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Numerical Analysis and Experimental Study of Symmetric Stepped Magnetic Fluid Seal with Three Magnetic Sources

Fuxiang Hao and Anle Mu*

School of Mechanical and Precision Instrument Engineering, Xi'an University of Technology, Xi'an 710048, Shaanxi, China

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A symmetric stepped magnetic fluid seal (SSMFS) structure with three magnetic sources is designed with the goal of improving the leakage problem under the large clearance rotary seal condition. The magnetic field distribution in the sealing clearance is analyzed using the finite element method when the radial and axial clearances are both 0.4 mm. The pressure capacity is calculated, and the effects of the height of permanent magnets, the length of the pole teeth, and the number of pole teeth are compared with those of diverging stepped magnetic fluid seal (DSMFS) and converging stepped magnetic fluid seal (CSMFS) with three magnetic sources. The numerical outcomes demonstrate that the SSMFS with three magnetic sources has a greater pressure capacity than the other two seal structures. The effects of magnetic fluid injection volumes, radial and axial clearances, various rotational speeds, and holding times are then investigated in tests to determine the pressure capacity of the SSMFS with three magnetic sources. The results are compared to those of the other two structures. The experimental date indicate that the SSMFS with three magnetic sources has a magnetic fluid injection saturation of around 7 ml. The advantages of the SSMFS structure become more clear with the modification of the radial clearance and axial clearance. With an increase in rotation speed and holding time, the pressure capacity of SSMFS with three magnetic sources has no obvious change, but it is obviously higher than that of the other two structures.

Keywords : symmetric stepped structure, magnetic fluid seal, large clearance, numerical analysis, experimental study

1. Introduction

Leakage problems often occur in the operation of the machine. Once the machine leaks, it will cause the equipment to stop running, resulting in energy waste and even endangering people's lives [1, 2]. Therefore, preventing the leakage of machinery and equipment is still of great research significance in the fields of national defense industry, aviation, aerospace and navigation [3, 4]. Traditional sealing methods, such as floating ring seal, mechanical seal, gasket seal, labyrinth seal, etc., are effective ways to solve static seal. However, in the case of a dynamic seal, there is significant friction between them and the spinning shaft, which results in a short seal life, low dependability, and a substantial leakage issue [5].

A novel functional material called magnetic fluid is a stable colloidal liquid whose primary constituents are magnetic particles, an essential carrier liquid, and surfactant [6-8]. Under the influence of the magnetic field, magnetic fluid exhibits a variety of properties that conventional liquid does not have [9]. Magnetic fluid sealing technique is the use of highly saturated magnetic fluid to seal connected equipment via a magnetic field. Its benefits include no leakage, a long useful life, low torque, excellent reliability, self-healing capacity, high and low temperature change, and a straightforward structure [10, 11]. At present, there are many research on the magnetic fluid rotary with small clearance on the ordinary straight shaft. Zhang and Li analyzed the performance of split magnetic fluid plane seal by using the effective magnetic circuit design theory and finite element analysis method [12]. Wang *et al*. designed a gas-isolated magnetic fluid sealing method to avoid direct contact between magnetic fluid and sealed liquid [13]. Cheng *et al*. analyzed the sealing pressure and friction heat under the sudden change of main shaft speed of different water turbines through experiments [14]. Li *et al*. studied the magnetic fluid sealing mechanism of flexible pole pieces theoretically and experimentally [15]. Chen *et al*. studied the effect of eccentricity on the sealing performance of magnetic fluid

*Corresponding author: Tel: +86-18049538650
Fax: +86-18049538650, e-mail: muanle@xaut.edu.cn

[16]. Chen *et al*. studied the acoustic emission signals produced by different magnetic fluid seals through experiments, so as to evaluate the sealing condition [17]. Yuan *et al*. proposed an axial-radial bidirectional magnetic fluid seal structure with radial helical teeth, the results show that when the helical angle is small, the pressure capacity is high [18]. Yu *et al*. studied the influence of magnetic fluid evaporation on the pressure resistance of magnetic fluid seal through theoretical analysis and experiment [19]. However, the leakage of a common magnetic fluid seal structure is challenging to fix when the sealing clearance is higher than 0.3 mm. For this reason, Yang *et al*. presented a converging stepped magnetic fluid seal (CSMFS) and diverging stepped magnetic fluid seal (DSMFS) structure with higher sealing pressure capacity than the conventional sealing structure [20-22]. On this premise, Hao *et al.* used an orthogonal method to improve the converging stepped magnetic fluid seal construction, and the optimized result was 11.2 % higher than that before optimization [23].

Therefore, a SSMFS structure with three magnetic sources is proposed in this research with the intention of better adapting to the operating circumstances of large clearance rotary seals. The effects of the permanent magnet height, the length of the pole teeth, and the number of pole teeth on the sealing pressure capacity are investigated by numerical analysis when the axial clearance and radial clearance are both 0.4 mm. The outcomes are compared with those of DSMFS and CSMFS with three magnetic sources. The numerical results show that the pressure capacity of SSMFS with three magnetic sources is better than that of the other two structures. The effects of the magnetic fluid injection volume, various radial and axial sealing clearances, rotation speed, and holding time are then investigated through tests, and the results are compared with those obtained for the other two structures. According to the experimental findings, the magnetic fluid injection saturation volume of the SSMFS with three magnetic sources structure is around 7 ml. The benefits of the SSMFS structure with three magnetic sources are more pronounced by altering the radial and axial clearances, which can be increased by 14.83 % compared with the CSMFS structure. With the increase of rotation speed and holding time, the pressure capacity of SSMFS with three magnetic source has no obvious change, which is obviously higher than that of the other two structures. The results show that the SSMFS structure with three magnetic sources can better solve the leakage problem, and it can also provide a reference for the application of other rotary seal with large clearances.

