ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 22(2), 299-305 (2017) https://doi.org/10.4283/JMAG.2017.22.2.299

Non-uniform Distribution of Magnetic Fluid in Multistage Magnetic Fluid Seals

Wang Zhongzhong, Li Decai*, and Zhou Jing

School of Mechanical Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China

(Received 28 March 2017, Received in final form 27 April 2017, Accepted 28 April 2017)

Magnetic fluid, a new type of magnetic material, is a colloidal liquid constituted of nano-scale ferromagnetic particles suspended in carrier fluid. Magnetic fluid sealing is one of the most successful applications of magnetic fluid. As a new type of seal offering the advantages of no leakage, long life and high reliability, the magnetic fluid seal has been widely utilized under vacuum- and low-pressure-differential conditions. In practical applications, for improved pressure capacity, a multistage sealing structure is always used. However, in engineering applications, a uniform distribution of magnetic fluid under each tooth often cannot be achieved, which problem weakens the overall pressure capacity of the seals. In order to improve the pressure capacity of magnetic fluid seals and broaden their applications, the present study theoretically and experimentally analyzed the degree of non-uniform distribution of multistage magnetic fluid seals. A mathematical model reflecting the relationship between the pressure capacity and the distribution of magnetic fluid under a single tooth was constructed, and a formula showing the relationship between the volume of magnetic fluid and its contact width with the shaft was derived. Furthermore, the relationship of magnetic fluid volume to capacity was analyzed. Thereby, the causes of non-uniform distribution could be verified: injection of magnetic fluid; the assembly of magnetic fluid seals; the change of magnetic fluid silhouette under pressure loading; the magnetic fluid sealing mechanism of pressure transmission, and seal failure. In consideration of these causes, methods to improve the pressure capacity of magnetic fluid seals was devised (and is herein proposed).

Keywords : magnetic fluid, magnetic fluid seal, multistage magnetic fluid seal, distribution of magnetic fluid seals

1. Introduction

Magnetic fluid is a new type of magnetic material, specifically a colloidal liquid constituted of nano-scale ferromagnetic particles suspended in carrier fluid. One of the most successful applications of magnetic fluid is magnetic fluid sealing. As a new modality offering the advantages of no leakage, long life and high reliability, the magnetic fluid seal has been widely utilized under vacuum- and low-pressure-differential conditions [1-3]. In order to improve the pressure capacity of magnetic fluid seals in practical applications, a multistage sealing structure is always used. The total sealing capacity of multistage magnetic fluid seals can be approximately expressed as [2-5]

$$\Delta p_i = \int_{H_{i\min}}^{H_{i\max}} \mu_0 M dH \approx M_s (B_{i\max} - B_{i\min}) \tag{1}$$

$$\Delta p = \sum_{i=1}^{N} \Delta p_i \tag{2}$$

where $H_{i\min}$ and $H_{i\max}$ are the minimum and maximum magnetic field strengths under the i pole tooth, respectively, μ_0 is the permeability of the vacuum, M is the magnetization of magnetic fluid, M_s is the saturation magnetization of magnetic fluid, N is the number of pole teeth, $B_{i\max}$ is the maximum magnetic flux density under the i pole teeth, and $B_{i\min}$ is the minimum magnetic flux density under the i pole teeth. The total sealing capacity of the multistage magnetic fluid seal is equal to the sum of the respective capacities of all of the single stages. However, in engineering applications, the total pressure capacity of multistage magnetic fluid sealing is far lower than the sum of the respective pressure capacities of all of the pole teeth stages. This phenomenon is more prominent when the number of stages is large. Dr. Yang [6] of Beijing Jiaotong University found that when the number of stages reached a certain value, increasing the magnetic source and the number of stages seldom enhanced the total pressure capacity of magnetic fluid sealing. This is entirely due to the non-uniformity of the distribution of

*Corresponding author: Tel: +86-010-51684006
Fax: +86-010-51684006, e-mail: dcli@bjtu.edu.cn

magnetic fluid in multistage magnetic fluid seals. In some engineering practice instances, only a few pole teeth, after a certain multistage magnetic fluid sealing element is unpacked, are found to have magnetic fluid. Such non-uniform distribution of magnetic fluid in multistage magnetic fluid seals seriously weakens the total pressure capacity of magnetic fluid seals.

