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Application of a magnetic fluid seal to rotary blood pumps

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Abstract
A magnetic fluid seal enables mechanical contact-free rotation of a shaft without frictional heat and material wear and hence has excellent durability. However, the durability of a magnetic fluid seal decreases in liquid. The life of a seal applied to a rotary blood pump is not known. We have developed a magnetic fluid seal that has a shield mechanism minimizing the influence of the rotary pump on the magnetic fluid. The developed magnetic fluid seal worked for over 286 days in a continuous flow condition, for 24 days (on-going) in a pulsatile flow condition and for 24 h (electively terminated) in blood flow. The magnetic fluid seal is promising as a shaft seal for rotary blood pumps.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Heart diseases are one of the major causes of death in the world. To treat severe heart disease, heart transplantations have been successfully conducted. However, a shortage of donor hearts is a serious problem and all the patients on a waiting list cannot have heart transplantations. To solve this problem artificial hearts have been developed and used in many patients. Recently many rotary blood pumps have been clinically used as well as pulsatile blood pumps, because rotary blood pumps have smaller volume and do not require artificial heart valves.

In a rotary blood pump an impeller is driven in several ways, including direct drive, magnetic coupling, and magnetic suspension. Magnetic suspension eliminates abrasive wear, and a long life can be expected because of the wear-free operation. Magnetic suspension, however, requires an additional control system and electric power to suspend and control the impeller. A direct drive system connects an impeller to a motor directly. Although it is a simple mechanism and high efficiency can be expected, it requires a shaft seal at the boundary between the blood chamber and the motor, and life expectancy of a conventional mechanical seal is much shorter than that required for long-term usage.

To overcome the problems of the magnetic suspension and purge system, we have proposed the use of a magnetic fluid seal at the blood chamber–motor interface of the rotary blood pump. A magnetic fluid seal enables mechanical contact-free rotation of the shaft without frictional heat and material wear and hence has excellent durability. In previous studies, we investigated the performance of the magnetic fluid seal [1–3]. Those studies showed that a sealing pressure of over 66.5 kPa (500 mmHg) was obtained at 10 000 rpm in bovine blood, that the magnetic fluid seal worked perfectly for more than one year against a pressure of 20 kPa (150 mmHg) at 7000 rpm in water, and that the magnetic fluid did not show cytotoxicity in tests using L929 fibroblast cells. Liu *et al* also developed a magnetic fluid seal that worked perfectly for 10 weeks at 1200 rpm in lubricating oil [4]. A magnetic fluid seal generally has a short life when used in liquids. It has been reported that the reason for the short life is the interface instability of the two liquids [4, 5]. Successful operation of a magnetic fluid seal in water for a long time was achieved with a magnetic fluid seal of a rotating shaft without an impeller [1–5]. However, the interface instability problem and long-term durability of the magnetic fluid seal installed in a rotary blood pump have not been studied in detail. To the best of our knowledge, the maximum durability of a magnetic fluid seal installed in

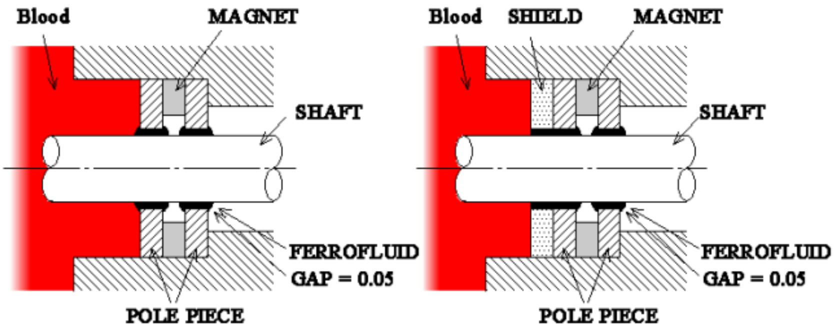

Figure 1. Magnetic fluid seal without a shield (left) and with a shield (right).

Table 1. Magnetic fluids.