2. Theoretical Analysis of SSMFS with Three Magnetic Sources

According to the Maxwell equation, the magnetic field in the sealing structure may be expressed as follows:

$$\nabla \times \boldsymbol{H} = 0 \tag{1}$$

$$\nabla \cdot \boldsymbol{B} = 0 \tag{2}$$

$\boldsymbol{H}$ is the magnetic field strength and $\boldsymbol{B}$ is the magnetic induction strength. The relationship between $\boldsymbol{H}$ and $\boldsymbol{B}$ is expressed as $\boldsymbol{B}=\mu_0(\boldsymbol{H}+\boldsymbol{M})$ where $\boldsymbol{M}$ is the magnetization, μ_0 is the permeability constant.

Magnetic fluid is considered as a stable, incompressible and homogeneous fluid. Therefore, the critical pressure can be calculated according to Bernoulli's theorem:

$$P+\frac{1}{2}\rho_f V^2+\rho_f gh-\mu_0\int_0^{\boldsymbol{H}} \boldsymbol{M}d\boldsymbol{H}=C \tag{3}$$

where P, v, ρ_f, g, and h are the total pressure in the fluid, the velocity of the fluid, fluid density, gravitational acceleration, and height of the fluid, respectively. The magnetic field intensity's direction and the magnetization's direction are parallel. As a result, formula (3) may be written as follows.

$$P+\frac{1}{2}\rho_f V^2+\rho_f gh-\mu_0\int_0^{H} MdH=C \tag{4}$$

where M and H are modules of magnetization and magnetic field intensity, respectively. The effects of gravity in the sealing clearance as well as the influence of velocity on the magnetic fluid seal may both be disregarded for the static pressure in the magnetic fluid seal. As a result, the magnetic fluid seal formula is as follows:

$$\Delta P=\mu_0 M_S\sum_{j=1}^{N}(H_{\max}^{j}-H_{\min}^{j})=M_S\sum_{i=j}^{N}(B_{\max}^{j}-B_{\min}^{j}) \tag{5}$$

Where $H_{\max}^{j}$ and $H_{\min}^{j}$ are the maximum and minimum magnetic field strengths under the j pole tooth respectively, $B_{\max}^{j}$ and $B_{\max}^{j}$ are the maximum and minimum magnetic flux densities under the j pole tooth respectively, M_S is the saturation magnetization of magnetic fluid. The structure of SSMFS with three magnetic sources is shown in Fig. 1, which is composed of diverging stepped seal structure and converging stepped seal structure. Therefore, the pressure theory of SSMFS structure is:

$$\Delta P_{Sym}=\Delta P_{\mathrm{Div}}+\Delta P_{\mathrm{Con}} \tag{6}$$

The pressure formula of DSMFS is expressed as [10, 21]:

$$\Delta P_{Div} \approx M_S \sum_{i}^{N} (\Delta B_{ir} + \alpha \Delta B_{ia}) \tag{7}$$

ΔB_{ia} represents the magnetic induction densities difference in the axial clearance between the i-th pole piece and the diverging stepped shaft. ΔB_{ir} represents the magnetic induction densities difference in the radial clearance between the i-th pole piece and the diverging stepped shaft. When $\Delta B_{ir} < \Delta B_{ia}$, $\alpha = 1$, otherwise $\alpha = 0$.

The pressure formula of CSMFS is expressed as[10, 22]:

$$\Delta P_{Con} \approx M_S \sum_{j}^{N} (\Delta B_{ja} + \beta \Delta B_{jr}) \tag{8}$$

ΔB_{ja} represents the magnetic induction densities difference in the radial clearance between the j-th pole piece and the converging stepped shaft. ΔB_{jr} represents the magnetic induction densities difference in the radial clearance between the j-th pole piece and the converging stepped shaft. When $\Delta B_{ja} < \Delta B_{jr}$, $\beta = 1$, otherwise $\beta = 0$.

3. Structure Design of SSMFS with Three Magnetic Sources

A SSMFS structure with three magnetic sources is designed in this study to better handle the leakage problem under the large clearance rotary seal condition, as illustrated in Fig. 1, and its essential structural characteristics are presented in Table 1. The model is created in finite element software using the model parameters listed in Table 1. The permanent magnet is built of Nd-Fe-B material and has a coercive force of 1356 kA/m and a

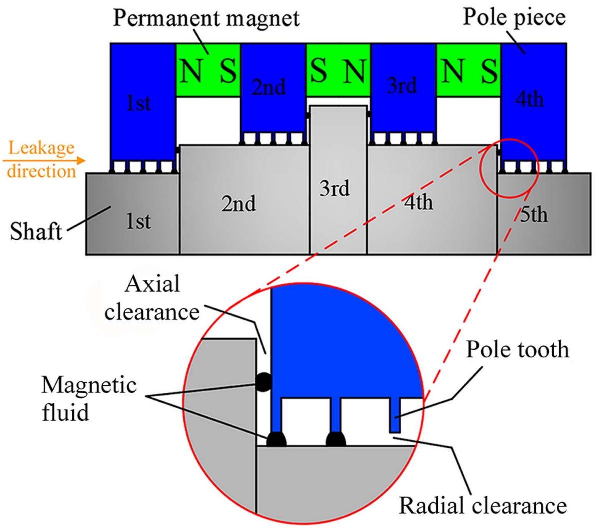

Fig. 1. (Color online) The 2-D structure model of symmetric stepped magnetic fluid seal.

