluid seal is required to be not less than 4.8×10^5 Pa, the length and cross-sectional area of permanent magnet should be 5.6 mm and 243 mm^2 according to the formula (13) and (15).

Validating the reliability of the designed diverging stepped magnetofluid seal, the finite element method of magnetic field has been employed to investigate the effects of the sealing clearance and pole tooth on the critical pressure of diverging stepped magnetofluid seal according to magnetic circuit method. Due to the symmetry of the seal structure, the axisymmetric phenomenon of magnetofluid seal in three dimensions can be simplified to a two dimensions. The material of the permanent magnet is NdFeB with the coercive force H_c 1.356×10^6 A/m and the magnetic permeability 1.05, and the materials of the pole pieces and stepped shaft are both 2Cr13. Oil-based magnetofluid is employed with the saturation magnetization of 30.7 kA/m. Since the magnetic field strength in the sealing clearance generated by the permanent magnet is greater than the saturation magnetization of the magnetofluid, the magnetofluid is saturated magnetized. Moreover, the magnetic permeability of magnetofluid is almost the same as that of the air, thus the magnetofluid can be treated as air. Smart Meshing is selected with the accuracy of 4, and lines of magnetic force would be diverginged, which is a boundary condition applied to the model boundary.

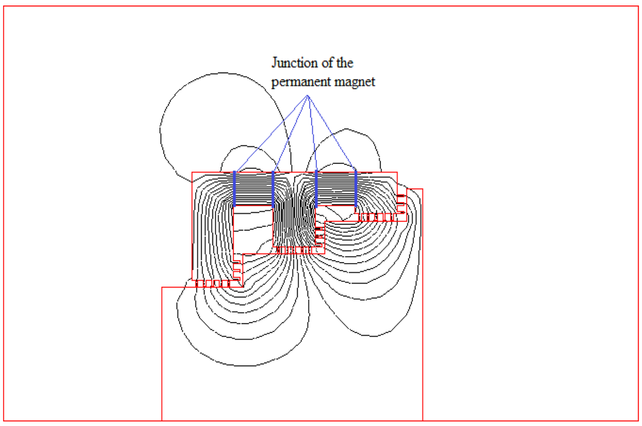


Fig. 3. (Color online) Distribution of magnetic force line.

4. Results Analysis and Discussion

4.1. Reliability of magnetic circuit design method

To prove the accuracy of the magnetic circuit design method, distributions of magnetic force line and magnetic induction intensity in the sealing clearance are shown in Fig. 3 and Fig. 4. According to the structure parameters in Table 1 and the permanent magnet dimensions, the critical pressure Δp of the diverging magnetofluid seal can be calculated as following in formula 1 and 2:

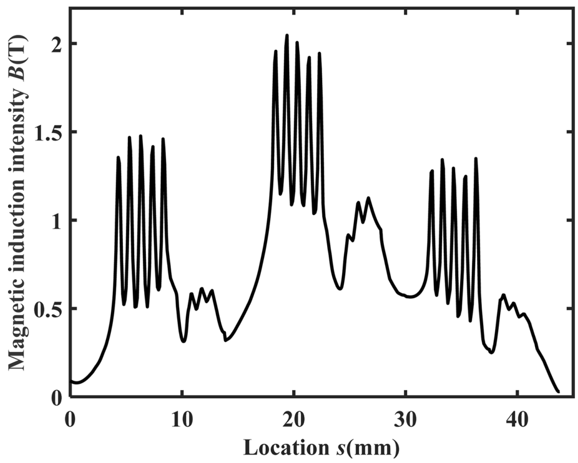


Fig. 4. Distribution of magnetic induction intensity.

$$\Delta P = M_s \sum_{i-1}^{N} (B_{\max}^i - B_{\min}^i) = \sum_{i}^{N} (P_{ia} + \lambda P_{ja})$$

$$= 30.7\times10^3\times14.02 \text{ Pa} = 4.3\times10^5 \text{ Pa} < 4.8\times10^5 \text{ Pa}$$

Therefore, the result proves the reliability of the magnetic circuit method, the critical pressure of the diverging stepped magnetofluid seal calculated by the finite element method is smaller than the requirement by magnetic circuit design method which is 4.8×10^5 Pa. According to Fig. 3, magnetic flux leakage occurred at the junction of the permanent magnet and pole piece is the main reason for this phenomenon. Therefore, the permanent magnet should be inserted into the pole piece to reduce magnetic flux leakage, which can ensure that the critical pressure of the diverging stepped magnetofluid seal designed by the magnetic circuit method is closer to the value calculated by the finite element method.

