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# Numerical Study on Key Parameters of Magnetorheological Fluid Reciprocating Seal with Four Magnetic Sources

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**In order to improve the pressure capability of Magnetorheological fluid (MRF) reciprocating seal with four magnetic sources, MRF reciprocating seal structure was designed based on the formula of MRF reciprocating seal. The magnetic field distributons in the sealing gap of MRF reciprocating seals were analyzed by using finite element analysis of magnetic field. The influences of structure parameters such as sealing gap, ratio of permanent magnet height to length, ratio of pole tooth length to width, ratio of slot width to pole tooth width and ratio of pole piece height to the shaft radius on the sealing capabilities were studied. The results were analyzed and discussed. The results show that the pressure capability of MRF seal decreases significantly with the increase of sealing gap. The pressure capability of the MRF seal increases firstly and then decreases with the increase in the ratio of permanent magnet height to its length. The pressure capability of the MRF seal increases firstly and then decreases with the increase in the ratio of pole tooth length to its width. The pressure capability of the MRF seal increases firstly and then decreases with the increase in the ratio of slot width to pole teeth width. The pressure capability of MRF seal decreases with the increase in the ratio of pole piece height to shaft radius.**

**Keywords :** MRF, reciprocating seal, finite element analysis

## 1. Introduction

MRF is an intelligent fluid, consisting of fine magnetic particles in an oil-based carrier fluid with special properties that significantly change its apparent viscosity under the influence of a magnetic field [1]. MRF materials belong to the so-called smart materials because of their properties diversity. They can respond to changes in the environment and actively change some physical properties based on these changes. This responsiveness defines the practical importance of these materials and their wide application in different fields from daily development to industrial applications [2-7]. MRF sealing technology is one of the application of MRF under the applied magnetic field [8-10].

There are lots of work on the magnetic fluids reciprocating seals. In 1980, M. Goldowsky [11] published experimental results of magnetic fluids for reciprocating seals. S. Mijak [12] pointed out through experiments that during the reciprocating motion of the shaft, the magnetic fluid would be constantly thrown out, which led to the decrease of the magnetic fluid in the sealing gap and the failure of the seal. S. I. Evsing [13] systematically studied the magnetic fluid seal of the reciprocating shaft and pointed out that the failure of the magnetic fluid seal was due to the deformation and removal of magnetic fluids in the sealing gap. Li Decai carried out the test of reciprocating shaft magnetic fluid seal and the formula of pressure capability for magnetic fluid reciprocating seal was deduced according to the theoretical analysis of magnetic fluid amount carried away by reciprocating shaft [14-16]. At present, magnetic fluid reciprocating seals have been studied, However, the MRF reciprocating seals are seldom studied.

In order to improve the pressure capability of four magnetic sources MRF reciprocating shaft seals, the influence of numerical study such as sealing gap, ratio of permanent magnet height to length, ratio of pole teeth length to width, ratio of pole teeth width to slot width and the ratio of pole piece height to shaft radius on their sealing performance was analyzed by finite element method. The magnetic field intensity generated by the sealing structure


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is simulated and the pressure capability of MRF seal is determined, which provides an important reference for designing the four magnetic sources MRF reciprocating sealing structure under high capability and heavy load conditions.

## 2. Formula of Magnetic Fluid Seal Capability for Reciprocating Shaft

The physical model of magnetic fluid reciprocating seals is shown in Fig. 1 and the magnetic fluid film in the sealing gap moves from the beginning to a stable position according to the position shown by the dotted line in Fig. 1.

