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Experimental Study on Divergent Magnetic Fluid Seal with Small Clearance and Double Magnetic Source

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In order to solve the problem of poor sealing performance of rotating machinery under the condition of small clearance, a new type of divergent magnetic fluid seal device with small clearance and double magnetic source is designed in this paper. The effect of magnetic fluid injection, tooth number and sealing clearance on the sealing pressure resistance of dual magnetic source divergence were studied and compared with the experimental value of ordinary magnetic fluid seal. The experiment results show that the pressure resistance ability of divergent magnetic fluid seal is at least 3 times that of ordinary magnetic fluid seal, which verifies the correctness of divergent magnetic seal with small clearance and double magnetic source pressure resistance theory, and has important theoretical guiding significance for solving the problem of poor magnetic fluid seal performance under small clearance.

Keywords : small clearance, dual magnetic source, divergent type, sealing

1. Introduction

The vacuum seal of magnetic fluid - has obvious advantages compared with traditional seal, such as zero leakage, self-repair, long life, zero maintenance, reducing wear between moving parts, adapting to harsh environment, minimizing shaft jitter and so on. By increasing the number of permanent magnets, the sealing performance can be further increased. The performance of the seal depends on the various design parameters of the seal assembly (shaft diameter, rotational speed, sealing environment, etc.), as well as the suitability magnetic fluid for the clearance between the seal shaft and the surrounding structure -. The shape and aspect ratio of pole boots reported in - play an important role in sealing strength. In a single-stage seal, the seal strength is proportional to the product of magnetic fluid magnetization and magnetic field gradient . Magnetic fluid seals are simple, however, in order to obtain the best performance in practical application, the advantage of divergent magnetic fluid seal with small clearance and double magnetic source is that it can effectively improve the sealing performance of magnetic fluid seal device without increasing the shaft length, especially when the length of sealing shaft is small. In order to overcome the difficulty of low sealing performance of vacuum mechanical equipment under small clearance condition, the geometry of magnetic fluid seal structure must be optimized. In order to increase the flux density in the gap at less series to obtain higher sealing strength, it is necessary to change the pole boot structure. In order to obtain the ideal sealing ability, a two-stage magnetic source is used to obtain the best sealing performance.

In order to make the design compact and able to withstand high sealing pressure, the structure parameters of the pole shoe are focused, that is, the number of radial and axial teeth of the pole shoe. Through structural design, the basic size structure of magnetic fluid seal is obtained. The divergent magnetic fluid seal with small clearance and double magnetic source is fabricated and tested. The influence of pole boot parameters on the pressure parameters of divergent magnetic fluid seal with small clearance and double magnetic source device is obtained by experimental test. The correctness of the differential pressure theory of small clearance and double magnetic source seal is verified, which has important theoretical significance for solving the problem of low sealing performance of magnetic fluid under small clearance

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condition.

2. Divergent Magnetic Fluid Seal Pressure Theory

Generally speaking, the Bernoulli equation of magnetic fluid can be expressed the following formula:

$$P+\frac{1}{2}\rho_f V^2+\rho_f gh-\mu_0\int_0^H MdH=\Phi(t) \quad (1)$$

The formula P is the pressure of a magnetic fluid at a particular location, h, ρ_f, V and M are the height of the magnetic fluid at a certain position, the density, the velocity and the saturation magnetization; g is the acceleration of gravity, μ_0 is the permeability of vacuum; H is the intensity of external magnetic field; $\Phi(t)$ is the constant. The effect of velocity on magnetic fluid seal can be ignored, and the gravity effect in seal clearance can also be ignored. Therefore, the total sealing ability of magnetic fluid seal is simplified to the following expression:

$$\Delta P=\mu_0 M_S\sum_{i=1}^{N}\left(H_{\max}^i-H_{\min}^i\right)=M_S\sum_{i=1}^{N}\left(B_{\max}^i-B_{\min}^i\right) \quad (2)$$

Among them, $H_{\max}^i$ and $H_{\min}^i$ are the maximum and minimum magnetic field intensity at the i pole tooth; $B_{\max}^i$ and $B_{\min}^i$ are the maximum and minimum magnetic flux density at i pole tooth.