Magnetic fluids	LS-40	Exp.03043	Exp.03045	Exp.01167
Saturated magnetization (kA m^{-1})	24.3	70	47.9	67.9
Viscosity (Pa s)	0.45	11.8	0.568	0.16
Density (g cm^{-3})	1.32	1.696	1.621	1.58
Solvent	Alkyl-naphthalene	oil	oil	oil
Particles	Fe_3O_4	Fe_3O_4 and γ-Fe_2O_3	Fe_3O_4 and γ-Fe_2O_3	Fe_3O_4

a rotary blood pump is only 2 days [6]. We have developed a magnetic fluid seal that has a 'shield' mechanism minimizing the influence of the rotary pump on the magnetic fluid. The purpose of this study was to investigate the long-term durability of a magnetic fluid seal installed in a rotary blood pump.

2. Magnetic fluid liquid seals

Two types of magnetic fluid seal were used (figure 1). One was a conventional seal without a shield and the other was a seal with a shield. The seal consisted of a magnet (Nd–Fe–B, Hc: 1.14 MA m^{-1}, Br: 1.26 T, inside diameter (ID): 3.6 mm, outside diameter (OD): 8 mm, L: 1 mm) sandwiched with pole pieces (SUS420, ID: 3.1 mm, OD: 8 mm, L: 1 mm). The seal was installed on an impeller shaft (SUS420, D: 3 mm). The gap between the pole piece and the shaft was 50 μm. The 'shield' is made of a non-magnetic material (SUS303). The thickness was 1 mm and the gap between the shield and the shaft was 50 μm. The objective of installing the 'shield' was to prevent the pump flow from entering into the restricted shield-shaft gap so as to minimize the influence of surrounding fluid flow.

Three magnetic fluids were used (table 1). They were LS40, Exp.03043 and Exp.03045. The LS40 is a commercially available magnetic fluid suitable for a magnetic fluid seal. It has a relatively high viscosity of 0.45 Pa s and a low evaporating rate. Exp.03043 and Exp.03045 were developed for this study. They have a higher saturated magnetization of 70 and 47.9 kA m^{-1} and a higher viscosity of 11.8 and 0.568 Pa s.

3. Long-term endurance in continuous flow

Long-term durability of the magnetic fluid seal installed in a rotary blood pump was tested. A DeltaStream pump and a centrifugal pump were used. A magnetic fluid seal was installed on the impeller shaft of each of the rotary blood pumps. The DeltaStream Blood Pump (DeltaStream Blood Pump, MEDOS, Stolberg, Germany) is a rotary pump with a diagonally streamed rotor. The motor and the blood chamber were separated by a magnetic fluid seal without a shield. Magnetic fluid (Exp.03043, saturated magnetization: 70 kA m^{-1}, Ferrotec, Japan) was used. The impeller is positioned between the pump inlet and the motor housing and is supplied with two washout holes. A centrifugal pump was manufactured in our laboratory (figure 2). The same impeller as that used in the DeltaStream pump was used. A DC brushless motor (EC22, Maxon Japan, Tokyo, Japan) and the blood chamber were separated by a magnetic fluid seal with a shield. Two different magnetic fluids were used: LS-40 (saturated magnetization: 24.3 kA m^{-1}, Taiho Industry, Japan) and Exp.03045 (saturated magnetization: 47.9 kA m^{-1}, Ferrotec, Japan).

The pump was connected to a reservoir through a flow meter with polyvinyl chloride (PVC) tubes (figure 3). The pressure difference across the pump was varied by changing occlusion of the outflow PVC tube. Inlet and outlet pressures of the pump were measured with pressure sensors. Distilled water was used as a working fluid. In the experiments (Nos 1 and 2) using the DeltaStream pump, the pump outlet pressure was kept at 150 mmHg and the pump flow was kept at 5 l min^{-1}. In the experiments using the centrifugal pump, the pump outlet pressure was maintained at 107 mmHg (No. 3) or 150 mmHg (No. 4) and the pump flow was maintained at 4.0 l min^{-1} (No. 3) or 3.9 l min^{-1} (No. 4).

The results are shown in table 2. In experiments Nos 1 and 2, the magnetic fluid seal failed after 8.1 days and 6.2 days, respectively. Although the magnetic fluid seal without a 'shield' failed in one week, the seal with a 'shield' showed long-term durability. In experiment No. 3 the magnetic fluid seal worked perfectly for 286 days. Mean pump flow during the experiment was 4.0 l min^{-1}, mean pump outlet pressure 107 mmHg, mean pump inlet pressure 22 mmHg, and mean

Table 2. Results of the long-term endurance tests.