2. Mathematical Model

In order to obtain the operative mechanism of non-uniform multistage magnetic fluid distribution under different stages of pole teeth on the pressure capacity of magnetic fluid sealing, the relationship between the pressure capacity of a single pole tooth and the volume of magnetic fluid under that tooth was studied by theoretical analysis.

The most widely applied, rectangular pole tooth was chosen as the example to be analyzed. The model is shown in Fig. 1. When the high-pressure surface of magnetic fluid is pushed to the maximum magnetic field position (#A) at the single tooth interval, as is shown in Fig. 1, the lower the magnetic field of the low-pressure surface location is, the greater the maximum sealing capacity is. Also, the location of the low-pressure surface is a function of the volume of magnetic fluid under the pole tooth. The maximum sealing capacity is correlated with the distribution volume of magnetic fluid. The boundary membrane of magnetic fluid is complex. Prof. Chi [7] concluded that in magnetic fluid sealing with teeth of sawtooth structure, the pressure surface approximates to an arc in a small range. Under some conditions moreover, the surface of magnetic fluid is also unstable. For the purposes of the present discussion, the following hypotheses are made:

(1) The shape of the low-pressure surface of the magnetic fluid is a straight line that runs perpendicular to the axis of the rotating shaft (shown as α_1 in Fig. 1) when the point of intersection of the low-pressure surface with the shaft is within the scope of AO, and is an arc centered on O (shown as α_1 in Fig. 1) while the point of intersection is within the scope of OC.

(2) The parameters of the rectangular pole tooth satisfy $L_s \le 2(L_h + L_g)$ (J Walowit [8] and O Pinkus [9] obtained the optimal parameters of sealing with rectangular pole teeth by studying the magnetic field distribution in a sealing gap by a complex function and performing a series of experiments. The optimal parameters were as follows: $L_t/L_g = 2$, $L_s/L_g = 3$, $L_g = 0.1\text{-}0.3$ mm, $L_s \approx L_h$, where L_g is the seal gap, L_t is the tooth width, L_h is the tooth height, and L_s is the clearance between two teeth).

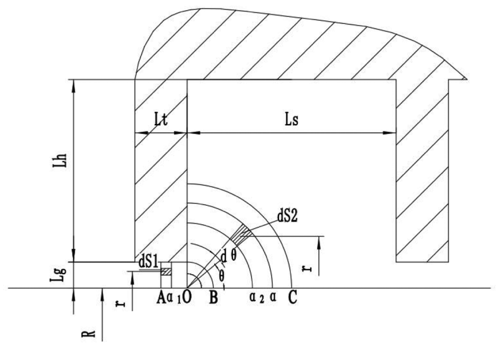

Fig. 1. Pole tooth model.

When the point of intersection of the low-pressure surface with the shaft is within the scope of AO (as Fig. 1 shows), the micro-element area dS_1 can be expressed as

$$dS_1 = sdr \tag{3}$$

where s is the width of A α, which is the contact width between the magnetic fluid and the shaft, the average radial distance of dS_1 is r, and the micro-element area dS_1 rotates around the central line of the shaft and forms the micro-element volume dV_1,

$$dV_1 = 2\pi r dS_1 = 2\pi rsdr\,. \tag{4}$$

Integrating (4) yields

$$V_1 = \int dV_1 = \int_R^{R+L_g} 2\pi rsdr\,. \tag{5}$$

Therefore,

$$V_1 = \pi s(L_g^2 + 2RL_g)\,. \tag{6}$$

When the point of intersection of the low-pressure surface with the shaft is within the scope of OC as Fig. 1 shows, the area of element dS_2 can be written

$$dS_2 = \left(s - \frac{L_t}{2}\right) d\theta ds\,, \tag{7}$$

where the average radial distance of dS_2 is r,

$$r = R + \left(s - \frac{L_t}{2}\right)\sin\theta, \tag{8}$$

and the micro-element area dS_2 rotates around the central line of the shaft and forms the micro-element volume dV_2,

$$dV_2 = 2\pi r dS_2 = 2\pi\left[R + \left(s - \frac{L_t}{2}\right)\sin\theta\right]\left(s - \frac{L_t}{2}\right) d\theta ds\,. \tag{9}$$