According to the theoretical of divergent magnetic fluid seal, the pressure resistance of divergent magnetic fluid seal is as follows:

$$\Delta P=\sum_{i=1}^{n}\left(p_{ir}+\delta p_{ia}\right) \quad (3)$$

p_{ir} is the magnetic fluid seal pressure resistance within the radial seal clearance height formed between the i pole boot and the step shaft, p_{ia} is the Capability of magnetic fluid seal pressure within the width of the axial seal gap formed between the i pole boot and the step shaft; δ is a constant, its size is calculated by the following formula:

$$\delta=\begin{cases}1 & p_{ir}<p_{ia}\\ 0 & p_{ir}\geq p_{ia}\end{cases} \quad (4)$$

3. Structure Design of Divergent Magnetic Fluid Seal with Small Clearance and Double Magnetic Source

The two-dimensional planar symmetric model of the divergent magnetic fluid seal structure with small clearance and double magnetic sources was designed, as shown in Fig. 1.

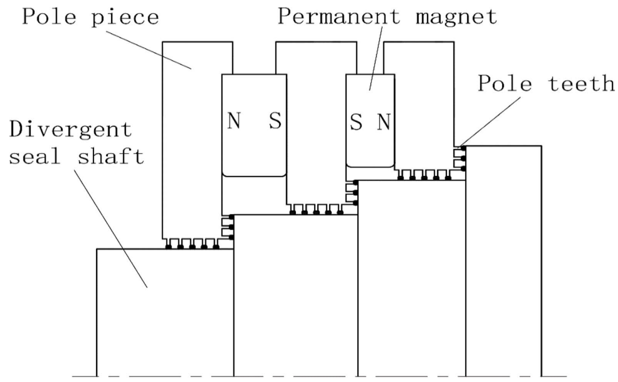

Fig. 1. Schematic diagram of magnetic fluid seal in the experiment.

Table 1. Parameters of magnetic fluid seal.

Parameter	Size
Axial length of the pole piece (mm)	5.3
Outer radius of the pole piece (mm)	30
Inner radius of the first pole piece (mm)	13
Inner radius of the second pole piece (mm)	17
Inner radius of the third pole piece (mm)	21
Radial sealing stage width (mm)	0.8/1.1/1.5/2.5
Axial sealing stage width (mm)	0.8
Axial seal clearance width *s* (mm)	0.1/0.2/0.3/0.4
Radial seal clearance height *s* (mm)	0.1/0.2/0.3/0.4
Pole tooth width (mm)	0.3
Height of Pole tooth (mm)	0.7

According to the divergent magnetic fluid seal with small clearance and double magnetic source as shown in Fig. 1, both the ladder shaft and pole boots are #45 steel, select permanent magnet materials NdFeB, residual magnetization Br is 1.05 T, and coercive force Hc is 1.35×10^6 A/m. The structural parameters of magnetic fluid seal tooth are shown in the table below.

4. Experimental Process and Methods

The double magnetic source divergent magnetic fluid seal experiment is shown in Fig. 2. The test bench consists of nitrogen cylinder, sealing cavity, pressure gauge, magnetic fluid seal assembly and motor.

The experimental steps are as follows: The first step is to heat the seal shell with a high and low temperature test chamber, and heat the sealing component and the shell; The second step is to put the magnetic fluid sealing components completed by hot charging into the high and low temperature test box for cooling; The third step is to connect the magnetic fluid sealing assembly with the sealing chamber using bolts; The fourth step is to connect