Exp. No.	Pump	Motor speed (rpm)	Outlet press. (mmHg)	Flow ($l\ min^{-1}$)	Magnetic fluid	Shield	Days	Comment
1	DeltStream pump	5312	150	5	Exp.03043	Not used	8.1	Seal failed
2	DeltStream pump	5389	150	5	Exp.03043	Not used	6.2	Seal failed
3	Centrifugal pump	3622	107	4	LS40	Used	286	Pump chamber failure
4	Centrifugal pump	4290	150	3.9	Exp.03045	Used	190+	On-going

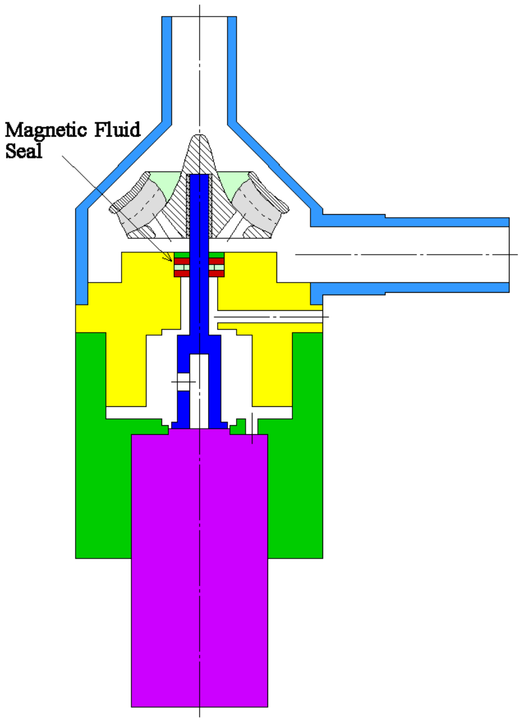

Figure 2. Centrifugal pump. A magnetic fluid seal with a shield is installed on an impeller shaft. The blood chamber and the motor room are separated by the magnetic fluid seal.

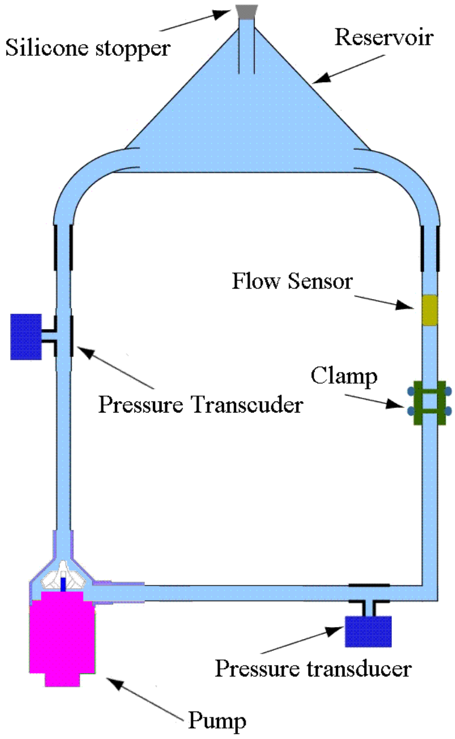

Figure 3. Circulatory system to test the long-term endurance of a magnetic fluid seal installed in a rotary pump.

impeller speed 3622 rpm. The experiment was terminated due to the pump housing leak failure. The seal was perfect. In experiment No. 4 the magnetic fluid seal had remained in perfect condition for 190 days as of 30 June 2007, and the seal failed after 273 days. Mean pump flow was 3.9 $l\ min^{-1}$ and mean pump outlet pressure 150 mmHg.