The formula of pressure capability of magnetic fluid reciprocating seal [16, 17] is

$$\Delta P = P_h - P_0 = [H(X_C) - H(X_B)]\mu_0 M_S + \eta 6V \left\{ \frac{1}{h^2_{(x_C)}} x_C - \frac{1}{[0.66D(6V/\sigma)^{2/3}]^2} x_B \right\} \quad (1)$$

Where $P_h$ is the pressure at high pressure side, $P_0$ is the pressure at atmospheric side, $X_C$ is coordinate of point $C$, $H(X_B)$ and $H(X_C)$ are magnetic field strengths at $X_B$ and $X_C$ respectively, $\mu_0$ is air permeability, $M_S$ is saturated magnetization of magnetic fluid, $\eta$ is dynamic viscosity of magnetic fluid, $V$ is velocity of reciprocating shaft, $h(x_C)$ is film thickness of magnetic fluid corresponding to point $x_C$, $D$ is gap between reciprocating shaft and pole teeth, $\sigma$ is surface tension of magnetic fluids.

Experiments show [18] that when the amount of magnetic fluid is sufficient and the velocity of reciprocating shaft is not fast, the magnetic fluid film can return to the static position of reciprocating shaft after the velocity of reciprocating shaft is zero. Because the static capability state of magnetic fluid seals is studied, the effect of velocity on magnetic fluid seals can be neglected, and the effect of surface tension and viscosity of magnetic fluid seals can also be neglected. So the pressure capability of

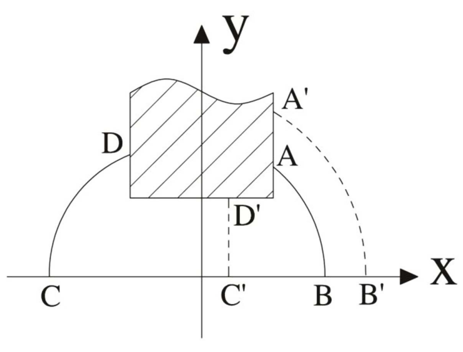



**Fig. 1.** Physical model of magnetic fluid reciprocating seals.

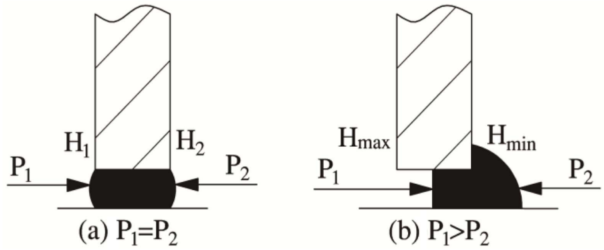



**Fig. 2.** Pressure capability process of one pole tooth.

single pole tooth seals can be simplified as follows:

$$\Delta P = P_h - P_0 = [H_{(x_C)} - H_{(x_D)}]\mu_0 M \quad (2)$$

Therefore, the pressure capability process of the i pole tooth seal in the horizontal direction is shown in Fig. 2. The pressure capability formula of magnetic fluid seal of the i pole tooth is obtained, as shown in formula (3):

$$\Delta P_i = P_1 - P_2 = \int_{H_2}^{H_1} M_S dH \quad (3)$$

When $P_1 = P_2$, the pressure capability of reciprocating shaft seals is zero. When $P_1 > P_2$, under the new balance of the pressure capability, the magnetic fluid in the sealing gap will be pulled to the appropriate position along the direction of capability gradient difference. Considering that the saturation magnetization of the magnetic fluid is much less than external magnetic field, formula (3) can be simplified to formula (4):

$$\Delta P_i = P_1 - P_2 = \int_{H_{\min}}^{H_{\max}} M_S dH \quad (4)$$

According to the superposition principle [19], the total pressure capability of the reciprocating MRF seal with four magnetic sources is deduced as shown in equation (5):

$$\Delta P = \sum_{i=1}^{N} \sum_{j=1}^{M} \Delta P_{ij} \quad (5)$$

## 3. Structure Design of MRF Reciprocating Seal with Four Magnetic Sources

In order to study the influences of the sealing structure parameters on the pressure capabilities of MRF reciprocating seal, this paper designs the structure of MRF reciprocating seal with four magnetic sources as shown in Fig. 3, and its structural items are shown in Table 1. The permanent magnet materials are selected as NdFeB, its remanence Br = 1.13T, coercive force $H_C = 1.356 \times 10^6$ A/m. Pole pieces and shaft materials are the same 2Cr13. Magnetic fluid is selected as MRF and its saturation