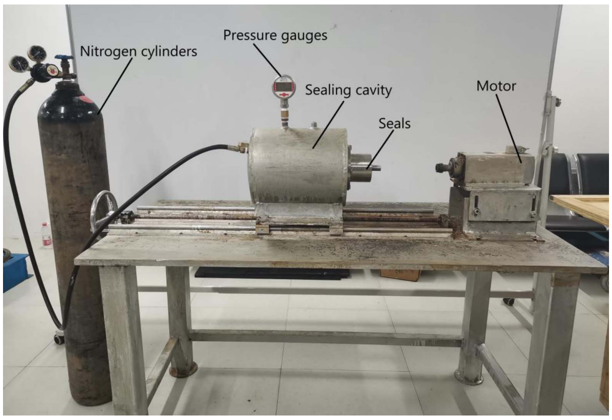

Fig. 2. (Color online) Design of test bench for magnetic fluid seal.

the motor to the sealed shaft through the coupling. The fifth step is to add 60 kPa pressure to the sealing cavity per minute.

5. Experimental Results and Discussion

5.1 Effect of Magnetic Fluid Injection Volume

The amount of magnetic fluid injection will affect the pressure resistance of divergent magnetic fluid seal with small clearance and double magnetic source to a certain extent, so when studying the pressure resistance of divergent magnetic fluid seal, it is necessary to study the injection quantity first. The amount of saturated magnetic fluid injection needed in the experiment is obtained. The axial and radial tooth numbers are 2, the radial clearance is 0.2 mm, the axial clearance is 0.1 mm, and the effect of magnetic fluid injection on the pressure resistance is shown in Fig. 3.

We can see from Fig. 3 that with the increase of the amount of magnetic fluid injection, the pressure resistance of magnetic fluid seal is also increasing. When the injection amount of magnetic fluid exceeds 0.5 mL, the sealing pressure resistance does not increase greatly and gradually becomes stable. Therefore, the saturated magnetic fluid injection of divergent magnetic fluid seal is 0.5 ml.

5.2. Influence of Radial Teeth Number on Seal Pressure Resistance of Double Magnetic Source

When the number of axial teeth is 2, the radial clearance is 0.2 mm, the axial clearance is 0.1 mm, the amount of magnetic fluid injection is 0.5 ml, the influence of the number of radial teeth on the pressure resistance of divergent magnetic fluid seal and ordinary magnetic fluid seal is shown in Fig. 4.

It can be seen from Fig. 4 that with the increase of radial teeth number, the experimental value of differential pressure of divergent magnetic fluid seal with small clearance and double magnetic source increases first and then decreases and then increases. As the number of radial teeth increases, the flux density gradient difference in radial clearance increases, and the pressure resistance in radial clearance increases. When the number of radial teeth is 1 or 2, the number of radial teeth is less than or equal to the number of axial teeth, and the pressure resistance value in the radial clearance is always less than the pressure resistance value in the axial clearance. The total pressure value of the sealing device is equal to the sum of the pressure resistance in radial and axial clearance. Therefore, when the radial teeth number is 1 to 2, the total pressure resistance of the device is increasing; When the number of radial teeth increases from 2 to 3, the

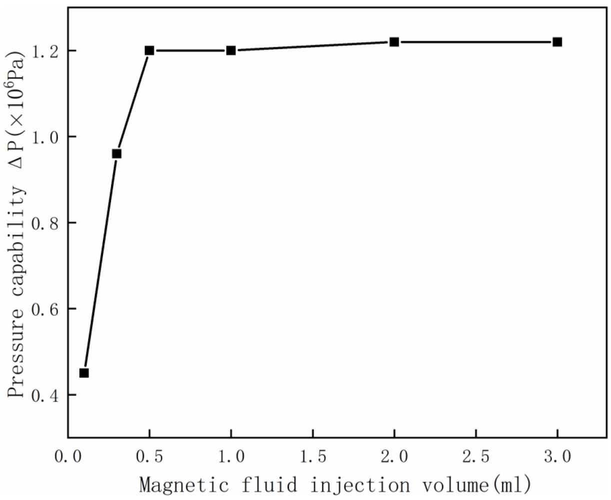

Fig. 3. Effect of magnetic fluid injection on pressure resistance of seal.