4. Long-term endurance in pulsatile flow

The long-term endurance of the magnetic fluid seal (with a shield) in a pulsatile flow condition was studied using a mechanical mock loop (figure 4). The magnetic fluid of Exp.03045 was used. A pneumatic pump [7] was used as the left ventricle, a reservoir as the left atrium and a closed air chamber and a clamp as the aorta. The rotary pump was connected between the left ventricle and the aorta as a bypass pump. Saline was used as the working medium. Outflow resistance was changed by partially compressing the outflow tube with a clamp. The total flow was measured with an electromagnetic flowmeter. The left ventricular pressure was measured at the air-driven blood pump chamber and

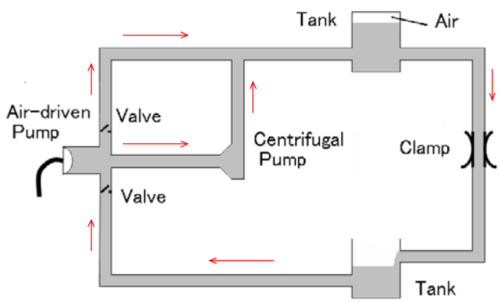

Figure 4. Mechanical mock loop to test long-term endurance of a magnetic fluid seal in pulsatile flow conditions. A pneumatic pump is used as the left ventricle, a reservoir as the left atrium and a closed air chamber and a clamp as the aorta. The rotary pump is connected between the left ventricle and the aorta as a bypass pump.

the aortic pressure at the outflow cannulae with pressure transducers. Differential pressure (0–150 mmHg) between the aortic pressure and the left ventricular pressure was applied to the magnetic fluid seal. The drive rate of the pneumatic pump was 75 bpm and the motor speed of the rotary pump was

3000–4000 rpm. Seal failure was monitored by the liquid leakage through the leakage hole of the pump.

The magnetic fluid seal had remained in perfect condition for 24 days as of 30 June 2007, and the magnetic fluid seal remained in perfect condition for 30 days (the experiment was electively terminated).

5. Performance in blood flow

The performance of the magnetic fluid seal installed in a rotary blood pump in blood flow was tested. An axial flow pump developed in our laboratory was used [8, 9]. The impeller is directly connected to a DC brushless motor. The motor shaft is supported by ball bearings. The motor assembly is waterproofed with a magnetic fluid seal with a shield. The magnetic fluid of Exp.03045 was used.

The axial flow pump was connected to a reservoir through a 10 mm flow probe with silicone tubes. The same circulatory circuit as shown in figure 3 was used. The pump flow was measured with an electromagnetic flowmeter. Inlet and outlet pressures of the pump were measured with pressure sensors. Human preserved blood obtained from the Hokkaido Red Cross Blood Center was used. The test was continued for 24 h. Mean pump flow was 5.2 l min^{-1}, mean outlet pressure 143 mmHg and mean motor speed 7410 rpm.

After the experiment the pump was disassembled and no seal leak was confirmed.

6. Mixing of magnetic fluids and water

In the magnetic fluid seal used in liquids the magnetic fluid directly contacts the liquids. Therefore mixing of the magnetic fluid and the sealing liquids and also deterioration of the magnetic fluid are suspected. These impair the seal life. Mixing of magnetic fluids and water and changes in magnetic characteristics of the magnetic fluids were studied.

6 ml of the magnetic fluid (Exp.01167, saturated magnetization: 67.9 kA m^{-1}, viscosity: 0.16 Pa s, density: 1.58 g cm^{-3}, Ferrotec, Japan) was poured into a 100 ml beaker and then 50 ml of distilled water was poured into the beaker. The experiments were classified into three groups. In group A the beaker was kept still on a table for 5 and 10 days. In group B the beaker was placed on a magnetic stirrer (HS-38, Iuchi, Japan) and the liquids were stirred for 5 days. In group C the liquids in the beaker were stirred for 10 days. After the experiments, the magnetic fluids in the beaker were sampled by a syringe. The magnetization curve of the samples was measured by a vibrating sample magnetometer (BHV-35H, Riken Denshi, Japan). Thermogravimetric analysis of the samples was conducted with a thermo-gravimetric/differential thermal analyzer (TG/DATA 6300, SIINT, USA). Infrared spectroscopic analysis of the samples was conducted by a Fourier transfer infrared spectrometer (FTIR-8300, Shimadzu, Japan).

Results of the measurements are summarized in table 3. The saturated magnetization of the samples stirred for 5 days (group B) and 10 days (group C) decreased. Also the saturated magnetization of the samples kept still for 5 and 10 days decreased. Decrease of weight was not observed in the sample kept still for 5 days (group A) but weight decreased in other samples. In the infrared spectroscopic analysis sharp peaks were observed in the wavelength of 1600–1700 1 cm^{-1} and 3100–3700 1 cm^{-1} in the samples kept still for 10 days and the samples stirred for 5 and 10 days. The sample kept still for 5 days showed the same spectroscopic pattern as the original magnetic fluid. No peaks relating to water were observed. These results suggested mixing of the magnetic fluid and water when the magnetic fluid was stirred in water.

