Study on Axial Parameters of Stepped Ferrofluid Seals

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Abstract. As a new type of intelligent material seal technology, ferrofluid seal has been widely used in high speed, heavy load and large eccentricity occasions in recent years because of its long life, low leakage and high pressure resistance. Because of the limitation of the axial height of the axis, most of the existing studies are focused on the radial parameters, but the specific research on the axial parameters has not yet been carried out. In this study, the theoretical pressure capabilities of height of the distribution of axial teeth and axial slot width was calculated according to the theory of stepped ferrofluid seals by finite element method. And by changing the radial gap, the stepped ferrofluid seal is compared with the ordinary seal, and the calculation results are analysed and discussed. The results show that the distribution mode of the axial teeth has a great influence on the theoretical sealing pressure resistance. And the theoretical sealing pressure resistance reaches the maximum when the distribution mode is evenly distributed. The influence of the width of the axial slot on the theoretical sealing pressure resistance can be neglected, so the technological property and the design should be considered as far as possible. By comparing the stepped seal with the ordinary seal, the practicability of the stepped seal is further verified.

1. Introduction

As a new type of intelligent material, ferrofluid seal has been widely used in modern industry [1]-[4]. At present much more studies of ferrofluid seals with parameter of radial. Fan C et al. proposed a new type of structure for large gap ferrofluid seal, and analysed the influence of radial parameters on the sealing pressure resistance [5]. Yanjuan Z et al. studied the influence of radial teeth number and sealing gap on the pressure resistance of small gap ordinary seal, and obtained the functional relationship between clearance and pressure resistance [6]. Du H et al. theoretically analysed and experimentally verified the relationship between starting moment, viscous resistance moment and pressure resistance of MHD seals at high and low temperatures [7]. However there are few literatures about the research of parameter of radical. In this paper, a converging stepped ferrofluid seal structure was used to study the stepped axial parameters.

2. Ferrofluid seal theory

Generally speaking, the method for computing the pressure resistance of ferrofluid seals is as follows [8]:

\[
\Delta P = \mu_0 M_s \sum_{i=1}^{y} (H_{\text{max}}^i - H_{\text{min}}^i) = M_s \sum_{i=1}^{y} (B_{\text{max}}^i - B_{\text{min}}^i) \tag{1}
\]

where \(H_{\text{max}}^i\) are the maximum magnetic field strengths, \(H_{\text{min}}^i\) are the minimum magnetic field...
strengths, $B_{\text{max}}^i$ are the maximum magnetic flux densities and $B_{\text{min}}^i$ are minimum magnetic flux densities.

The total sealing capability as [8]:

$$\Delta P = \sum_{i} \left( P_{ia} + \lambda P_{ir} \right)$$  \quad (2)

In (2), $P_{ia}$ are the pressure capabilities of the ferrofluid seal in the axial gaps formed by the $i$th pole piece and the stepped shaft. $P_{ir}$ are the pressure resistance of the ferrofluid seal in the radial gaps formed by the $i$th pole piece and the stepped shaft. If $P_{ia} < P_{ir}$, then $\lambda = 1$, otherwise $\lambda = 0$, $P_{ia}$ and $P_{ir}$ can be calculated by theory (1).

3. Structure design and finite element analysis

The design is illustrated in Figure 1. Under the working environment of small gap, this design scheme changes the leakage direction of sealed medium on the one hand, and on the other hand, a number of axial and radial gap are formed between the stepped axis and the pole piece, thus improving the overall pressure capability [8]. The dimensions of each part of the sealing structure are shown in Table 1.

![Figure 1. Two-dimensional physical model.](image)

**Table 1.** Parameter of converging stepped ferrofluid seals.

| Item                              | Value        | Item                              | Value |
|-----------------------------------|--------------|-----------------------------------|-------|
| Inner radius of the 1/2 pole piece (mm) | 21/17        | Number of radial teeth under the 1/2 pole piece | 2     |
| Outer radius of the 1/2 pole piece (mm) | 30          | Width of pole teeth (mm) | 0.3   |
| Length of the 1/2 pole piece (mm) | 5.3          | Axial gap width (mm) | 0.1   |
| Inner radius of the permanent magnets (mm) | 26         | Radial gap height (mm) | 0.1   |
| Permanent magnets length (mm) | 5            | Slot depth (mm) | 0.8   |
| Outer radius of the permanent magnets (mm) | 30         | Slot width (mm) | 0.7   |
| Number of axial teeth under the 1/2 pole piece | 3          |                                    |       |

The physical model of the ferrofluid seal is created in the pre-processor of ANSYS finite element analysis software by using the ferrofluid seal structure of small gap polymerized stepped ferrofluid seal as shown in Figure 1. The pole pieces and shaft are made from 2Cr13. The permanent magnetic coercive force and permeability are $H_c = 1.356 \times 10^6$ A/m and 1.05. And the saturation magnetization of ferrofluid is 30.7 kA/m.

4. Results and discussion

In the post-processor of ANSYS software, a path is defined along the leak path of sealed medium, and the calculated flux density is mapped to the path. In order to verify the influence various factors on the
pressure capability of the converging stepped ferrofluid seals, various factors were discussed.