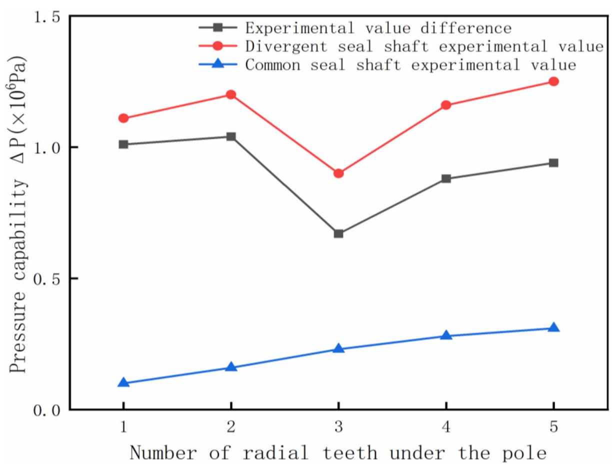

Fig. 4. (Color online) Effect of radial teeth number on sealing pressure resistance.

pressure resistance in the radial clearance is greater than that in the axial clearance. When the number of radial teeth is greater than or equal to 3, the gradient difference of flux density in radial clearance increases continuously. The pressure resistance in the radial clearance is greater than that in the axial clearance, and the axial pressure resistance can be ignored. Therefore, the variation law of radial teeth number to divergent magnetic fluid seal device with small clearance and double magnetic source is to increase first and then decrease and then increase.

As Fig. 4 shows, the experimental value of divergent magnetic fluid seal is much larger than that of ordinary magnetic fluid seal. When the number of radial teeth is 2, the experimental value of divergent magnetic fluid seal is 7.5 times that of ordinary magnetic fluid seal. In the case of the same number of pole tooth and the same height of radial clearance, the maximum difference between the experimental pressure resistance of divergent magnetic fluid and that of ordinary magnetic fluid is 1.04 MPa and the minimum difference is 0.67 MPa. When the number of radial pole tooth is 3, the minimum pressure resistance value of divergent magnetic fluid seal is 0.9 MPa, which is nearly 0.59 MPa larger than the maximum pressure resistance value of ordinary magnetic fluid seal when the number of radial pole tooth is 5, which is 0.31 MPa. The axial clearance width of the divergent type and the pole tooth in the axial clearance have great influence on the sealing performance of the divergent magnetic fluid seal with small clearance and double magnetic source, can greatly enhance the pressure value of divergent magnetic fluid.

5.3. Effect of Axial Teeth Number on Pressure Resistance of Double Magnetic Divergent Magnetic Fluid Sealing

When the number of radial teeth is 2, the radial clearance is 0.2 mm, the axial clearance is 0.1 mm, the amount of magnetic fluid injection is 0.5 ml, the influence of the number of axial teeth on the pressure resistance of divergent magnetic fluid seals and ordinary magnetic fluid seals is shown in Fig .5.

It can be seen from Fig. 5 that with the increase of axial teeth number, the pressure value of divergent magnetic fluid seal increases sharply first and then slowly increases.

When the axial clearance is 0.1 mm and the radial clearance is 0.2 mm and the radial teeth number is 2, with the increasing of the axial teeth number, the flux density gradient difference in the axial clearance is increasing, and the pressure value in the axial clearance is increasing. When the number of axial teeth is 1 and the number of radial teeth is 2, the pressure resistance value in the axial clearance is less than that in the radial clearance, and the pressure resistance value of the device is equal to the pressure resistance value in the radial clearance. When the number of axial teeth is 2, the number of radial teeth is 2, the number of radial teeth is equal to that in axial clearance, and the pressure value in axial clearance is greater than that in radial clearance. The pressure value of the device is equal to the sum of the pressure value in axial and radial clearance, so the pressure value of the device increases sharply with the increase of axial number from 1 to 2. When the number of tooth at the axial clearance increases from 2 to 3, the step difference of the total magnetic flux density of the device only increases by one step difference of the number of axial teeth, so the increase of the total pressure value of the device is not large and the increase is relatively slow. Therefore, the change law of axial tooth number to divergent magnetic fluid seal device with small clearance and double magnetic source is to increase sharply first and then slowly.