Integrating (9) affords

$$V_2 = \int dV_2 = \int_{\frac{L_t}{2}}^{s} \int_0^{\pi/2} 2\pi\left[R + \left(s - \frac{L_t}{2}\right)\sin\theta\right]\left(s - \frac{L_t}{2}\right) d\theta ds\,; \tag{10}$$

therefore,

$$V_2 = \frac{\pi^2}{2}R\left(s - \frac{L_t}{2}\right)^2 + \frac{2}{3}\pi\left(s - \frac{L_t}{2}\right)^3. \qquad (11)$$

Additionally, the volume of the AO region needs to be added,

$$V = \frac{\pi^2}{2}R\left(s - \frac{L_t}{2}\right)^2 + \frac{2}{3}\pi\left(s - \frac{L_t}{2}\right)^3 + \pi\frac{L_t}{2}(L_g^2 + 2RL_g), \qquad (12)$$

Now, the relationship between the volume of magnetic fluid and the contact width of the magnetic fluid with the shaft can be expressed as

$$V = \begin{cases} \pi s L_g^2 + 2RL_g & \left(s \le \frac{L_t}{2}\right) \\ \frac{\pi^2}{2}Rs - \frac{L_t^2}{2} + \frac{2}{3}\pi s - \frac{L_t^3}{2} + \pi\frac{L_t}{2}L_g^2 + 2RL_g . & \\ & \left(\frac{L_t}{2} < s \le \frac{L_t}{2} + \frac{L_s}{2}\right) \end{cases} \qquad (13)$$

When $s > \frac{L_t}{2} + \frac{L_s}{2}$, the excessive magnetic fluid will be drawn to the next stage of the pole tooth.

The above formula shows the function between the volume V of magnetic fluid under a single pole tooth and the contact width s of the magnetic fluid with the shaft, namely $V = V(s)$. Moreover, the correlation of V with s is positive within the range of $0 < s \le \frac{L_t}{2} + \frac{L_s}{2}$; that is to say, s increases with the increase of V. The magnetic flux density B_L of the low-pressure surface also is a function of s, namely $B_L = B_L(s)$; moreover, the correlation of B_L with s also is positive within the range of $0 < s \le \frac{L_t}{2} + \frac{L_s}{2}$, which is to say that B_L decreases with the increase of s. According to Formula (1), it can be seen that with the weakening of low-pressure surface B_L, the pressure capacity is reinforced. Therefore, the higher the volume of the magnetic fluid under a single pole tooth is, the stronger the sealing capacity of a single-stage pole tooth is, until it reaches the maximum pressure capacity $\Delta p_{i\,\max}$.

3. Theoretical Analysis

The causes of non-uniform distribution can be considered to be the following: magnetic fluid injection and magnetic fluid seal element assembly; magnetic fluid silhouette change under pressure loading; the magnetic fluid sealing mechanism of pressure transmission, and seal failure.

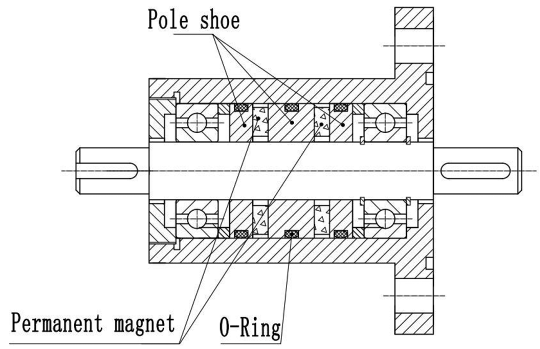

Fig. 2. Structure of magnetic fluid seal.

3.1. Injection of magnetic fluid and assembly of magnetic fluid seal

The injection method is determined by the structure of the magnetic fluid seal and the size of the pole tooth. For the common multistage sealing structure shown in Fig. 2, the assembly process is as follows: assemble the pole shoe and permanent magnet together; inject the magnetic fluid onto the inner surface of the permanent magnet; assemble the pole shoe and magnet to the shaft. Then, the magnetic fluid is assigned to each pole tooth automatically. However, that with automatic distribution by magnetic field, it is difficult to ensure a uniform distribution of magnetic fluid under each pole tooth.

After injection of the magnetic fluid, the shaft is always mounted from one end of the pole shoe (the upstream end) during the shaft assembly process, and the shaft will draw the magnetic fluid from the upstream end to the downstream end.

