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Magnetic fluid seals working in liquid environments: factors limiting their life and solution methods

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Abstract

A magnetic fluid (MF) seal enables mechanical contact-free rotation of a shaft and hence has excellent durability. The performance of an MF seal, however, decreases in liquids. We developed an MF seal that had a “shield” mechanism. Factors limiting the seal life in liquids and their solution methods were studied. Factors limiting seal life were MF flowing away and mixing of MF with liquids. Two types of shield were placed in MF seals installed in rotary pumps. Long-term durability tests were conducted. The MF seal with a small cavity space shield showed a longer life (143+ days, ongoing) while the MF seal with a large cavity space shield failed after 28, 32and 31 days.

When a rotary pump is connected to an afterload, water flows into the shield space until air pressure in the shield space reaches the afterload pressure. The volumes of water that flowed into the shield space were estimated to be almost zero in the case of small cavity space shield and about 0.12 μL in the case of large cavity space shield. Less water in contact with the MF prolonged the seal life.

In conclusion, the use of an optimally designed-shield prolongs an MF seal life by preventing the MF from flowing away and mixing with liquids.

Keywords

Magnetic fluid seal, seal durability, rotary blood pump, water

1. Introduction

A magnetic fluid (MF) seal is one of the most successful applications of MFs. An MF seal enables mechanical contact-free rotation of a shaft and hence has excellent durability. The life of a conventional MF seal, however, has been reported to decrease in liquids [1]. MF seals used in our previous study failed after 6 days and 11 days [2]. Therefore the effect of the seal structure on the long-term performance of an MF seal in liquid was investigated [2]. Three types of magnetic fluid seal were used（Fig．1）. Seal “A” was a conventional seal without a shield. Seal “B” had the same structure as that of Seal “A”, but the seal was installed at one mm below the liquid level. Seal “C” was a seal with a shield. Each seal consisted of a magnet (Nd-Fe-B, Hc: 1.14 MA/m, Br: 1.26 T, ID: Φ3.6 mm, OD : Φ8 mm, L : 1 mm) sandwiched with pole pieces (SUS420, ID: Φ3.1 mm, OD: Φ8 mm, L: 1 mm). The seal was installed on an impeller shaft (SUS420, Φ3 mm). The gap between the pole piece and the shaft was 50 μm. The shield was made of a non-magnetic material (SUS303). The thickness of the shield was l mm, and the gap between the shield and the shaft was 50 μm. The objective of installing the shield was to prevent magnetic fluid from flowing away with surrounding fluid flow.

Long-term durability of the MF seal installed in a rotary blood pump was tested. The pump was connected to a reservoir through a flowmeter. Distilled water was used as a working fluid. The pump flow rate was maintained at about 4 L/min with outlet pressure of 160 to 175 mmHg. The motor speed was set between 4,300 and 5,300 rpm. Each test was continued until seal failure. In the pumps with Seal “A”, the MF seals failed after 6 days and 11 days. Seal “B” showed better results（failure after 20 days and 73 days）. Seal “C” with a shield showed long-term durability. The MF seals remained in perfect condition for 217 days and 275 days. The reason for the short life of the MF seal (Seal “A”) in liquid is that MF is directly exposed to the flow field, and the interface of the two liquids (MF and working fluid) becomes instable, resulting in MF flowing away with the fluid. Therefore, a shield was installed to minimize the influence of pump flow on the MF. The MF seals with a shield remained in perfect condition for 217 days and 275 days. These results showed that the factor limiting seal life was the MF flowing away with the pump flow and that this problem can be solved by installation of a shield.