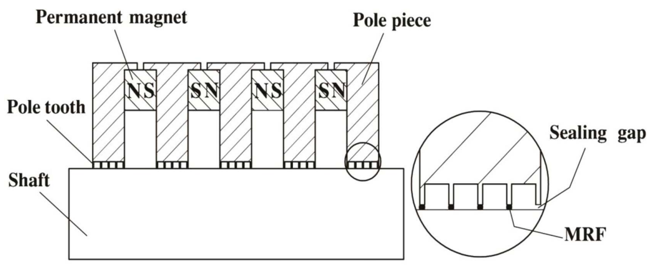



**Fig. 3.** Schematic diagram of two-dimensional physical model of MRF seal.

**Table 1.** Table of parameters to calculate sealing structure.

| Item | Value |
|---|---|
| Inner radius of the pole piece (mm) | 25.1 |
| Outer radius of the pole piece (mm) | 40.1/45.1/50.1/55.1 |
| Length of the pole piece (mm) | 5 |
| Permanent magnets length (mm) | 5 |
| Inner radius of each permanent magnets | 31.1/32.1/33.1/34.1/35.1 |
| Outer radius of each permanent magnets | 39.1 |
| Number of teeth under the pole piece | 5 |
| Width of pole teeth (mm) | 0.2 |
| Sealing gap height (mm) | 0.1/0.2/0.3/0.4 |
| Slot depth (mm) | 0.4/0.6/0.8/1.0 |
| Slot width (mm) | 1.0/1.2/1.4/1.6 |

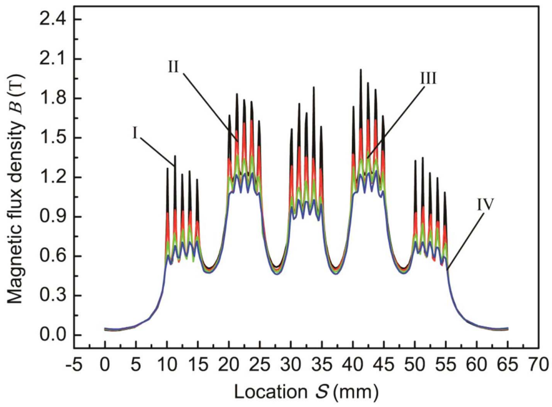
magnetization is 307 KA/m. The method of intelligent mesh is selected and the mesh precision is applied. The boundary condition is that magnetic field lines is parallel to physical model boundary. The magnetic flux density in the sealing gap can be obtained by the solver.

## 4. Results and Analysis

### 4.1. Effect of sealing gap on sealing performance

Sealing gap is one of the key parameters affecting the MRF reciprocating seal. So it is of great significance to study the effect of sealing gap on the pressure capability of MRF seal to develop the MRF seal device with high sealing performance. Magnetic flux density distribution under different sealing gaps is shown in Fig. 4.

It can be seen from Fig. 4, as the sealing gap increases from 0.1 mm to 0.4 mm, the variation of magnetic flux density under the pole teeth decreases uniformly. This is because as the sealing gap increases, the reluctance in the sealing gap also increases. From the comparison in Fig. 4, it can be found that the magnetic flux density in different sealing gap under the pole teeth of the middle three pole pieces is significantly greater than the magnetic flux density under the pole teeth of the pole pieces on both sides. The reason is that the magnetic flux in the middle




I, II, III, IV denote magnetic distribution with 0.1mm, 0.2mm, 0.3mm, 0.4mm sealing gap height respectively.