4.2. Effect of sealing clearance on critical pressure of diverging stepped magnetofluid seal

Figure 5 is the distribution of magnetic induction intensity when the axial clearance is 0.3 mm and the radial clearance is 0.1 mm to 0.4 mm. When the radial clearance is increased, the magnetic induction intensity in the radial clearance is significantly reduced and the magnetic induction intensity in the axial clearance is slowly increased. Because the increase in the radial clearance leads to the increase in the reluctance of the radial clearance, the reluctance of the entire magnetic circuit increases and its magnetic flux decreases.

Moreover, reluctance of the axial clearance remains the same, and the increasing rate of the magnetic potential is much less than that of its reluctance in the radial clearance according to the magnetic circuit theory. Therefore, the

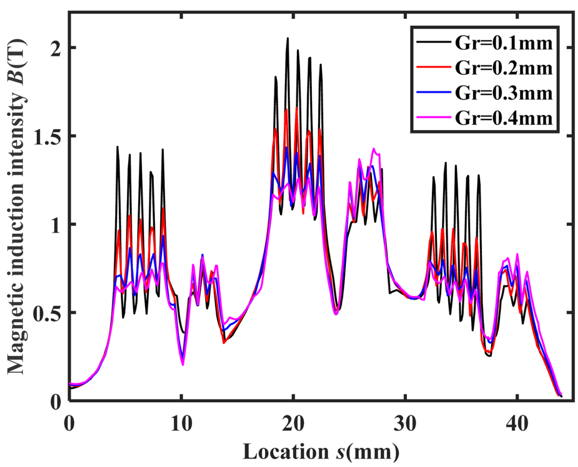
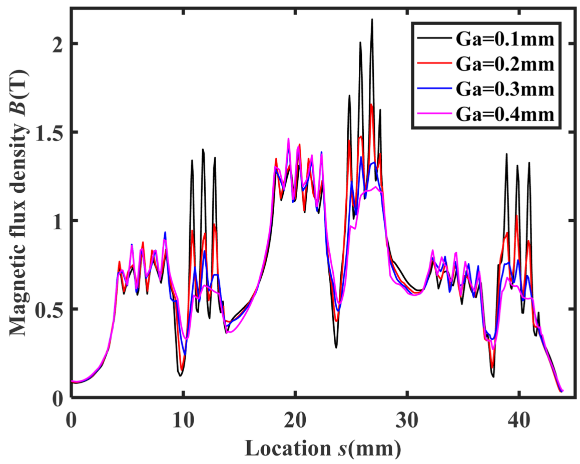


Fig. 5. (Color online) Distribution of magnetic induction intensity in different radial clearance.



Ga: axial clearance width

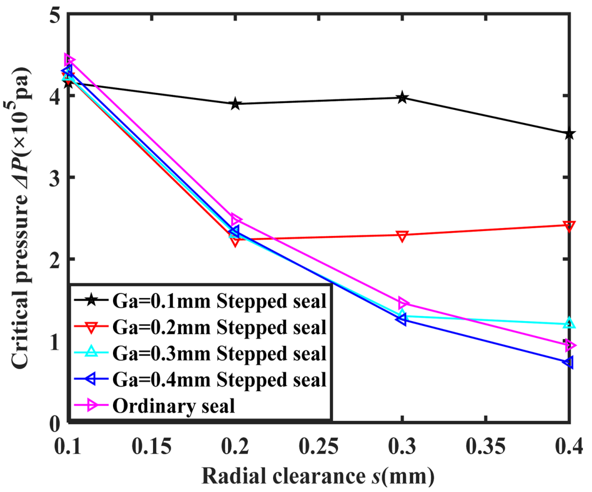
Fig. 6. (Color online) Distribution of magnetic induction intensity in different axial clearances.

magnetic induction intensity decreases in the radial clearance with the increase of the radial clearance. At the same, reluctance of the axial clearance does not change, but its magnetic potential increases, thus the magnetic induction intensity in the axial clearance increases slowly with the increase of the radial clearance.