Table 1. Model parameters of SSMFS structure in Fig. 1.

Item	Value
Inner diameter of the 1/2/3/4 pole piece (mm)	29.8/37/37/29.8
Outer diameter of the 1/2/3/4 pole piece (mm)	62
Axial width of every pole piece (mm)	5
Axial width of every permanent magnet (mm)	5
Inner diameter of every permanent magnet (mm)	44/46/48/50/52
Outer diameter of every permanent magnet (mm)	60
Width of pole teeth (mm)	0.2
Length of pole teeth (mm)	0.3/0.5/0.7/0.9
Number of pole teeth	3/4/5/6

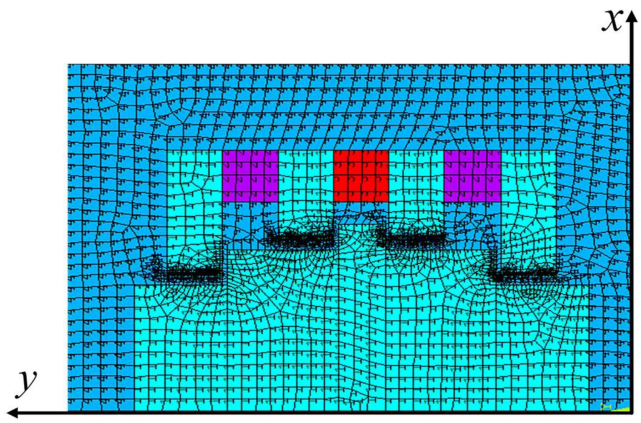

Fig. 2. (Color online) Grid diagram of two-dimensional model of symmetrical stepped structure.

permeability of 1.05, respectively. The shaft and pole pieces have material characteristics of 2Cr13. Oil-based magnetic fluid with a saturation magnetization of 32.7 kA/m is used. The model may be condensed to a two-dimensional model since the structure is symmetric along the y axis, as seen in Fig. 2. When the solver has completed, the boundary conditions guarantee that the magnetic lines of force are parallel to the model's border.

4. Numerical Analysis and Results Discussion

4.1. Effect of the height of permanent magnet

Studying the effect of the permanent magnet height on the pressure capacity of the magnetic fluid seal is crucial for the development of a seal device that satisfies the large clearance criterion because permanent magnets as magnetic sources supply the magnetic energy for the whole SSMFS structure. The distribution of the magnetic flux density for a permanent magnet at various heights is depicted in Fig. 3.

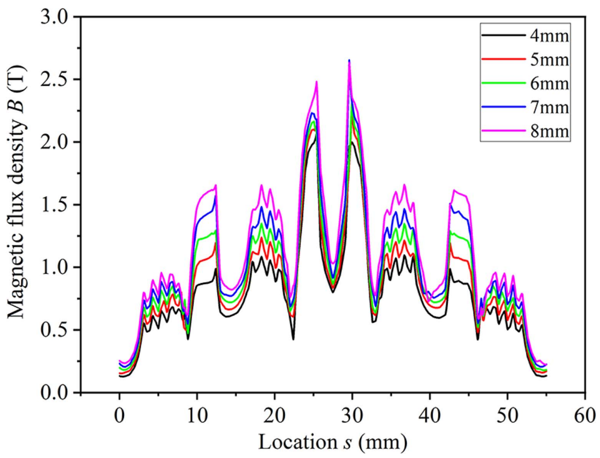

Fig. 3. (Color online) Magnetic flux densities of different heights of permanent magnet.

As seen in Fig. 3, as the height of the permanent magnet increases, so does the magnetic flux density in the axial and radial clearances. The reason is that the permanent magnet serves as a magnetic source for the whole magnetic circuit, and as its height increases, so does the amount of magnetic energy it can supply to the circuit. Moreover, the magnetic flux density corresponding to the middle two pole pieces is obviously much larger than that corresponding to the two pole pieces on both sides, because the magnetic energy of the middle two pole pieces is provided by two permanent magnets, whereas that of the two pole pieces on both sides is provided by one permanent magnet. The pressure capacity of SSMFS with three magnetic sources can be calculated by the magnetic flux density curves in Fig. 3 and the pressure capacity formula, the calculated results are compared to those of DSMFS and CSMFS structures. And Fig. 4 shows the outcomes.

As can be seen from Fig. 4, when the height of the permanent magnet increases from 4 mm to 8 mm, the pressure capacity of the magnetic fluid seal corresponding to the three structures increases firstly and then decreases, and the pressure capacity is at its maximum when the permanent magnet is 7 mm tall. The explanation is that when the height of permanent magnets increases, the contact area between permanent magnets and pole pieces will increase, thus providing more magnetic energy for the whole magnetic circuit. When the height of the permanent magnet reaches about 7 mm, it should be because the magnetic energy of the whole magnetic circuit reaches the best saturation state. Fig. 4 also makes it evident that the SSMFS structure has a higher sealing pressure capacity than that of the other two structures. Especially when the height of the permanent magnet is 6 mm, the sealing pressure of the SSMFS with three magnetic sources is 2.568bar, that of the DSMFS with three magnetic sources is 2.387bar and that of the CSMFS with three magnetic sources is 2.423bar.