**Fig. 4.** (Color online) Magnetic flux densities under different gaps conditions.

three pole pieces is the sum of the magnetic flux generated by the two permanent magnets, and the magnetic flux in the pole pieces on both sides is generated by a single permanent magnet. Therefore, in the case of equal cross-sectional areas, the magnetic flux density of the middle three pole pieces should be much larger than the magnetic flux density of the pole teeth on both sides.

According to the magnetic fluid reciprocating seal pressure capability formula and the magnetic flux density under different gaps in Fig. 4, the pressure capability of the MRF reciprocating seal with four magnetic sources can be calculated, as shown in Fig. 5.

It can be seen from the Fig. 5, MRF reciprocating sealing pressure capability with the four magnetic sources decreases significantly with the increase of the sealing gap. The reason is that the larger the sealing gap is, the larger the magnetic resistance of the sealing gap is in the case where the sealing structure parameters are not chang-

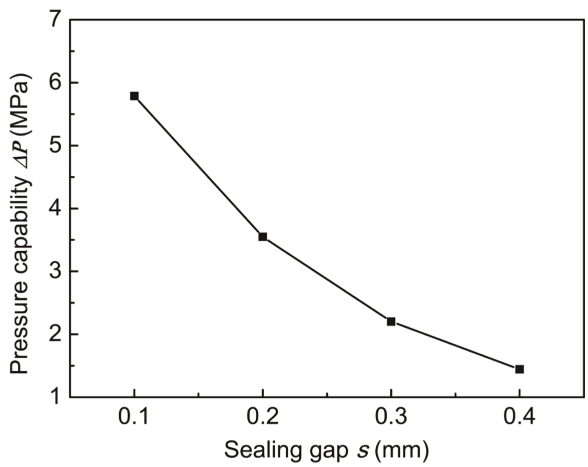



**Fig. 5.** Sealing capability as a function of sealing gap height.

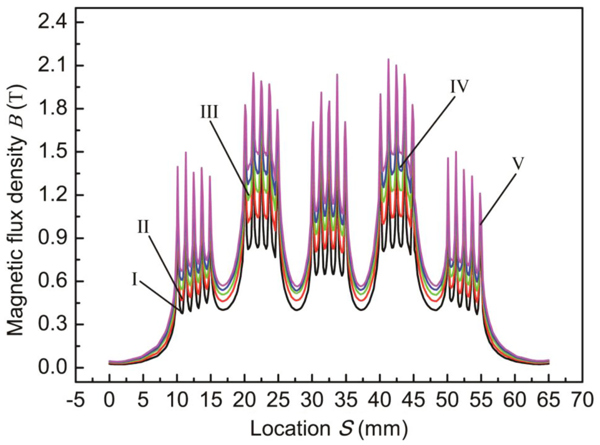
ed. According to the magnetic circuit law, the magnetic flux density in the sealing gap is reduced and the magnetic flux density difference is also correspondingly reduced. Therefore, the pressure capability of the four magnetic sources MRF reciprocating seal is reduced.

### 4.2. Effect of ratio of permanent magnet height to its length

Ratio of permanent magnet height to its length is a key parameter affecting the MRF reciprocating seal. Therefore, studying the influence of the ratio of permanent magnet height to its length is of great significance for the development of MRF sealing devices with high sealing performance. The magnetic flux density distributions in the MRF seal with 0.1 mm sealing gap height under the different ratio of permanent magnet height to its length are shown in Fig. 6.

It is not difficult to find from the Fig. 6 that when the ratio of permanent magnet height to its length increases from 0.8 to 1.6 and the axial length is fixed at 5 mm, the magnetic flux density in the sealing gap under a single pole tooth increases with the increase of the height of permanent magnet. The reason is that the bigger ratio of permanent magnet height to its length, the less the amount of magnetic flux leakage. It is easy to find from the figure that when the ratio of permanent magnet height to its length is 1.4, the gradient of magnetic flux density under a single pole tooth changes significantly. This is because when the ratio of permanent magnet height to its length is 1.4, the permanent magnet approximately works at the best magnetic energy product position.