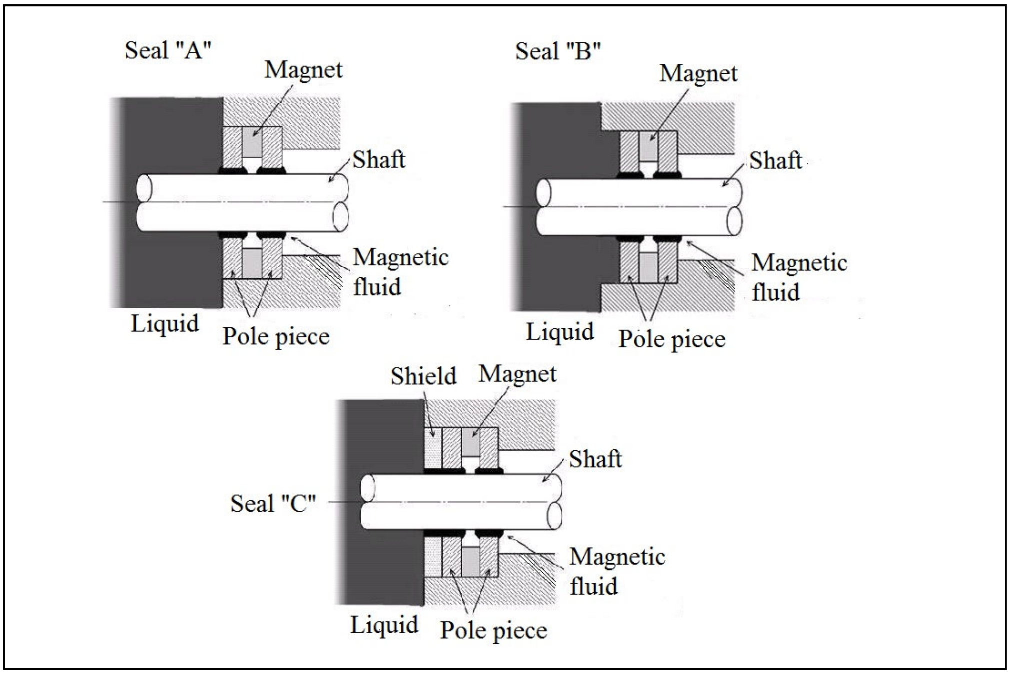


Figure 1 Three types of magnetic fluid seal.

However, it was not clear why the MF seal with a shield failed after 275 days (experiment in which the MF seal failed after 217 days, inlet and outlet tubes of the pump were accidentally kinked on the 217th day). We assumed that water flowed into a cavity space of the shield and came into contact with the MF. This resulted in mixing of the MF and water and also deterioration of the MF, which would have reduced seal life. Therefore, the mixing of MFs and water and changes in the magnetic characteristics of the MFs were studied [3]. Six mL of an MF was poured into a 100 mL beaker and then 50 mL of distilled water was poured into the beaker. Three sets of experiments were carried out (Fig. 2): in group B, the beaker was kept still on a table for 5 days or 10 days; and in group C, the beaker was placed on a magnetic stirrer and the liquids were stirred for 5 days or 10 days. After the experiments, the MFs in the beakers were sampled by a syringe.