A small amount of magnetic fluid will be drawn from upstream side to the downstream side during the process of assembling the pole shoe and magnet to the shaft. Magnetic fluid will be squeezed out from the downstream side when its quantity is superabundant. There is a strong attractive force between permanent magnet and the shaft, which makes the assembly process difficult to control.

3.2. Change of silhouette of magnetic fluid under pressure loading

The principle of the magnetic fluid seal is that magnetic fluid will be acted upon by magnetic force in a non-uniform magnetic field under a seal gap that carries the pressure difference. Therefore, the axial movement and the change of silhouette of magnetic fluid appears after sealing the pressure loading. The entire process of the change of the magnetic fluid silhouette in the sealing gap under pressure loading is shown in Fig. 3.

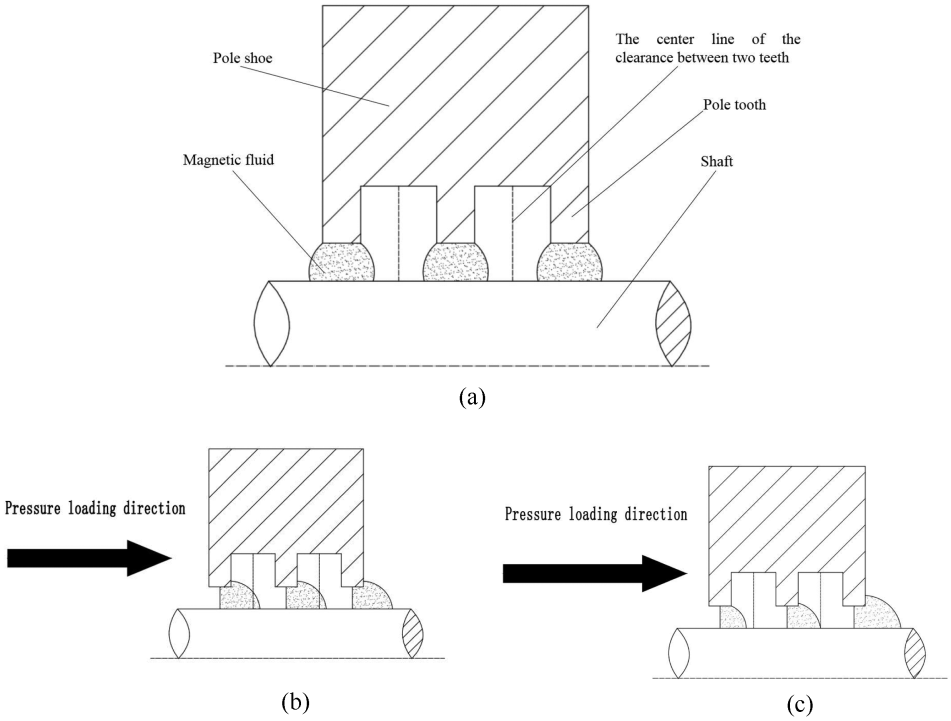

Fig. 3. Pressure loading of magnetic fluid seals. (a) Distribution of magnetic fluid before pressure loading, (b) Ideal distribution of magnetic fluid under pressure loading, (c) Practical distribution of magnetic fluid under pressure loading.

Assume that the magnetic field distribution under every pole tooth is totally identical and that the magnetic field distribution under every pole tooth is symmetric about the center line of each pole tooth [10]. Therefore, prior to pressure loading, the initial silhouette of the magnetic fluid in the sealing gap is as shown in Fig. 3(a). When pressure is loaded to the magnetic fluid seal, the magnetic fluid will show axial movement in the sealing gap, and the magnetic fluid silhouette and distribution will be as shown in Fig. 3(b). A portion of the magnetic fluid will be beyond the center line of the pole tooth. At that time, the excess magnetic fluid will jump to the next stage under the magnetic field force there. As a result, the distribution of magnetic fluid under each stage will be non-uniform, as shown in Fig. 3(c).

3.3. Magnetic fluid sealing mechanism of pressure transmission and seal failure

The mechanism of multistage magnetic fluid sealing is such that [9-12] when the applied Δp exceeds the capacity, say, of the first stage, fluid leakage occurs, causing the second stage to be pressurized. When the upstream pressure is further increased, the fluid in the second stage (as well as in the first stage) will leak and begin pressurizing the next stage, and so on until all of the stages are loaded. Provided that the seal as a whole is not overloaded, the inter-stage leaks will ultimately cease, and the seal will carry the total imposed Δp.