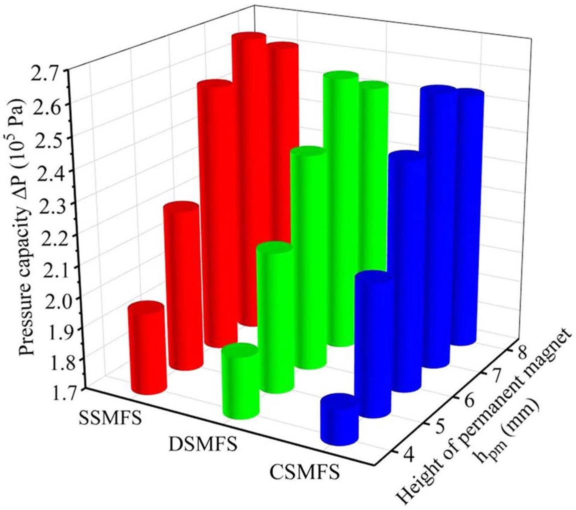

Fig. 4. (Color online) Comparison of theoretical pressure capacity of three magnetic fluid sealing structures in different heights of permanent magnet.

4.2. Effect of the length of pole teeth

The length of pole teeth is one of the key factors affecting the pressure capacity of magnetic fluid seals. Therefore, the study of the effect of the pole teeth length on the sealing performance can provide a theoretical basis for the magnetic fluid seal experiment. The magnetic flux density distribution under various lengths of pole teeth is illustrated in Fig. 5 when the radial clearance and axial clearance of the SSMFS with three magnetic sources are both 0.4 mm.

The magnetic flux density in the radial clearance is most noticeable when the length of the pole teeth is 0.3 mm, and it is least noticeable when the length of the pole teeth is 0.9 mm, as can be seen in Fig. 5. Because the pole teeth length is quite short and the magnetic resistance is relatively low, numerous magnetic induction lines pass through as a consequence. The magnetic resistance will rise as the length of the pole teeth increases, the magnetic induction line passing through the pole teeth will decrease, and the magnetic induction strength will decrease. In addition, this figure shows that when the length of the pole teeth is 0.3 mm, the magnetic flux density in the axial clearance decreases, whereas when the length is 0.9 mm, the magnetic flux density in the axial clearance increases. The primary explanation is that the magnetic energy in the whole magnetic circuit is constant, while the

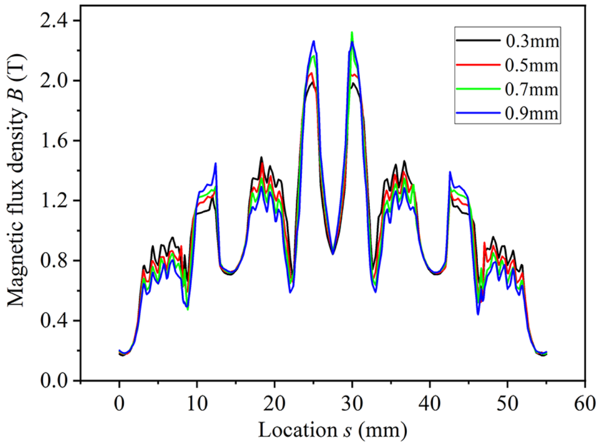

Fig. 5. (Color online) Magnetic flux densities of different length of pole teeth.

magnetic flux density in the radial clearance grows, the magnetic flux density in the axial clearance decreases. According to the magnetic flux density curve and the pressure theory, the pressure capacity value of SSMFS with three magnetic sources can be calculated, and the results are compared with the pressure value of the DSMFS and CSMFS. The results are shown in Fig. 6.

The sealing pressure capacity of the three structures increases initially and subsequently decreases, as seen in Fig. 6, as the length of the pole teeth grows. The sealing pressure capacity achieves its highest value at a length of 0.7 mm for the pole teeth. This is due to the fact that as the length of the pole teeth increases, so does the magnetic field gradient difference between the pole teeth and the shaft. As a result, according to the pressure theoretical

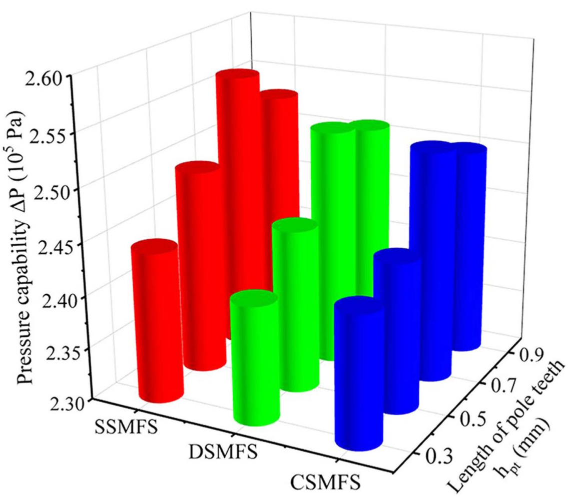

Fig. 6. (Color online) Comparison of theoretical pressure capacity of three magnetic fluid sealing structures in different length of pole teeth.

formula, the pressure capacity will ultimately grow. The highest magnetic energy product of the entire magnetic circuit may be attained when the length of the pole teeth is 0.7 mm. This figure also shows that regardless of how the length of the pole teeth changes, the pressure capacity of the SSMFS with three magnetic sources is always greater than that of the DSMFS and CSMFS, demonstrating that the SSMFS with three magnetic sources can effectively solve the leakage problem under large clearance conditions.