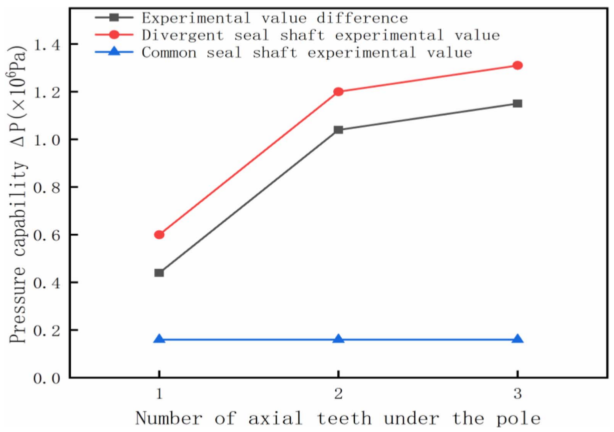

Fig. 5. (Color online) Effect of axial teeth number on pressure resistance of seal.

It can be seen from Fig. 5 that the experimental value of the ordinary magnetic fluid seal pressure is a straight line, which is because the ordinary magnetic fluid seal has no axial clearance. When the number of axial teeth is 3, the divergent magnetic fluid seal pressure value is 8.1875 times of the ordinary magnetic fluid pressure test value. Under the same number of pole tooth and the same height of radial clearance, the maximum difference between the experimental value of divergent magnetic fluid and that of ordinary magnetic fluid is 1.15 MPa, the minimum difference is 0.44 MPa. When the number of axial pole tooth is 1, the minimum pressure resistance value of divergent magnetic fluid seal is 0.6 MPa, which is nearly 0.44 MPa larger than the pressure resistance value of ordinary magnetic fluid seal is 0.16 MPa. It can be seen that the pole tooth in the axial clearance of the divergent magnetic fluid seal have a great influence on the sealing performance of the divergent magnetic fluid seal with small clearance and double magnetic source, and can enhance the pressure value of the divergent magnetic fluid seal.

5.4. Influence of Radial Clearance on Pressure Resistance of Double Magnetic Divergent Magnetic Fluid Sealing

When the number of axial and radial teeth is 2 and the axial clearance is 0.1 mm, the amount of magnetic fluid injection is 0.5 ml, the effect of radial clearance on the pressure resistance of divergent magnetic fluid seal and ordinary magnetic fluid seal is shown in Fig. 6.

It can be seen from Fig. 6 that with the increase of radial clearance, the pressure value of the divergent magnetic fluid seal with small clearance and double magnetic source increases first and then decreases. The main reason for the increase and decrease of seal pressure is that when the radial clearance is 0.1 mm, the axial clearance is 0.2 mm, the pressure value in the radial clearance is greater than that in the axial clearance, the total pressure value of the sealing device is equal to the radial pressure resistance. When the radial clearance is 0.2 mm and the axial clearance is 0.2 mm, the gradient difference of magnetic flux density in the radial clearance decreases, and the pressure resistance value is less than the pressure resistance value in the axial clearance. At this time, the total pressure resistance value of the sealing device is equal to the sum of the radial pressure resistance value and the axial pressure resistance value, so the pressure resistance value of the sealing device is increased first. When the radial clearance keeps increasing and the axial clearance remains unchanged, the gradient difference of flux density in the axial clearance is greater than that in the radial clearance, and the gradient difference of flux density in the radial clearance keeps decreasing. The pressure resistance value of the sealing device is equal to the sum of the axial and radial values, so the pressure resistance value of the subsequent device keeps decreasing.

It can also be seen from Fig. 6 that when the radial clearance is 0.2 mm, its pressure resistance value is about 5 times of the ordinary pressure resistance experimental value. The difference between the two magnetic fluid seal structures is about 0.86 MPa. The pressure resistance value of divergent magnetic fluid seal is not the smaller the gap the better, the maximum pressure resistance value of divergent magnetic fluid seals is 1.09 MPa when the radial clearance is 0.2 mm. The radial clearance of the sealing device is 0.2 mm, which can avoid the blockage of the sealing device caused by too small clearance, and also avoid the weakening of the performance of the sealing device caused by too large clearance.