Figure 6 is the distribution of magnetic induction intensity when the radial clearance is 0.3 mm and the axial clearance is 0.1 mm to 0.4 mm. When the axial clearance is increased, the magnetic induction intensity in the axial clearance is significantly reduced and the magnetic induction intensity in the radial clearance is slowly increased. Because the increase in the axial clearance leads to the increase in the reluctance of the axial clearance, the reluctance of the entire magnetic circuit increases and its magnetic flux decreases. Moreover, the reluctance of the radial clearance does not change and the increasing rate of the magnetic potential is much less than that of its reluctance in the axial clearance according to the magnetic circuit theory. Therefore, the magnetic induction intensity decreases in the axial clearance with the increase of the axial clearance. At the same time, the reluctance of the radial clearance does not change and its magnetic potential increases, so the magnetic induction intensity in the radial clearance increases slowly with the increase of the axial clearance.

According to the distributions of the magnetic field as shown in Fig. 5 and Fig. 6 and the pressure theory of stepped magnetofluid seal, it is showed in Fig. 7 that the critical pressure of the ordinary and diverging stepped magnetofluid seal in different axial clearances and radial clearances.

According to Fig. 7, the critical pressure of the diverging



Gr: radial clearance; Ga: axial clearance

Fig. 7. (Color online) Effect of the clearance on sealing capability.

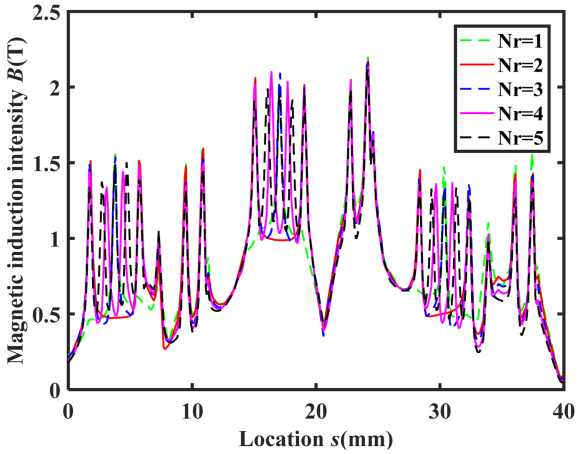
stepped magnetofluid seal increases slowly with the increase of the axial clearance when Gr = 0.1 mm and Ga ≥ Gr. Since when Gr = 0.1 mm and Ga ≥ Gr, the critical pressure of the magnetofluid seal in the axial clearance is less than that in the radial clearance. Therefore, according to the pressure theory of stepped magnetofluid seal in formula (2), the magnetofluid seal in the axial clearance does not work, that is, the critical pressure of the diverging stepped magnetofluid seal depends only on that in the radial clearance. On the other hand, the magnetic induction intensity in the radial clearance increases slowly with the increase of the axial clearance according to distribution of the magnetic field as shown in Fig. 6. As a result, the critical pressure of magnetofluid seal in the radial clearance slowly increases which causes the increase in critical pressure of the diverging stepped magnetofluid seal.