4.3. Effect of the number of pole teeth

The number of pole teeth affects the theoretical pressure capacity of SSMFS. Therefore, researching how the number of pole teeth affects the sealing abilities of magnetic fluid might offer a crucial theoretical foundation for the construction of SSMFS structure in large clearance situations. The magnetic flux density distribution of various numbers of pole teeth is illustrated in Fig. 7 when the radial clearance and axial clearance of the SSMFS with three magnetic sources are both 0.4 mm.

When can be observed in Fig. 7, the magnetic flux density in the radial clearance rises as the number of pole teeth does, whereas it slightly declines in the axial sealing clearance. This is so that the magnetic resistance in the radial sealing clearance will reduce, the magnetic flux lines traveling through the radial clearance will grow, and the magnetic flux density will increase as the number of pole teeth increases. The magnetic energy in the magnetic circuit is certain, and the magnetic flux density in the axial sealing clearance will necessarily decrease as the magnetic flux density in the radial sealing clearance increases according to the magnetic circuit theorem. According to the magnetic flux density curves in Fig. 7

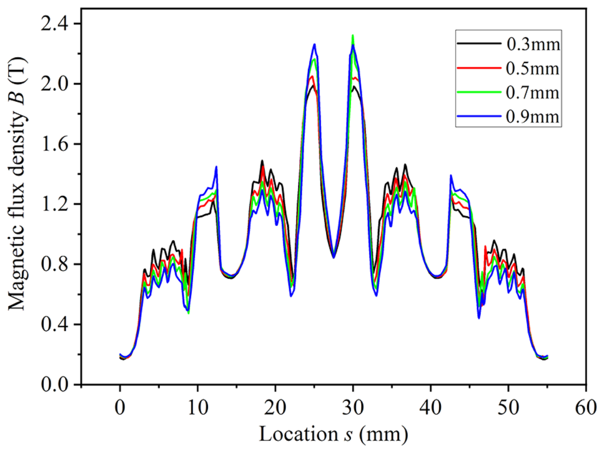

Fig. 7. (Color online) Magnetic flux densities of different number of pole teeth.

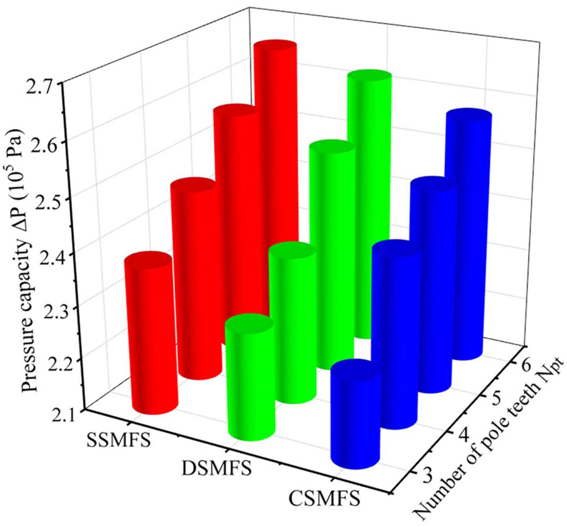

Fig. 8. (Color online) Comparison of theoretical pressure capacity of three magnetic fluid sealing structures in different number of pole teeth.

and the pressure theoretical formula, the pressure capacity of SSMFS with three magnetic sources can be calculated, and the results are contrasted with the pressure capacity of CSMFS and DSMFS. The outcomes are displayed in Fig. 8.

The pressure value of the three magnetic fluid seal structures is at its lowest when there are three pole teeth, as shown in Fig. 8. The respective pressure values of three sealing structures are at their highest when there are six pole teeth. However, there shouldn't be too many pole teeth used in the actual process because doing so would raise the processing time and expense. In addition, this figure also shows that the pressure value of SSMFS structure with three magnetic sources is always greater than both DSMFS structure and CSMFS structure.

5. Experimental Study on SSMFS with Three Magnetic Sources

In this study, SSMFS structure with three magnetic sources is developed in order to confirm the accuracy of the numerical analysis in the fourth part. The DSMFS structure and CSMFS structure are also built at the same time in order to compare the experimental findings. Their parameters are shown in Table 2.

When assembling the magnetic fluid seal assembly, the assembly mode between the pole pieces and the shell is an interference fit, so it is necessary to use the hot assembly to reduce the assembly difficulty. Put the shell used for sealing into the high and low temperature test box as shown in Fig. 9, heat it for half an hour, and then take it out. Then put the seal assembly into the shell. During the assembly, the clearance between the outer circular surface of the seal and the inner circular surface of the shell should be avoided. The outer surface of the seal and the inner surface of the shell should be coated

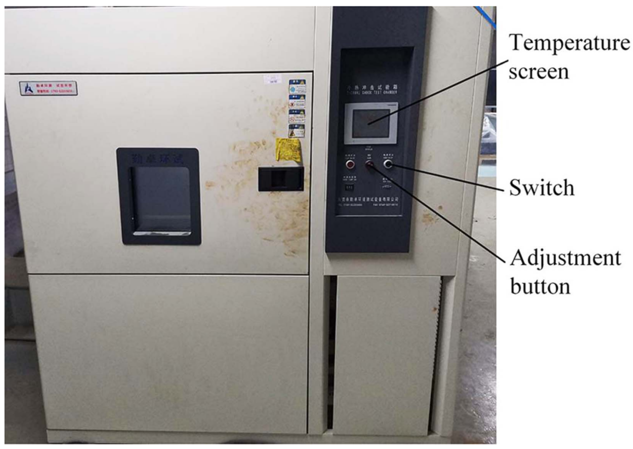

Fig. 9. (Color online) High and low temperature test box.