5.5. Influence of Radial Clearance on Pressure Resistance of Double Magnetic Divergent Magnetic Fluid Sealing

When the number of axial and radial tooth is 2, the radial clearance is 0.2 mm, and the magnetic fluid injection amount is 0.5 ml, the influence of the axial clearance on the pressure resistance of divergent magnetic fluid seals and ordinary magnetic fluid seals is shown in Fig. 7.

It can be seen from Fig. 7 that with the increase of axial clearance, the pressure value of the divergent magnetic fluid seal with small clearance and double magnetic source

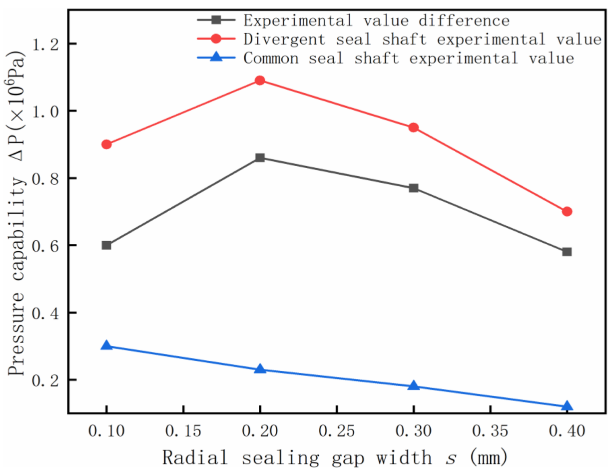

Fig. 6. (Color online) Effect of radial gap on sealing pressure resistance.

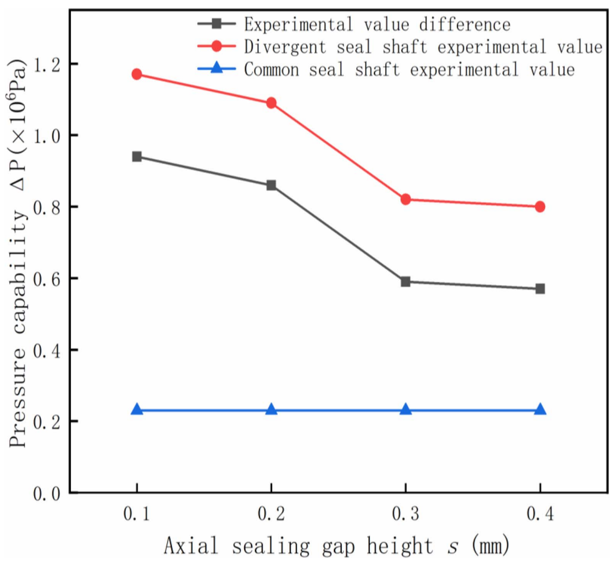

Fig. 7. (Color online) Effect of axial gap on sealing pressure resistance.

decreases slowly first, then decreases greatly, and finally remains basically unchanged. The main reason is that when the radial clearance is 0.2 mm, the axial clearance is 0.1 mm to 0.2 mm, the axial clearance pressure value is decreasing, whereas the radial clearance pressure value is basically constant, the axial clearance pressure value is larger than the radial clearance pressure value, the total pressure value of the sealing device is equal to the sum of the radial and axial pressure values. In this process, the total pressure value of the device decreases slowly; when the radial clearance is 0.2 mm, the axial clearance is 0.3 mm, the magnetic flux density gradient difference in the axial gap is less than that in the radial gap, and the pressure value of the axial gap is less than that in the radial gap. The total pressure resistance of the sealing device is equal to the pressure resistance of the radial clearance. When the axial clearance changes from 0.2 mm to 0.3 mm, the pressure resistance of the device decreases sharply. When the axial clearance changes from 0.2 mm to 0.3 mm, the pressure resistance value in the radial clearance basically remains unchanged, and the total pressure resistance value of the sealing device is equal to the pressure resistance value of the radial clearance. Therefore, the influence rule of the axial clearance on the pressure resistance performance of the sealing device is to decrease slowly first, then sharply, and finally remain basically unchanged.