According to the magnetic fluid reciprocating seal pressure capability formula and the magnetic flux density in the sealing gap of the MRF sealing structure with different ratio of permanent magnet height to its length as shown in Fig. 6, the changing relationship between the pressure capacity of the MRF reciprocating sealing with four magnets and the ratio of permanent magnet height to its length is shown in Fig. 7.




I is for 0.8; II is for 1.0; III is for 1.2; IV is for 1.4;V is for 1.6;

**Fig. 6.** (Color online) Magnetic flux densities under the different ratio of permanent magnet height to its length.

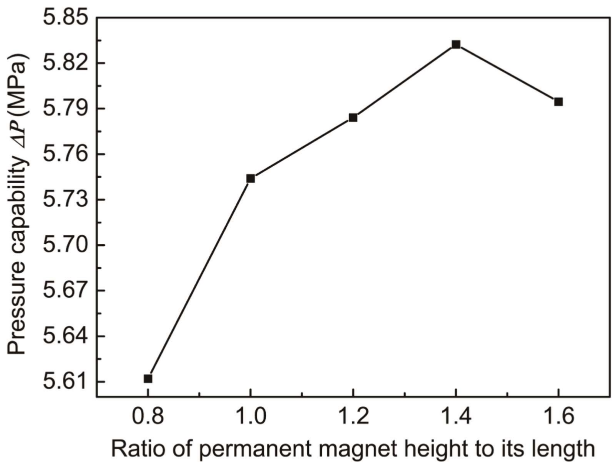


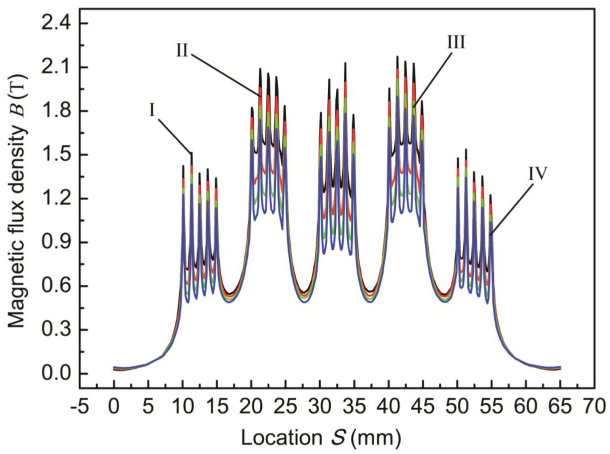

**Fig. 7.** Effect of the ratio of the permanent magnet height to its length on sealing pressure capacity.

It is not difficult to find from the Fig. 7 that the pressure capability of MRF seal with the four magnetic sources increases firstly and then decreases with the increase of the ratio of the permanent magnet height to its length. The reason is that the optimal working position of permanent magnet is approximately at ratio of the permanent magnet height to its length of 1.4. So, when the ratio of the permanent magnet height to its length increases and approaches 1.4, the magnetic flux of magnetic circuit increases, and the sealing pressure capability increases. When the ratio of the permanent magnet height to its length exceeds 1.4, the total magnetic energy product of magnetic circuit decreases, which leads to the decrease of sealing pressure capability with the increase of the ratio of the permanent magnet height to its length.

### 4.3. Effect of the ratio of pole teeth length to its width

Ratio of pole teeth length to its width is a key parameter affecting MRF reciprocating seals. Therefore, it is important to study the influence of ratio of pole teeth length to its width on the pressure capability of MRF seals for the development of MRF seals with high sealing performance. The distribution of magnetic field in MR sealing gap with different ratio of pole teeth length to its width is shown in Fig. 8.