Thus it can be seen that when pressure is transferred, the sealing medium will repeatedly break through the magnetic fluid ring under each pole tooth. The magnetic fluid will be taken to the next stage when the sealing medium passes into the next clearance between two pole teeth, which causes non-uniform distribution of magnetic fluid. This explains why the total sealing capacity is reduced after sealing self-repairing.

4. Experimental Study

4.1. Experimental Setup

The model seal constructed for the present study is shown in Fig. 4. It consists of a rotary shaft, two pole pieces, a permanent magnet, and a shell. This model seal differs from the traditional ones in that the position of the pole tooth is on the outer cylinder of the pole piece, which is to say between the pole piece and the shell, so that the pressure of the interspace between stages can be measured more easily. The stepped holes in the shell connect to the interspace between stages. Through these holes, the interspaces between stages are connected with pressure gauges. The material of the pole pieces and the shell are 2Cr13 stainless steel, while that of the shaft is

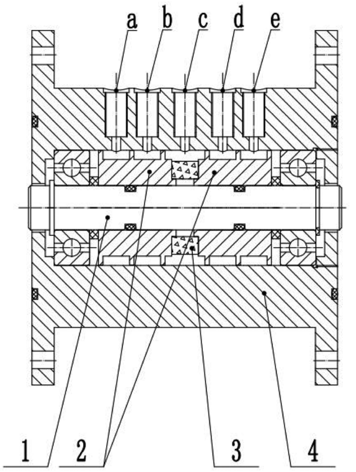

Fig. 4. Structure of model seal. a, b, c, d, e. Signs of hole in shell. 1. Shaft, 2. Pole piece, 3. Permanent magnet, 4. Shell

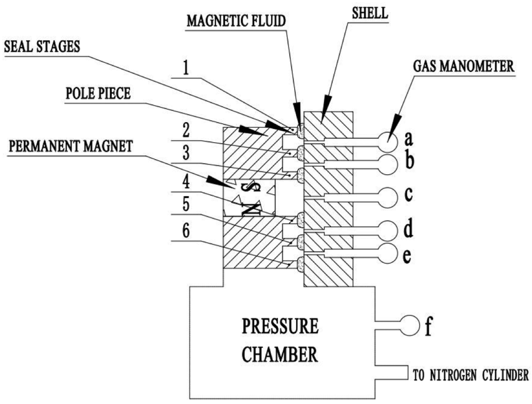

Fig. 5. Schematic of experimental device.

304 stainless steel. The magnetic fluid used in the current experiment was engine-oil-based magnetic fluid.

The heart of the device with its six stages magnetic fluid sealing is shown in the Fig. 5 schematic. Stage No.1 is exposed to the atmosphere, while stage No.6 is connected to the pressure chamber. The pressures of the interspaces between them were measured by gas manometers (#a to #e), respectively. Nitrogen was used as the pressure loading sealing medium. A photograph of the experimental stand is shown in Fig. 6.

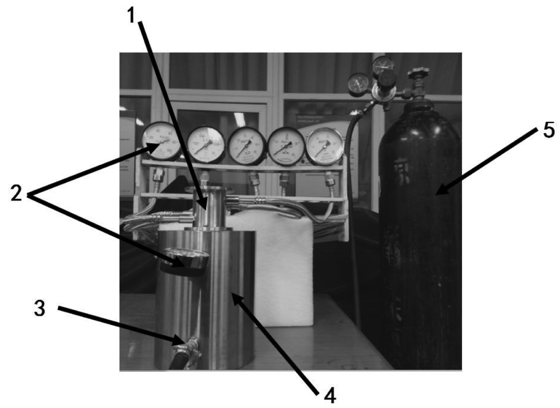

Fig. 6. Photograph of experimental stand. 1. Sealing device, 2. Gas-pressure gauge, 3. Intake valve, Pressure chamber, 5. Nitrogen cylinder

4.2. Magnetic fluid

The magnetic fluid used in this experiment was formulated at Beijing Jiaotong University with an engine-oil carrier liquid to the following specifications:

Saturation Magnetization: 350-400 gauss

Density: 1200-1300 kg/m^3.