When the axial clearance is 0.3 mm to 0.4 mm, the pressure resistance value of the axial clearance width to the divergent magnetic fluid seal with small clearance and double magnetic source is basically unchanged, and the axial clearance is 0.3 mm to 0.4 mm, which can reduce the processing difficulty, but still can satisfy the requirements of the sealing device.

6. Conclusion

In this paper, a divergent magnetic fluid seal with small clearance and double magnetic source is proposed. This divergent magnetic fluid seal structure is designed according to the divergent seal theory formula. By means of experiment, the saturation magnetic fluid injection amount of the divergent magnetic fluid seal with small clearance and double magnetic source was measured, and then the influence of each parameter on the pressure resistance of the divergent magnetic fluid seal with small clearance and double magnetic source was studied. Finally, the experimental value of divergent magnetic fluid seal with small clearance and double magnetic source is compared with that of ordinary magnetic fluid seal. The experimental value of divergent magnetic fluid seal with small clearance and double magnetic source is at least 3 times that of ordinary magnetic fluid seal.

The condition of small sealing gap, the saturation injection of magnetic fluid in the sealing gap of double magnetic source with small gap is 0.5 ml.

By comparing the pressure values of divergent magnetic fluid seal with small clearance and double magnetic source and ordinary magnetic fluid seal, we can see that the axial tooth number and axial gap have great influence on the pressure value of divergent magnetic fluid seal with small clearance and double magnetic source. In order to obtain better sealing ability, the radial pole tooth number should be smaller than the axial pole tooth number, the radial clearance height is 0.2 mm, the axial clearance width should not be too small, otherwise the axial clearance will be blocked. When the sealing pressure value is determined to satisfy the sealing requirements, the axial clearance can be set at 0.3 mm to 0.4 mm.

The experimental value of the pressure resistance of the divergent magnetic fluid seal with small clearance and double magnetic source is at least three times that of the ordinary magnetic fluid seal.

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References

[1] J. Patel, K. Parekh, and R. V. Upadhyay, Int. J. Therm. Sci. **103**, 35 (2016).
[2] T. Okabe, Y. Kondo, S. Yoshimotoc, and S. Sasakic, Vacuum. **164**, 34 (2019).
[3] S. Marcin, IEEE T Magn. **54**, 6 (2018).
[4] X. X. Zhang, L. Y. Sun, Y. R. Yu, and Y. J. Zhao, Adv. Mater. **31**, 51 (2019).
[5] Y. Mitamura, T. Yano, W. Nakamura, and E. Okamoto, Magnetohydrodynamics **23**, 1 (2013).
[6] M. Cong, H. Y. Wen, Y. Du, and P. L. Dai, Chin J. Mech. Eng. **25**, 4 (2012).
[7] L. Matuszewski, Pol. Marit. Res. **26**, 2 (2019).
[8] H. M. Zhou, Y. B. Chen, Y. J. Zhang, and D. C. Li, Tribol. Trans. **64**, 1 (2021).
[9] J. W. Chen, D. C. Li, and H. Du, J. Magn. **23**, 3 (2018).
[10] S. Parmar, V. Ramani, R. V. Upadhyay, and K. Parekh,

Vacuum. **172**, 109087 (2020).
[11] S. Marcin, J. Magn. **24**, 1 (2019).
[12] Radionova, A. Podoltsevb, and A. Zahorulko, Procedia Engineering **39**, 327 (2012).
[13] Z. Z. Wang, and D. C. Li, Int. J. Appl. Electrom. **48**, 1 (2015).
[14] X. L. Yang, P. Sun, F. Chen, F. X. Hao, D. C. Li, and P. J. Thomas, IEEE. T. Magn. **55**, 3 (2019).