Table 2. Experimental parameters of three sealing structures.

Item	SSMFS	DSMFS	CSMFS
Inner diameter of the 1/2/3/4 pole piece (mm)	29.8/37/37/29.8	22.6/29.8/37/44.2	44.2/37/29.8/22.6
Outer diameter of the 1/2/3/4 pole piece (mm)	62	62	62
Radial sealing clearance (mm)	0.4/0.5/0.6/0.7	0.4/0.5/0.6/0.7	0.4/0.5/0.6/0.7
Axial sealing clearance (mm)	0.4/0.5/0.6/0.7	0.4/0.5/0.6/0.7	0.4/0.5/0.6/0.7
Axial length of every pole piece (mm)	5	5	5
Axial length of every permanent magnet (mm)	5	5	5
Inner diameter of every permanent magnet (mm)	48	48	48
Outer diameter of every permanent magnet (mm)	60	60	60
Width of every tooth slot (mm)	0.8	0.8	0.8
Depth of every tooth slot (mm)	0.7	0.7	0.7

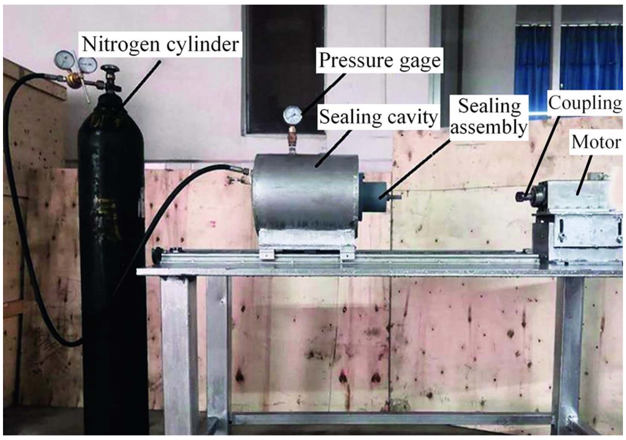

Fig. 10. (Color online) Magnetic fluid sealing test bench.

with a layer of lubricating oil to reduce friction and facilitate assembly, thus effectively ensuring the reliability of assembly. When the temperature of the magnetic fluid seal assembly is reduced to normal temperature, install the magnetic fluid seal assembly on the sealing test bench shown in Fig. 10 by screws, and connect the rotating shaft of the magnetic fluid seal assembly with the motor with a coupling.

5.1. Effect of magnetic fluid injection volume on SSMFS with three magnetic sources

Magnetic fluid is an important part of SSMFS with three magnetic sources, so it is very important to study the effect of magnetic fluid injection volume on the pressure capacity of the seal through experimental method. In this experiment, the effect of injection volume ranging from 3 ml to 8 ml on the pressure values of the SSMFS with three magnetic sources is investigated and the results are presented in Fig. 11.

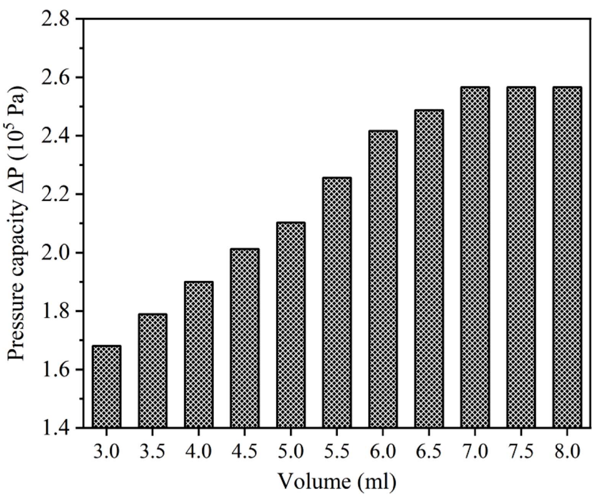

Fig. 11. (Color online) Effect of magnetic fluid injection volume on pressure capacity.

As is evident from Fig. 11, the pressure values of the SSMFS structure improves initially firstly and then remains unchanged as the magnetic fluid injection volume is increased. The maximum sealing pressure value is reached at the injection volume of 7 ml. Magnetic fluid will fill up the tooth slots as well as the sealing clearance between the pole pieces and the shaft during the test, however, this portion will not be involved in the sealing process. As a result, the SSMFS with three magnetic sources has a 7 ml saturation of magnetic fluid injection.

5.2. Effect of sealing clearance on SSMFS with three magnetic sources

In order to prove that the SSMFS structure with three magnetic sources can better adapt to the large clearance working conditions, the effect of various radial and axial sealing clearances on the pressure capacity of SSMFS with three magnetic sources is studied in this experiment by using the control single variable method. At the same time, the effect of different radial sealing clearances and axial sealing clearances on the pressure capacity of DSMFS and CSMFS are also studied, and the experimental results of three different structures are compared.