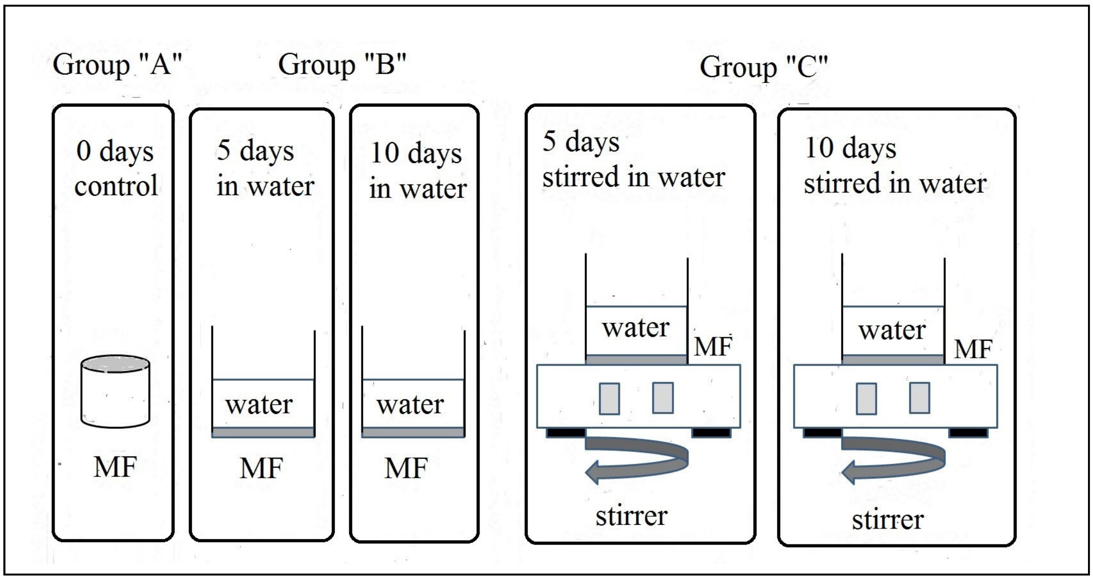


Figure 2 Three sets of experiments.

Magnetization curves of the samples were obtained by using a vibrating sample magnetometer (BHV-35H, Riken Denshi, Tokyo, Japan). The saturated magnetization of the samples stirred in water for 5 days and 10 days decreased by −7.4% and −15.5%, respectively, and the saturated magnetization of the sample kept still in water for 10 days decreased by −13.5%. Infrared spectroscopic analysis of the samples was conducted by using a Fourier-transfer infrared spectrometer (FTIR−8300, Shimadzu, Kyoto, Japan). Water absorption spectra were obtained at 3500 1/cm, 1650 1/cm and 600 to 300 1/cm. The infrared spectroscopic analysis revealed sharp peaks in the frequency ranges of 1600 to 1700 1/cm and 3100 to 3700 1/cm in the samples kept still in water for 10 days and in the samples stirred in water for 10 days, respectively. No peaks related to absorption spectra of water were observed in the original (control) MF.

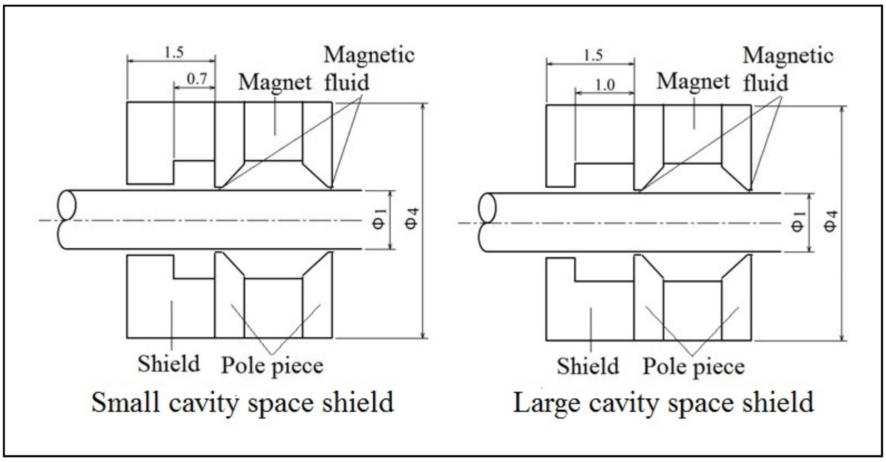
These results showed that the MF and water were mixed when the MF was stirred in water. This phenomenon seemed to occur in an MF seal and to induce seal failure after 275 days. The results suggested that another factor limiting seal life was mixing of MF and water in a shield space. A solution for this limiting factor is to prevent water from mixing with MF in a shield space. Therefore, the objective of this study was to investigate the effect of shield structure on mixing of MF and water in a shield space.