When the radial clearance is 0.2 mm and also within the effective range of the axial clearance $(Ga)_{min}$ < Gr < $(Ga)_{max}$, the critical pressure of the diverging stepped magnetofluid seal decreases sharply at first, and then increases slowly with the increase of axial clearance. Because when Gr = 0.2 mm and Ga < Gr, the critical pressure of magnetofluid seal in the axial clearance is greater than that in the radial clearance, the critical pressure of the diverging stepped magnetofluid seal summates that of radial clearance and axial clearance, according to the pressure theory of stepped magnetofluid seal in formula (2). Moreover, When Gr = 0.2 mm and Ga ≥ Gr, the critical pressure of magnetofluid seal in the axial clearance is less than that in the radial clearance. Therefore, according to the pressure theory of stepped magnetofluid seal in formula (2), the magnetofluid seal in the axial clearance does not work. In Fig. 6, the distribution of magnetic field shows that the magnetic induction intensity in the radial clearance increases slowly with the increase of the axial clearance, and the reduction of the magnetic induction intensity in the axial clearance is much larger than the increase of that in the radial clearance, thus the theoretical critical pressure of the diverging stepped magnetofluid seal decreases sharply with the increase of the axial clearance at first. Meanwhile, the magnetic induction intensity in the axial clearance decreases sharply with the increase of axial clearance, and the magnetic induction intensity in the radial clearance increase slowly with the increase of the axial clearance, moreover, the decrease of the magnetic induction intensity in the axial clearance is slightly greater than the increase of that in the radial clearance in Fig. 6. Therefore, the theoretical critical pressure of the diverging stepped magnetofluid seal increases slowly with the increase of the axial clearance.

When the axial clearance is larger than the radial clearance, the sealing effect of diverging stepped magnetofluid seal is better than that of the ordinary magnetofluid seal, since the critical pressure of the diverging stepped magnetofluid seal is the sum of the its pressure capabilities in both axial and radial clearances according to the pressure theory of the stepped magnetofluid seal. However, it turns out just the opposite, when the axial clearance is smaller than the radial clearance, since the critical pressure of the diverging stepped magnetofluid seal depends only on that of magnetofluid seal in the radial clearance according to the pressure theory of stepped magnetofluid seal, which means the magnetofluid seal in the axial clearance does not work. As a result, the critical pressure of ordinary magnetofluid seal is greater than that of diverging stepped magnetofluid seal at this time.

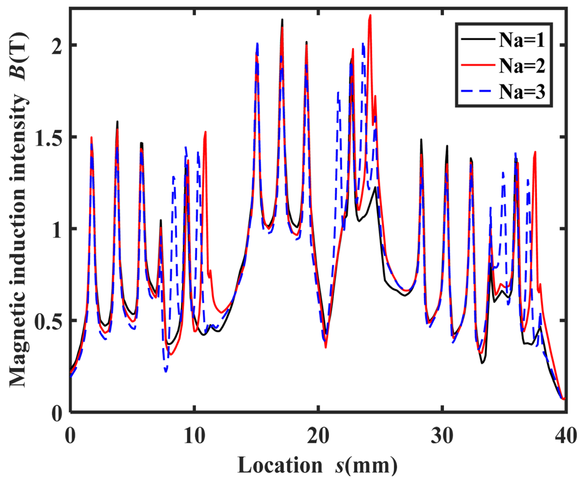
4.3. Effect of the number of pole tooth in the diverging stepped magnetofluid seal

When the pole tooth number in the axial clearance is 2, Fig. 8 shows the distributions of magnetic field in the sealing clearance of the diverging stepped magnetofluid seal with different numbers of pole tooth in the radial clearance. The magnetic flux densities in the radial clearance and the axial clearance gradually decrease with the increase of the pole tooth number in the radial clearance, since when the pole tooth number in the radial clearance increases, the total reluctance of the pole tooth in the radial clearance decreases relatively, and the total reluctance in the magnetic circuit decreases correspondingly, which causes a relatively increase of the magnetic flux in the magnetic circuit. According to the magnetic circuit theory, when there is less magnetic flux passing through



Nr: number of pole tooth in the radial clearance

Fig. 8. (Color online) Distribution of magnetic induction intensity in different number of pole tooth in the radial clearance.