5.2.1. Effect of radial sealing clearance on sealing pressure capacity

In this section, axial sealing clearance is set at 0.4 mm, and the effect of various radial sealing clearances on pressure capacity of the SSMFS with three magnetic sources is investigated. In Fig. 12, the experimental

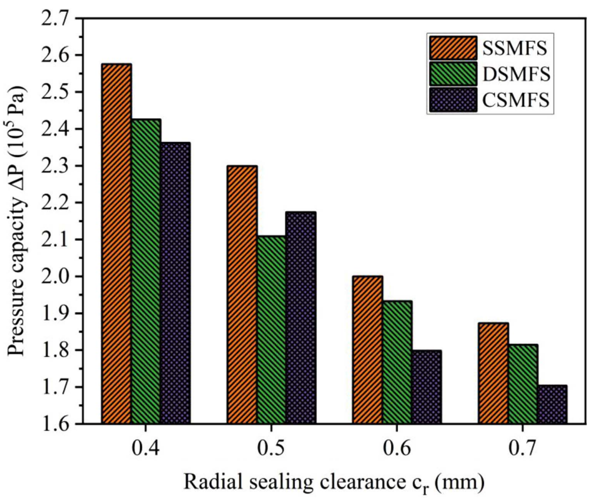

Fig. 12. (Color online) Comparison of experimental pressure capacity of three magnetic fluid sealing structures in different radial clearances.

findings are compared with those of the other two seal structures.

As shown in Fig. 12, the sealing pressure values of the three sealing structures reduces as the radial sealing clearance increases, because the magnetic capacity increases with the increase of the radial sealing clearance. This figure also demonstrates that the SSMFS structure with three magnetic sources always has a better sealing pressure capacity than the other two structures, regardless of how the radial sealing clearance varies. The pressure capacity of the SSMFS with three magnetic sources is 9.07 % higher when the radial sealing clearance is 0.4 mm than it is for the CSMFS, and it is 8.16 % higher when the radial sealing clearance is 0.5 mm than it is for the DSMFS.

5.2.2. Effect of axial sealing clearance on sealing pressure capacity

Similar to the previous part, this one has a radial sealing clearance of 0.4 mm and the effect of various axial clearances on the pressure capacity of SSMFS structure with three magnetic sources is analyzed. The findings of the comparison between the experimental values and those of the other two seal structures are displayed in Fig. 13.

As can be seen from Fig. 13, with the increase of axial sealing clearances, the pressure capacity of the three magnetic fluid sealing structures decreases. Intriguingly, the CSMFS with three magnetic sources has a pressure capacity that is larger than 0.5 mm when the axial sealing clearance is 0.6 mm, which may be explained by the pressure theoretical formula in the second section. When the axial sealing clearance is 0.5 mm, the magnetic flux density difference between the pole pieces and the shaft of the CSMFS is greater than its in the radial sealing clearance, so the total sealing pressure capacity is equal to the pressure value in the axial sealing clearance at this time. Particularly, the pressure capacity of the SSMFS structure with three magnetic sources is increased by 14.83 % when the axial clearance is 0.5 mm compared to that of the CSMFS, and by 11.42 % when the axial sealing clearance is 0.6 mm compared to that of the DSMFS. This effectively proves that the SSMFS structure with three magnetic sources can better meet the large sealing clearance working conditions.

5.3. Effect of rotation speed on SSMFS with three magnetic sources

In this experiment, when the axial clearance and radial clearance are both 0.4 mm. Firstly, pressurize the sealing cavity to the saturation pressure value close to the SSMFS structure with three magnetic sources, then turn on the power supply to make the motor run, and the motor will drive the spindle of the installed seal to rotate for 1 hour, observe whether the value of the pressure gauge changes, then adjust the rotation speed in turn. If the sealing pressure capacity does not change, stop the rotation of the motor, then turn on the DSMFS and CSMFS with three magnetic sources. The results are shown in Fig. 14. Magnetic fluid is an important part of the magnetic fluid sealing assembly, which is firmly adsorbed in the sealing clearance between the shaft and the pole piece by magnetic force. When the shaft rotates, magnetic fluid can play the role of lubrication, the influence of magnetic

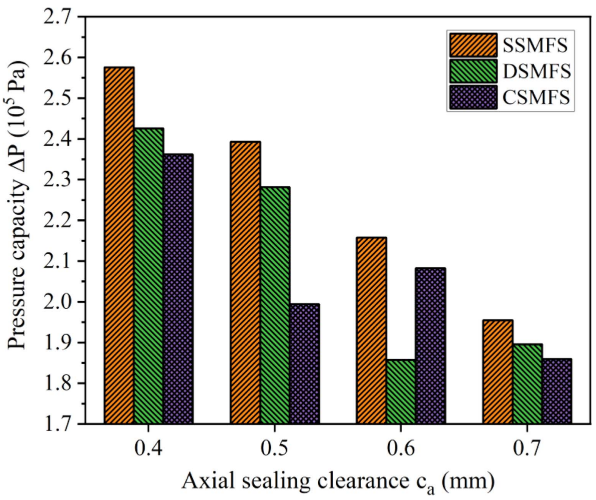

Fig. 13. (Color online) Comparison of experimental pressure capacity of three magnetic fluid sealing structures in different axial clearances.