2. Methods

2.1 Structures of two shields

A miniature MF seal was used in this study [4]. The miniature MF seal consisted of a magnet (Nd-Fe-B magnet, Hc: 876 kA/m, Br: 1.26 T, outer diameter (OD): Φ4 mm, inner diameter (ID): Φ2 mm, L: 1 mm) sandwiched by asymmetric trapezoidal pole pieces (SUS420, OD: Φ4 mm, ID: Φ1.1 mm, L: 0.5 mm). The MF seal was installed on a rotating shaft (Φ1.0 mm) of an impeller. The gap between the pole piece and the shaft was

50 μm. The gap was filled with MF (Ferrotec, Exp.15067) specially developed for this seal. The new MF (Exp.15067) has a higher saturated magnetization of 47.9 kA/m, a higher viscosity of 0.5 Pa･s and a density of 1.390 g/cc. The shield was made of a non-magnetic material (SUS303). Two types of shield were used (Fig. 3). One shield had a small cavity space and the other shield had a large cavity space. The gap between the shield and the shaft was 100 μm.



Small cavity space shield

Large cavity space shield

Figure 3 Two types of shield.

2.2 Long-term durability test

A rotary pump in which the miniature MF seal was installed was connected to a reservoir through a flowmeter (BBBC4168, TOFCO Corp. Tokyo, Japan) by silicone tubes (Fig. 4). The pump was placed on the floor and the reservoir was hung at 136 cm above the floor. The circuit was filled with distilled water. The motor was driven at 24,000 rpm against an afterload of 100 mmHg. Pump flow rate was maintained between 1.2 L/min and 1.7 L/min. Seal failure was detected by monitoring the exhaust port of the pump.

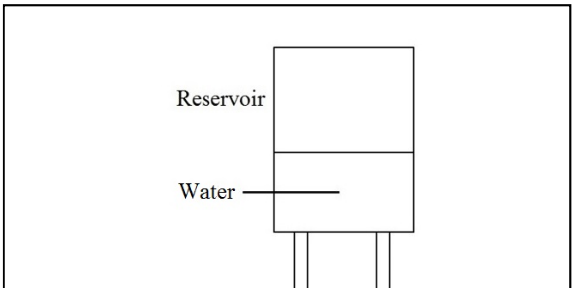


Figure 4 Experimental setup for long-term durability test

3. Results

MF seals with the large cavity space shield failed after 28 days (#1705), 32 days (#1706) and 31 days (#1808) (Fig. 4). On the other hand, the MF seal with the small cavity space shield worked perfectly in water for 143+ days (ongoing as of this writing) (#1910).

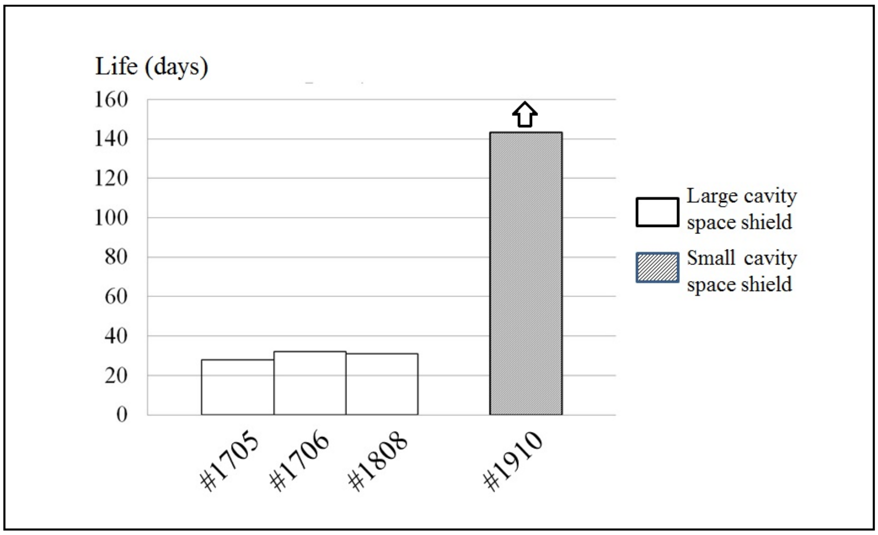


Figure 5 Long-term tests with two types of shield.