Table 3. Results of measurements of magnetic properties and thermogravimetric analyses of magnetic fluids stirred in water. In group A the magnetic fluid was kept still in water in a beaker for 5 and 10 days. In group B the beaker was placed on a magnetic stirrer and the magnetic fluid was stirred in water for 5 days. In group C the magnetic fluid was stirred in water for 10 days. Control indicates the magnetic fluid.

Sample	Saturated magnetization (emu g^{-1})	Weight decrease rate room temperature $\sim$ 100 °C (%)
Group A (5 days)	42.4	0.41
Group A (10 days)	37.3	6.01
Group B	37.2	1.35
Group C	36.4	3.40
Control	43.1	0.33

7. Discussion and conclusion

As reported in other studies [6], the life of a conventional magnetic fluid seal installed in a rotary blood pump is short (8.1 and 6.2 days), as we also saw in this study. However, the life of the magnetic fluid seal increased dramatically with a shield compared with the life of a seal without a shield, as shown in table 2. The magnetic fluid seal with a shield worked perfectly in continuous flow for 286 days and 190 days (on-going). In clinical cases a rotary blood pump is implanted between the left ventricle and the aorta and used as a left ventricular bypass pump. Differential pressure across the rotary blood pump changes periodically according to the cardiac cycle and the pump flow also changes periodically even when the motor speed is kept constant. The life of a magnetic fluid seal in pulsatile flow may be different from that in continuous flow. The magnetic fluid seal was tested in pulsatile flow using a mechanical mock loop, as shown in figure 4. The magnetic fluid seal has remained in perfect condition for 24 days (on-going). In clinical cases a rotary blood pump ejects blood and the magnetic fluid seal contacts with blood. The performance of the magnetic fluid seal was tested in blood. The seal was perfect for 24 h (electively terminated). The magnetic fluid seal with a shield was tested in similar conditions as used in clinical applications and worked perfectly. The developed magnetic fluid seal showed promising results as a shaft seal for rotary blood pumps.

The reasons for the long-term durability of the magnetic fluid seal with a shield developed in this study are thought to be as follows. When the gap between the shield and the motor shaft is filled with magnetic fluid and water, that is, the magnetic fluid–water interface is in the shield, the velocity difference between the sealing liquid and the magnetic fluid at the interface is zero. The Kelvin–Helmholtz instability condition is not satisfied and the magnetic fluid remains stably in the seal [10]. When the gap between the shield and the motor shaft is filled with magnetic fluid, that is, the magnetic fluid–water interface is at the waterside end of the shield, there is a velocity difference between the magnetic fluid and the sealing liquid. However, the magnetic fluid in the narrow closed space between the shield and the motor shaft does not splash easily. The measurements of magnetic properties, the thermogravimetric analysis, and the Fourier transform infrared spectroscopic analysis of the magnetic fluid stirred in water suggested mixing of the magnetic fluid and water. The decreased magnetic property of the magnetic fluid decreases the sealing pressure and therefore shortens the life of the seal. Therefore the contacting area of a magnetic fluid with sealing liquids should be as small as possible. With the use of a shield the contacting area of the magnetic fluid with water decreased to 0.48 mm^2. Without a shield the contacting area was 2.96 mm^2. In a previous study behaviors of the magnetic fluid were observed using a high-speed camera and the shape of the magnetic fluid was measured [11]. The magnetic fluid appearing outside the seal changed the meniscus periodically according to the rotation of the shaft. The frequency of the changes of the meniscus was lower than that of the shaft rotation. The decrease of the contacting area is another reason for the longer life of the seal. In this study, magnetic fluids with different viscosity were used. Further studies are required to find the optimal viscosity for long seal life.

We have developed a magnetic fluid seal with a shield for a rotary blood pump that works in liquids for over 286 days in a continuous flow condition, for 24 days (on-going) in a pulsatile flow condition and for 24 h (electively terminated) in blood flow. The magnetic fluid seal is promising as a shaft seal for rotary blood pumps.

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