As shown in Fig. 8, it is not hard to find, when the sealing gap is 0.1 mm and the tooth width is a fixed 0.2 mm value, the magnetic flux density difference under the pole teeth of the middle three pole piece is twice as big as




I is for 2; II is for 3; III is for 4; IV is for 5;

**Fig. 8.** (Color online) Magnetic flux densities under the different ratio of pole teeth length to its width.

the magnetic flux density difference under the pole teeth of the pole pieces on both sides. The reason is that the magnetic flux in the middle three pole pieces are produced by two permanent magnets. In the case of equal cross-sectional area, any magnetic flux density differences under the pole teeth of the middle three pole pieces should be twice the pole pieces on both sides.

According to the magnetic fluid reciprocating seal pressure capability formula and the magnetic flux density in the sealing gap of the MRF sealing structure with different ratio of pole teeth length to its width in Fig. 8, the pressure capability of the MRF reciprocating seal with the four magnetic sources can be calculated, as shown in Fig. 9.

Figure 9 shows that the pressure capacity of MRF reciprocating seal with the four magnetic sources increased firstly and then decreased with the increase of ratio of pole teeth length to its width. When the ratio of pole teeth length to its width is 3, MRF seal with the four magnetic sources pressure capacity to achieve maximum value. This is because when the ratio of pole teeth length to its width at about 3, the total magnetic energy product in magnetic circuit reaches the maximum. When the ratio of pole teeth length to its width exceeds 3, this will lead to an increase in magnetic resistance and a decrease in the magnetic flux which reduces the sealing pressure capability since the radial cross-sectional area of the pole teeth is unchanged.

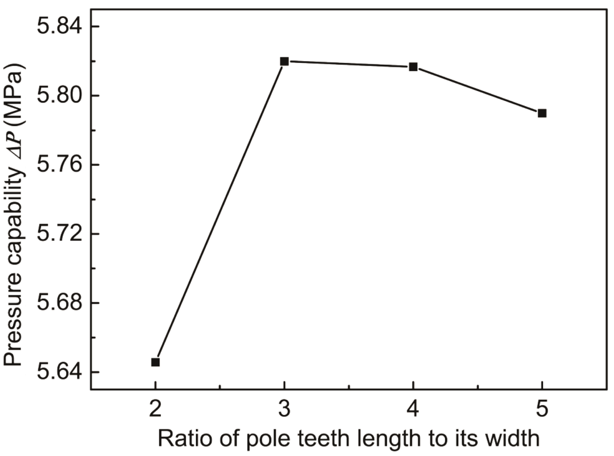
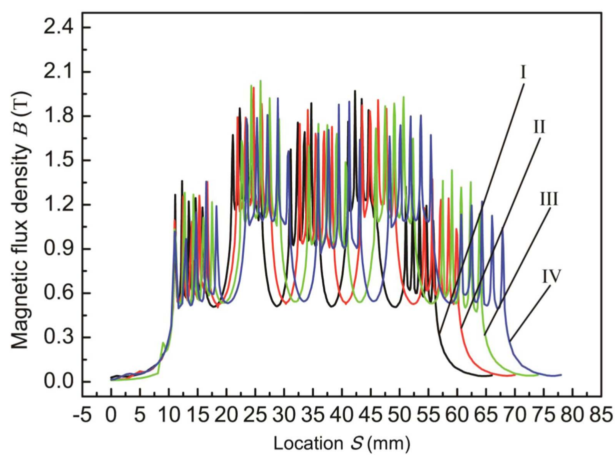



**Fig. 9.** Effect of the ratio of the pole teeth length to its width on sealing capacity.

### 4.4. Effect of the ratio of slot width to pole tooth width

Ratio of slot width to pole tooth width is a key parameter affecting MRF reciprocating seals. Therefore, it is important to study the influence of ratio of slot width to pole tooth width on the pressure capability of MRF seals for the development of MRF seals with high sealing performance. Magnetic flux densities in MRF sealing gap with different ratio of slot width to pole tooth width are shown in Fig. 10.