4. Discussion

Our previous study showed that the factor limiting seal life was MF flowing away with the pump flow and that this problem could be solved by installation of a shield [2]. Also, our previous study suggested that the MF and water were mixed when the MF was stirred in water. The saturated magnetization of MF stirred in water decreased [3]. This induces seal failure. Another factor limiting seal life is mixing of MF and water. To solve this problem, two types of shield were tested: one type had a large cavity space and the other type had a small cavity space (Fig. 3). As shown in the results section, MF seals with a large cavity space failed after 28 days, 32 days and 31 days. On the other hand, the MF seal with a shield with a small cavity space worked perfectly for over 143 days (ongoing).

When a rotary pump is connected to an afterload, water flows into the cavity space of the shield through a concentric annulus of the shield entrance until air pressure in the shield space reaches the afterload pressure. The shield space is a closed space when the MF seal works perfectly. The equivalent circuit model of water flow into the shield space is shown in Fig. 6. The resistance is given by

$$R = \frac{8\mu}{\pi}\frac{\ell}{a^4 - b^4 - (a^2 - b^2)^2/\ln(a/b)}, \quad (\mathrm{Pa\cdot s}/m^3)$$

where μ is viscosity of water (Pa· s) , a is radius of the entrance orifice of the shield (m), b is radius of a shaft (m), and ℓ is length of the entrance orifice of the shield. Capacitance is given by

$$C = V_0 / 1.01 \times 10^5, \ (\mathrm{m}^3 / \mathrm{Pa})$$

where V_0 is volume of the cavity space (m^3).

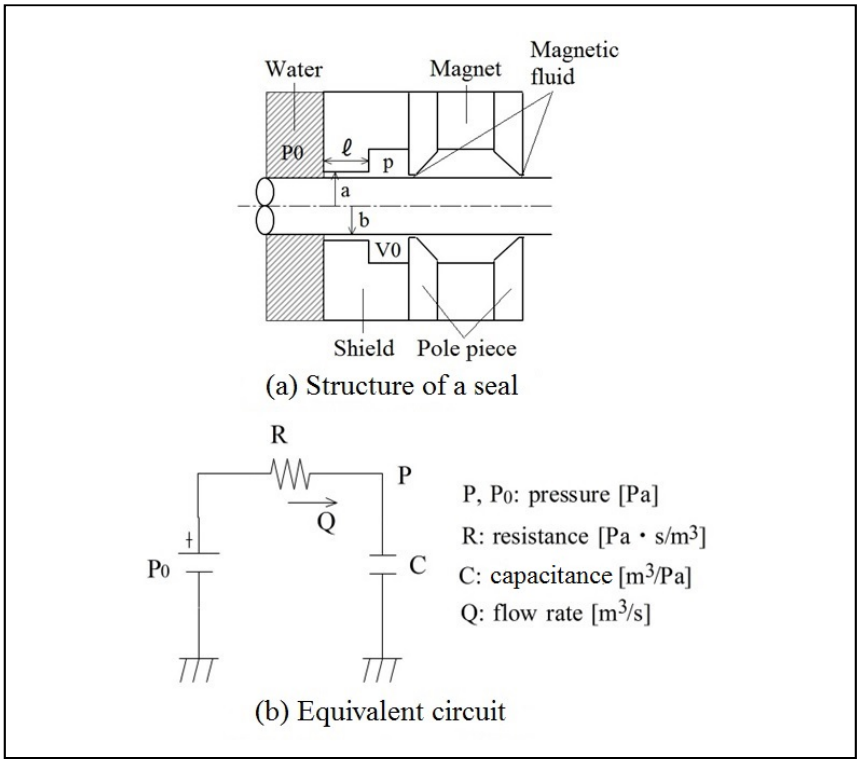


Figure 6 Equivalent circuit model of water flow in a shield.