4.3. Process of experiment

Magnetic fluid was injected into the stages (#1 to #6) by means of a hypodermic needle. The magnetic fluid mass injected into each stage was about 0.15 g. After installation of the test device, nitrogen was injected into the sealing chamber slowly by valve control. The shaft was static during the entire process of the experiment. A

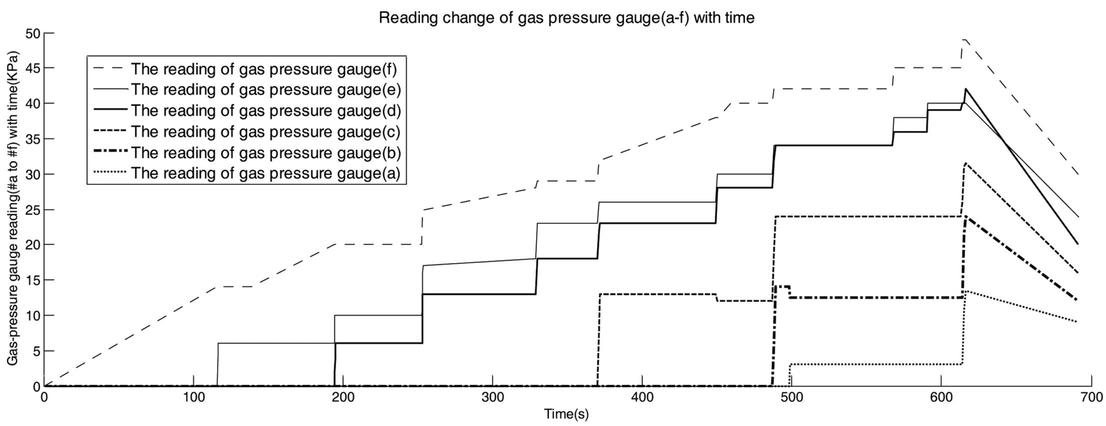

Fig. 7. Curve showing change of gas-pressure gauge (a-f) reading with time.

Table 1. Sealing capacity of each stage before seal failure.

Stage	1	2	3	4	5	6
Sealing capacity (kPa)	14	10	18	19	12.5	13.5

video camera was used to record the changes of the gas-pressure gauge (#a and #b) readings.

5. Results and Discussion

A series of experiments was conducted following the above process, and the results were similar. Fig. 7 shows the change of gas-pressure gauge (#a to #f) reading with time. It should be noted that the reading of pressure gauge (#e) began to increase once pressure gauge (#f) had reached a certain value; also, the reading of gas-pressure gauge (#f) once pressure gauge (#e) began to increase was the sealing capacity of stage (#6). We could obtain the sealing capacity of stages (#2-#5) in the same way. The reading of gas-pressure gauge (#a) once pressure gauge (#a) began to decrease was the sealing capacity of stage (#1). The sealing capacities of stages (#1-#6) were recorded as shown in Table 1.

From the table, it can be seen that the pressure capacity of magnetic fluid under different stages of pole teeth before the first breakthrough differs: specifically, the "big in the middle and small on both ends" phenomenon manifests. In this magnetic fluid sealing model, the middle stages (namely, stages (#3&#4)) are closest to the permanent magnet, and the corresponding magnetic field gradient is greatest, and so the pressure capacity is the strongest. In general, the sealing capacity of stage (#4) is stronger than that of stage (#3), while the sealing capacity of stage (#4) is stronger than that of stage (#2). This is due entirely to the non-uniformity of the magnetic fluid distribution caused by the silhouette change under pressure loading. However, as shown in Table 1, the sealing capacity of stage (#6) is weaker than that of stage (#1), because the magnetic field symmetry under stages (#1&#6) at the edge of the seal is poor, while the pressure loading direction is asymmetric. As a result, the sealing capacities of stages (#1&#6) differ even if the volume of magnetic fluid under those stages is the same. Therefore, the distribution of magnetic fluid at stages (#1&#6) cannot be judged merely in accordance with the pressure capacities of those stages as recorded in the above table.

The impact of the magnetic fluid sealing mechanism of pressure transmission and seal failure on the non-uniformity of the magnetic fluid distribution was studied. The breakthrough count (i.e., the number of breakthrough occurrences) under the first pole tooth stage was the highest. The change of the sealing capacity of stage (#1) with the change in the breakthrough count under the first pole tooth stage is shown in Fig. 8. It can be seen that the higher the breakthrough count, the more magnetic fluid is taken away and the lower the sealing capacity of the stage is.