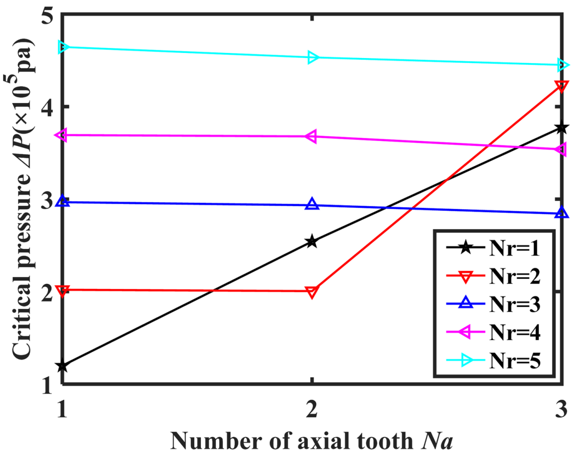
Na: number of pole tooth in the axial clearance

Fig. 9. (Color online) Distribution of magnetic induction intensity in different number of pole tooth in the axial clearance.

the reluctance of pole tooth in the axial clearance, the total magnetic flux increases relatively through that in the radial clearance. Thus, the magnetic induction intensity passing through the reluctance of each pole tooth in the radial clearance decreases due to the increase of the pole tooth number in the radial clearance.

When the pole tooth number in the radial clearance is 3, Fig. 8 shows the distributions of magnetic field in the sealing clearance of the diverging stepped magnetofluid seal with different numbers of pole tooth in the axial clearance. The magnetic flux densities in the axial clearance and the radial clearance gradually decrease with the increase of the pole tooth number in the axial clearance, since when the pole tooth number in the axial clearance increases, the total reluctance of the pole tooth in the axial clearance decreases relatively, and the total reluctance in the magnetic circuit decreases correspondingly, which causes a relatively increase of the magnetic flux in the magnetic circuit. According to the magnetic circuit theory, when there is less magnetic flux passing through the reluctance of pole tooth in the radial clearance, the total magnetic flux increases relatively through that in the axial clearance. Thus, the magnetic induction intensity passing through the reluctance of each pole tooth in the axial clearance decreases due to the increase of the pole tooth number in the axial clearance.

According to the distribution of magnetic field shown in Fig. 8 and Fig. 9 and the pressure theory of stepped magnetofluid seal, the paper studies the effects of different pole teeth numbers in the axial clearance and the radial clearance on ordinary magnetofluid seal and diverging stepped magnetofluid seal, which are shown in Fig. 10

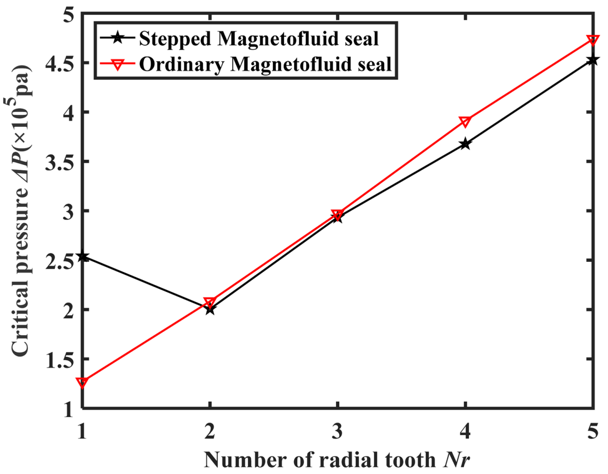


Na: number of pole tooth in the axial clearance

Fig. 10. (Color online) Effect of pole tooth number on critical pressure of diverging stepped magnetofluid seal.

and Fig. 11.

In Fig. 10 and Fig. 11, when Nr = 1 and Na ≥ Nr, the critical pressure of the diverging stepped magnetofluid seal increases dramatically with the increase of the pole tooth number in the axial clearance. Because when Nr = 1 and Na ≥ Nr, the critical pressure of magnetofluid seal in the axial clearance is greater than that in the radial clearance, the critical pressure of diverging stepped magnetofluid seal is the sum of that in both axial and radial clearances according to the formula (2). On the other hand, according to Fig. 9, the magnetic induction intensity in the radial clearance decreases slowly with the increase of the pole tooth number in the axial clearance. However, the decrement of magnetic induction intensity in the radial



Nr: number of pole tooth in the radial clearance

Fig. 11. (Color online) Critical pressure comparison between converging stepped seal and conventional seal.

clearance is much less than the increment of that caused by the increase of pole tooth number in the axial clearance. As a result, the critical pressure of the diverging stepped magnetofluid seal increases dramatically with the increase of the number pole tooth in the axial clearance.