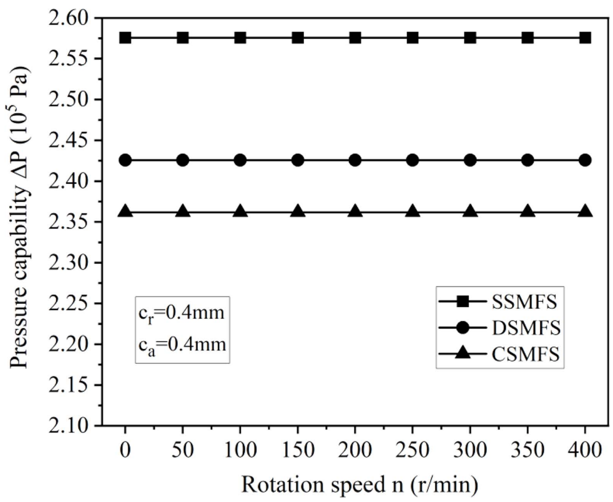

Fig. 14. (Color online) Comparison of experiment pressure capacity of three magnetic fluid sealing structures in different rotation speed.

fluid on shaft torque can be ignored, and the influence on shaft speed can be further ignored, so the influence on motor output power can also be ignored.

As can be observed in Fig. 14, regardless of how the rotation speed varies, the pressure capacity of the SSMFS structure with three magnetic sources is always greater than the pressure capacity of the other two sealing structures, which fully reflects the superiority of the SSMFS structure with three magnetic sources. Furthermore, it can be shown in this figure that when the rotation speed increases, the sealing pressure capacity of the three structures does not alter noticeably, which indicates that when the rotation speed is lower than 400 r/min, the stepped magnetic fluid rotary seal can be treated as a static seal approximately.

5.4. Effect of holding time on SSMFS with three magnetic sources

The pressure holding time is an important factor to verify the pressure capacity of the SSMFS structure with three magnetic sources. Therefore, in this experiment, he effect of 24 hours pressure holding time on the pressure capacity of the SSMFS with three magnetic sources is investigated. The findings are then compared to the experimental pressure values of the other two sealing structures. The outcomes are displayed in Fig. 15.

Evidently, as seen in Fig. 15 that when the rotating shaft is in a static state, the SSMFS with three magnetic sources has a constant pressure capacity of 2.577 bar from 0 hours to 24 hours, while the corresponding pressure capabilities of the other two magnetic fluid seal structures are maintained at 2.426 bar and 2.361 bar, respectively. Therefore, through the pressure holding experiment, it can be proved that the SSMFS structure with three magnetic sources has better pressure holding effect, and this research result can provide references for other rotary seal conditions.

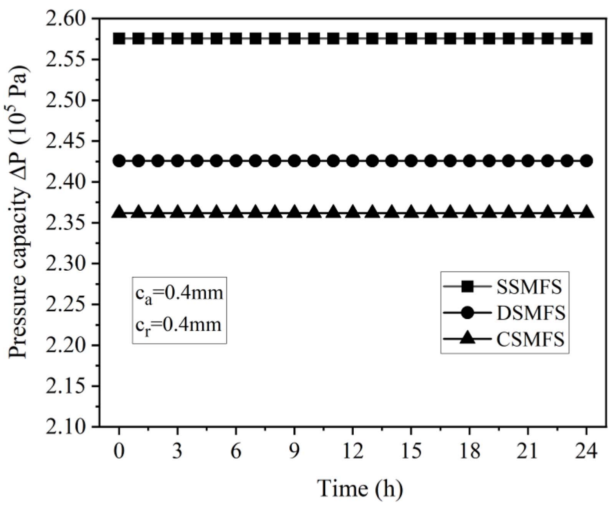

Fig. 15. (Color online) Comparison of experimental pressure capacity of three magnetic fluid sealing structures at different holding time.

6. Conclusion

With the intention of more effectively resolving the issue of leakage in the case of large clearance rotation sealing, a SSMFS with three magnetic sources is designed in this paper. The effects of the height of the permanent magnet, the length of the pole teeth, and the number of pole teeth on the sealing pressure capacity are analyzed by numerical analysis method with the fixed radial clearance and axial clearance of 0.4 mm, and the outcomes are compared with those of DSMFS and CSMFS with three magnetic sources. The numerical analysis results show that the pressure capacity of the SSMFS structure with three magnetic sources is higher than that of the other two seal structures. Then, the effects of magnetic fluid injection volume, different radial clearances and axial clearances, rotation speed and holding time on the pressure capacity of the SSMFS with three magnetic sources are studied by the experiments, and experimental values are compared with those of the other two structures. The experimental findings show that the magnetic fluid injection saturation volume of the SSMFS structure with three magnetic sources is about 7 ml. The benefits of the SSMFS structure become more clear with the modification of the radial sealing clearance and axial sealing clearance, particularly when compared to the CSMFS, which may rise by a maximum of 14.83 %. With the increase of rotation speed and holding time, the pressure capacity of SSMFS structure with three magnetic sources has no obvious change, but it is obviously higher than that of the other two structures. Therefore, the research results demonstrate that the SSMFS structure with three magnetic sources can both better address the issue of large clearance rotation leakage and provide as a useful reference for the use of other rotation sealing conditions.

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