6. Conclusion

(1) In multistage magnetic fluid seals, the total sealing capacity is lower than the sum of the respective sealing capacities of all of the single stages. This is due to the non-uniformity of the distribution of magnetic fluid in multistage magnetic fluid seals. In multistage magnetic fluid seals, there is actually little magnetic fluid under some pole teeth.

(2) The causes of the non-uniform distribution are as follows: injection of magnetic fluid; the assembly of the magnetic fluid seal; the change of silhouette of magnetic fluid under pressure loading; the magnetic fluid sealing mechanism of pressure transmission, and seal failure.

(3) According to the non-uniform distribution of magnetic fluid in multistage magnetic fluid sealing, the follow-

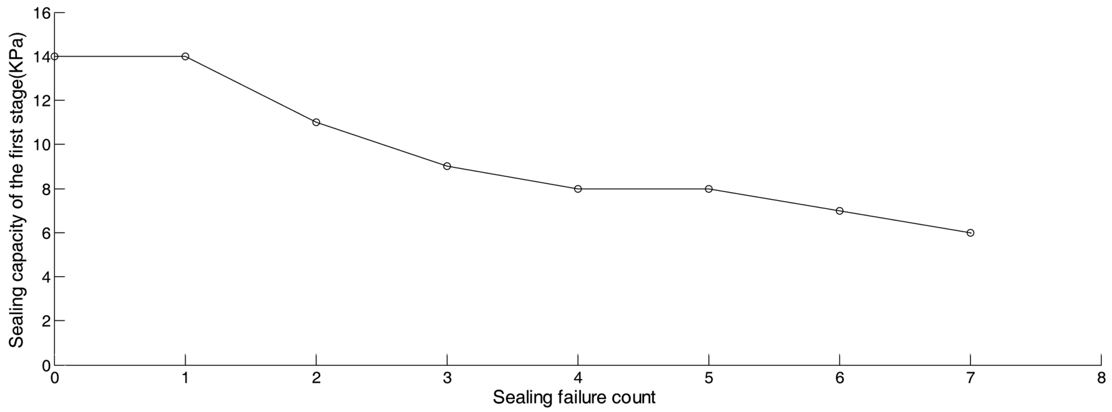

Fig. 8. Change of the sealing capacity of the first stage with sealing failure count.

ing improvement-effecting measures can be proposed: (a) obtainment of advanced technology for injection of magnetic fluid and magnetic fluid seal assembly; (b) injection of slightly more magnetic fluid into the magnetic fluid seal; (c) where possible, more gradual and slower loading of pressure.

Acknowledgments

Supported by the Fundamental Research Funds for the Central Universities (Grant No. 2015YJS145).

References

[1] Li Decai, The theory and application of magnetic fluid, Science Press, Beijing (2003) pp. 1-20.
[2] Li Decai, The theory and application of magnetic fluid seals, Science Press, Beijing (2010) pp. 62-83.
[3] Rosensweig, R. E., Ferrohydrodynamics, Dover Publications, New York (2002) pp. 54-61&142-146.
[4] B. M. Berkovsky, V. F. Medvedev, and M. S. Krakov, Magnetic Fluids: Engineering Applications, Oxford Scientific Publications, Oxford (1993) pp. 138-139.
[5] S. Taketomi and S. Chikazumi, Magnetic Fluids: Principles and Applications, Nikkan Kogyo Shimbun, Tokyo (1988) pp. 28-30 (in Japanese)
[6] Yang Xiaolong, Zhang Zhili, and Li Decai, Sci. China Tech. Sci. **56**, 2865 (2013).
[7] Chi Changqing, The basic and applied physics of ferrofluid, Beihang University Press, Beijing (2003) pp. 172-187.
[8] J. Walowit and O. Pinkus, ASLE Transactions **24**, 533 (1981).
[9] O. Pinkus, ASLE Transactions **25**, 79 (1982).
[10] Yang Xiaolong, Li Decai, Yang Wenming, Xing Feifei, and Li Qiang, Chinese Journal of Vacuum Science and Technology **32**, 919 (2012).
[11] Zhang Haina and Li Decai, Key Eng. Mater. **492**, 273 (2012).
[12] Wang Zhongzhong, and Li Decai, Int. J. Appl. Electrom. **48**, 101 (2015).