When the pole tooth number in the radial clearance is 2 and within the effective range of pole tooth number in the axial clearance $(Na)_{min} < Nr < (Na)_{max}$, the critical pressure of the diverging stepped magnetofluid seal decreases slowly at first, and then increases sharply with the increase of the axial clearance. Because when $Nr = 2$ and $Na \leq Nr$, the critical pressure of magnetofluid seal in the axial clearance is less than that in the radial clearance, which means the magnetofluid seal in the axial clearance does not work according to the pressure theory of stepped magnetofluid seal (2). That is, the critical pressure of the diverging stepped magnetofluid seal depends only on the critical pressure of magnetofluid seal in the radial clearance. In Fig. 9, the magnetic induction intensity in the radial clearance slowly decreases with the increase of the pole tooth number in the axial clearance, and the critical pressure of magnetofluid seal decreases slowly in the radial clearance, therefore, the critical pressure of the diverging stepped magnetofluid seal decreases slowly with the increase of the pole tooth number in the axial clearance. However, when $Nr = 2$ and $Na > Nr$, the critical pressure of magnetofluid seal in the axial clearance is greater than that in the radial clearance, thus the critical pressure of diverging stepped magnetofluid seal is the sum of the critical pressure of magnetofluid seal in both axial and radial clearances according to the pressure theory of stepped magnetofluid seal (2). Moreover, Fig. 9 shows that the magnetic induction intensity in the radial clearance decreases slowly with the increase of the axial clearance, and the increase of the magnetic induction intensity in the axial clearance is much larger than the decrease of that in the radial clearance. As a result, the theoretical critical pressure of the diverging stepped magnetofluid seal increases sharply with the increase of the axial clearance.

When $Nr \geq 3$ and $Na \leq Nr$, the critical pressure of the diverging stepped magnetofluid seal decreases slowly with the increase of the pole tooth number in the axial clearance, since the critical pressure of magnetofluid seal in the radial clearance is greater than that in the axial clearance. Therefore, the critical pressure of diverging stepped magnetofluid seal is the sum of the critical pressure of magnetofluid seal in both axial and radial clearances according to the formula (2). On the other hand, Fig. 9 shows the magnetofluid seal in the axial clearance does not work, that is, the critical pressure of the diverging stepped magnetofluid seal depends only on that of magnetofluid seal in the radial clearance. As a result, the critical pressure of the diverging stepped magnetofluid seal decreases slowly with the increase of the pole tooth number in the axial clearance. When the pole tooth number in the axial clearance is bigger than the pole tooth number in the radial clearance, the critical pressure of the diverging stepped magnetofluid seal is better than that of the ordinary magnetofluid seal, because the critical pressure of the diverging stepped magnetofluid seal is the sum of that of magnetofluid seal in both axial and radial clearances according to the pressure theory stepped magnetofluid seal. Hence, the effect of the diverging stepped magnetofluid seal is better than the ordinary magnetofluid seal.

When the tooth of axial is smaller than the tooth of radial, the ordinary magnetofluid seal is better than the diverging stepped magnetofluid seal, because the critical pressure of the diverging stepped magnetofluid seal depends only on that of magnetofluid seal in the radial clearance according to the pressure theory of stepped magnetofluid seal. That is to say, the magnetofluid seal in the axial clearance does not work, thus the critical pressure of ordinary magnetofluid seal is greater than that of diverging stepped magnetofluid seal in this case.

5. Conclusion

1. The finite element analysis results of diverging stepped magnetofluid seal verify the reliability of the magnetic circuit design method. The critical pressure of the diverging stepped magnetofluid seal designed by the

magnetic circuit method is slightly larger than that calculated by the finite element method of magnetic field. The main reason lies in the leakage occurred at the junction of the permanent magnet and the pole piece.

2. When the axial clearance is smaller than the radial clearance, the critical pressure of the diverging stepped magnetofluid seal is better than that of the ordinary magnetofluid seal.

3. When the pole tooth number in the axial clearance is more than that in the radial clearance, and the axial clearance is equal to the radial clearance, the critical pressure of the diverging stepped magnetofluid seal is better than that of the ordinary magnetofluid seal.

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