4.1. Effect of the distribution of axial teeth
When the distribution of axial teeth different, the magnetic flux density shown in Figure 2 can be obtained by finite element analysis.

As can be seen from Figure 2, the magnetic flux density of the radial teeth varies greatly with the change of the distribution of the axial teeth. When the distribution of the axial teeth is evenly distribute, the radial magnetic flux density reaches the maximum, and the difference of magnetic flux density also reaches the maximum. According to the distribution map of the magnetic force line, it can be found that when the distribution of the axial teeth is different, the leakage phenomenon of the axial teeth changes obviously, and when the distribution of the axial teeth is evenly distributed, the leakage phenomenon of the axial teeth is the lowest, so that the difference of magnetic flux density of the radial teeth increases.

When the distribution of axial teeth are close to the magnetic source, distributed at both ends, evenly distribution and keep away from magnetic source distribution, Figure 3 shows the theoretical comparison of the pressure capability of the stepped ferrofluid seals. It can be seen that when the axial tooth distribution is close to the magnetic source distribution and keep away from magnetic source distribution, the theoretical pressure capacity value of the stepped ferrofluid seal is alike. But greater than the distributed at both ends. When the distribution of the axial teeth is evenly, the theoretical pressure capability of the ferrofluid seal reaches the maximum. This is due to the difference of magnetic leakage phenomenon and magnetic gathering effect. When the distribution of the axial teeth is evenly, the magnetic leakage phenomenon of the axial teeth is the lowest, and the magnetic gathering effect of the radial teeth is the greatest. According to this result, when designing the axial polar teeth, the distribution of the axial polar teeth should be designed to be evenly due to the limitation of the axial height.

4.2. Effect of the axial slot width
When the axial slot width different, the magnetic flux density shown in Figure 4 can be obtained by finite element analysis.

From Figure 4, it can be concluded that the axial flux density increases with the increase of the axial slot width, while the radial flux density remains unchanged. This is due to the effect of magnetic flux leakage phenomenon, the magnetic flux leakage phenomenon in the axial direction reduce when the axial slot width enlarge, and the magnetic flux density distributed on the axial polar teeth enlarge.
Figure 4. Magnetic field distribution when axial slot width changes

Figure 5. Effect of axial slot width capacity

Figure 5 shows a comparison of theoretical pressure capacity of stepped ferrofluid seals with axial slot width ranging from 0.7 mm to 1.5 mm. It can be seen that the theoretical pressure capability of the stepped ferrofluid seals increases first and then reduces with the axial slot width enlarges, and the fluctuation range of the theoretical pressure capacity value is smaller. This is because when the axial slot width enlarges, the leakage phenomenon reduces with the increase of the width of the axial slot due to the influence of the leakage phenomenon. However, when the width of the slot continues to increase, according to the theory of stepped ferrofluid seal, when the sum of the pressure capacity of the axial teeth is greater than that of the radial teeth, the radial teeth have no effect on the pressure capacity and the theoretical pressure capacity reduces.

4.3. Effect of the axial height of radial gap

When the radial gap different, the magnetic flux density shown in Figure 6 can be obtained by finite element analysis. 

From Figure 6, It can be seen that the flux density in the radial gap reduces with the enlarge of the radial gap height, while the flux density in the axial gap enlarges slowly with the increase of the radial gap height. This is because when the axial gap is unchanged, the increase of the radial gap height will enlarge the reluctance in the radial gap, which will enlarge the reluctance of the whole magnetic circuit, so the total magnetic flux in the magnetic circuit will also reduce, and the magnetic flux in the radial gap will decrease. At the same time, as the axial height remains unchanged and the radial gap height enlarges, the distance between the shaft and the magnetic source enlarges, the magnetic flux leakage in the axial gap reduces, and the magnetic flux in the axial seal gap enlarges slowly.
Figure 6. Magnetic field distribution when radial gap changes

Figure 7. Comparison of theoretical pressure capacity

Figure 7 shows a comparison of theoretical pressure capacity between stepped ferrofluid seals and ordinary ferrofluid seals with radial gap of 0.1-0.4 mm. It can be seen that with the increase of radial gap, the theoretical pressure capacity of stepped ferrofluid seals and ordinary ferrofluid seals reduces, and the trend of decreasing pressure resistance of stepped ferrofluid seals is less than that of ordinary ferrofluid seals. This is because the stepped ferrofluid sealing capacity is related to both its axial and radial gap. And when the radial gap increases, it will only affect the sealing ability in the radial gap, but there is no axial gap in the ordinary ferrofluid seal, so the pressure resistance of the ordinary ferrofluid seal reduces more.

5. Conclusion

In this paper, Converging stepped ferrofluid seals are a new type of ferrofluid seals, the finite element method and numerical study are used to discuss the effect of the axial parameters of the converging stepped ferrofluid seals on the theoretical pressure capacity value. Some conclusions could be briefly listed as follows.

- The distribution mode of the axial teeth has a great influence on the theoretical sealing pressure resistance. And the theoretical sealing pressure resistance reaches the maximum when the distribution mode is evenly distributed.
- The influence of the width of the axial slot on the theoretical sealing pressure resistance can be neglected, so the technological property and the design should be considered as far as possible.
- By comparing the converging stepped seal with the ordinary seal, the practicability of the stepped seal is further verified.
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