It is not difficult to find from Fig. 10 that when the width of tooth is fixed 0.2 mm and the ratio of slot width to pole tooth width increases from 5 to 8, the magnetic flux density in the sealing gap under a single pole tooth also increases. This is because the greater the ratio of slot width to pole tooth width, the less the magnetic flux leakage. It is not difficult to find from the Fig. 10 that when the ratio of tooth slot width to pole tooth width is 7, the gradient of magnetic flux density difference under a single pole tooth changes significantly. At this time, the magnetic field strength in the sealing gap reaches the




I is for 5; II is for 6; III is for 7; IV is for 8;

**Fig. 10.** (Color online) Magnetic flux densities under the different ratio of slot width to pole tooth width.

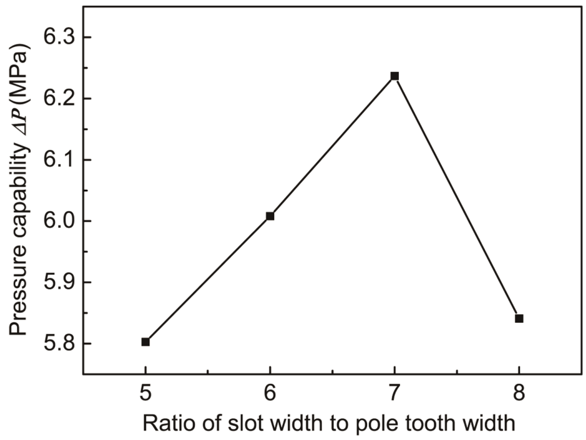



**Fig. 11.** Effect of the ratio of slot width to pole tooth width on sealing capacity.

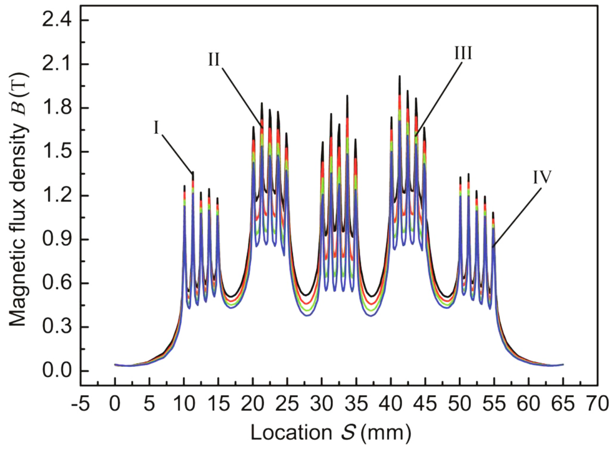
maximum value. This is because the permanent magnet works at the maximum magnetic energy product position approximately.

According to the magnetic fluid sealing theory and the magnetic flux density of different ratio of slot width to pole tooth width in Fig. 10, the pressure capability of the MRF reciprocating seal with the four magnetic sources can be calculated, as shown in Fig. 11.

As it can be seen from Fig. 11, the pressure capability of MRF seal with the four magnetic sources increases firstly and then decreases with the increase of the ratio of slot width to pole tooth width. When the width of tooth is fixed at 0.2 mm and the ratio of slot width to pole tooth width is 7, the sealing pressure capability reaches the maximum value. This is because when the ratio of tooth slot width to pole tooth width increases from 5 to 7, the total magnetic energy product of magnetic circuit increases continuously. When the ratio of slot width to pole tooth width reaches about 7, the total magnetic energy product position of magnetic circuit reaches the maximum value, so the sealing capability capacity is improved. When the ratio of tooth slot width to pole tooth width continues to increase, the magnetic field gradient formed in the slot becomes smaller and smaller, resulting in decreased sealing pressure capability.