From the equivalent circuit, pressure (P (Pa)) in a shield space is given by

$$P = P_0 (1 - \exp(-t/CR)),$$

where P_0 is afterload pressure (Pa) and t is time (s).

Water flow rate (Q (m^3/s)) is given by

$$Q = P_0 /R \cdot \exp(-t/CR)). \quad (1)$$

Changes in flow rate are shown in Fig. 7. The volume of water that flowed into the shield space was obtained by integrating the Equation (1). The volumes were 0.31 μL in the shield with a large cavity space shield and 0.22 μL in the shield with a small cavity space. The volumes of the concentric annulus of the shield entrance were 0.17 μL for the shield with a large cavity space shield and 0.28 μL for the shield with a small cavity space. Therefore, water flows into the shield space in the shield with a large cavity space (0.31 μL>0.17μL), while water does not flow into the shield space in the shield with a small cavity space (0.22 μL<0.28μL). Therefore, water does not come into contact with the MF in the shield with a small cavity space. This is the reason for the prolonged seal life as shown in Fig. 5. Surface tension of water was not included in the analysis, but surface tension works to resist water inflow. Temperature was assumed to be constant.

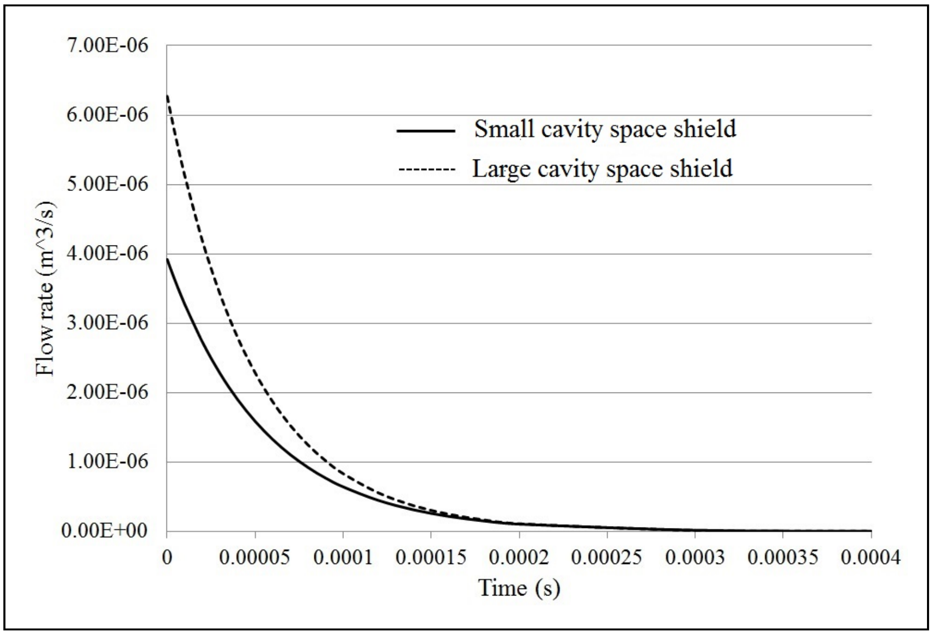


Figure 7 Changes in flow rate of water flowing into a shield space.

There have been several studies on MF seals working in liquid environments [7-11]. Wang et al. improved MF seal life by adding a gas isolation device to prevent direct contact between MFs and the sealed liquids [11]. The space between MFs and the sealed liquids was connected to compressed gas through the gas vent. The pressure of the compressed gas was equal to the pressure of the sealed liquids. This system, however, requires compressed gas. Our MF seal does not require an additional device. This is important when an MF seal is applied to an implantable blood pump. Further studies are required because only one experiment was performed using the shield with a small cavity space while three experiments were conducted using the shield with a large cavity space.

In conclusion, the use of an optimally designed-shield prolongs the life of an MF seal in liquid by preventing the MF from flowing away and mixing with liquids.

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