### 4.5. Effect of the ratio of pole piece height to the shaft radius

Ratio of pole piece height to the shaft radius is a key parameter affecting MRF reciprocating seals. Therefore, it is important to study the influence of ratio of pole piece height to the shaft radius on the pressure capability of MRF seals for the development of MRF seals with high sealing performance. When the sealing gap is 0.1 mm, the height of the pole piece is changed without changing the




I is for 0.6; II is for 0.8; III is for 1.0; IV is for 1.2;

**Fig. 12.** (Color online) Magnetic flux densities under the different ratio of pole piece height to the shaft radius.

radius of the reciprocating shaft, and magnetic flux densities under the different ratio of pole piece height to the shaft radius is obtained as shown in Fig. 12.

It is obvious from Fig. 12 that the magnetic flux density decreases with the increase of the ratio of pole piece height to the shaft radius. This is because as the radius of the reciprocating shaft remains unchanged, the increase in the height of the pole pieces leads to the increase of magnetic resistance of pole pieces which causes the decrease in magnetic field strength. It is also easy to see from Fig. 12 that the difference in the magnetic flux gradient of pole teeth in the middle three pole pieces is twice as big as the magnetic flux gradient difference under the pole teeth of the pole pieces on both sides. This is because the magnetic energies of the middle three pole pieces are provided by two magnetic sources, while the magnetic energies of pole pieces on both sides are provided by a

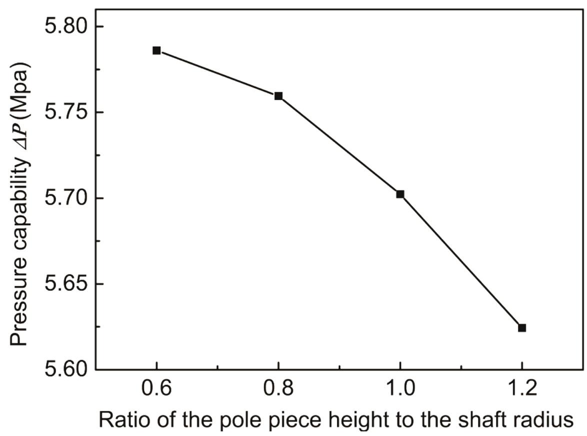



**Fig. 13.** Effect of the ratio of pole piece height to the shaft radius on MRF sealing pressure capability.

single magnetic source.

Based on MRF reciprocating seal capability formula and the magnetic flux density distribution, pressure capability of the MRF reciprocating seal with the four magnetic sources can be calculated as shown in Fig. 13.

It can be seen from Fig. 13, MRF reciprocating sealing pressure capability with the four magnetic sources decreases significantly with the increase of the ratio of the pole piece to the shaft radius. This is because when the shaft radius is fixed, the increase in pole piece height lead to the increase in magnetic resistance of the pole pieces. According to the law of magnetic circuit, magnetic flux density through the pole piece decreases, and the magnetic field strength is reduced accordingly, which can lead to MRF reciprocating seal with the four magnetic sources pressure capability decline.

## 5. Conclusion

This paper designs MRF sealing structure with four magnetic sources and the magnetic flux densities in the sealing gap of the MRF seal are calculated numerically by finite element method. The influences of the important structural parameters on MRF seal have been obtained. The results show that when the sealing gap increases from 0.1 mm to 0.4 mm, the pressure capability of MRF seal decreased by about 4.5 MPa. The pressure capability of the MRF seal increases firstly and then decreases with the increase of the ratio of permanent magnet height to its length. When the ratio of permanent magnet height to its length is 1.4, the permanent magnet approximately works at the best magnetic energy product position. With the increase of ratio of pole tooth length to its width, the pressure capability of MRF seal with four magnetic sources increases firstly and then decreases. When the ratio of pole tooth length to width is 3, the pressure capability of MRF seal reaches the maximum value. The MRF sealing pressure capability increases firstly and then decreases with the increase of ratio of slot width to pole tooth width, and when the ratio of slot width to pole tooth width is about 7, the pressure capability reaches the maximum. With the increase of the ratio of pole piece height to the shaft radius, the pressure capability of MRF reciprocating seal decreases gradually.

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