35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

A Magnetic Fluid Seal for Rotary Blood Pumps: Image and Computational Analyses of Behaviors of Magnetic Fluids

Yoshinori Mitamura, *Life Member, IEEE*, Tetsuya Yano, Eiji Okamoto, *Member, IEEE*

Abstract— **A magnetic fluid (MF) seal has excellent durability. The performance of an MF seal, however, has been reported to decrease in liquids (several days). We have developed an MF seal that has a shield mechanism. The seal was perfect for 275 days in water. To investigate the effect of a shield, behaviors of MFs in a seal in water were studied both experimentally and computationally. (a) Two kinds of MF seals, one with a shield and one without a shield, were installed in a centrifugal pump. Behaviors of MFs in the seals in water were observed with a video camera and high-speed microscope. In the seal without a shield, the surface of the water in the seal waved and the turbulent flow affected behaviors of the MFs. In contrast, MFs rotated stably in the seal with a shield in water even at high rotational speeds. (b) Computational fluid dynamics analysis revealed that a stationary secondary flow pattern in the seal and small velocity difference between magnetic fluid and water at the interface. These MF behaviors prolonged the life of an MF seal in water.**

I. Introduction

Heart transplantation is the most successful treatment for patients with advanced heart failure. As a consequence of limited donor availability, left ventricular assist device (LVAD) therapy has become an established treatment for patients with advanced heart failure. Historically, patients have been supported by devices engineered with a pulsatile design. Pulsatile devices, however, have limitations in their design such as a large pump size, requirement for extensive surgical dissection for implantation, and audible pump operation. The development of continuous-flow rotary pump technology represents an innovative design for LVADs. These devices have the advantages of smaller pump size and potential for greater mechanical reliability by simplification of the pumping mechanism [1].

In a rotary blood pump, the impeller is driven by various methods, including direct drive, magnetic coupling, magnetic suspension and hydrodynamic pressure suspension. A direct drive system connects an impeller to a motor directly. It is a simple mechanism and high efficiency can be expected; however, it requires a shaft seal at the boundary between the blood chamber and motor. The shaft seal is the most common site of thrombus formation and hemolysis. Also, life expectancy of a conventional mechanical seal is much shorter than that required for long-term usage.

To overcome these problems, we have proposed the use of a magnetic fluid seal at the blood chamber-motor interface of a 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. However, the life of a magnetic fluid seal has been reported to decrease in liquids. To the best of our knowledge, the maximum durability of a magnetic fluid seal installed in a rotary blood pump is only 2 days [2]. It has been reported that the reason for the short life is the interface instability of the two liquids [3, 4]. To solve this problem, we have developed a new magnetic fluid with higher saturated magnetization and have also modified the seal structure with a shield to minimize the influence of flow in a rotary pump on the magnetic fluid [5, 6].

Long-term durability of the magnetic fluid seal installed in a rotary blood pump was tested. The pump was connected to a reservoir. Distilled water was used as a working fluid. Pump flow was maintained at about 4 L/min with an outlet pressure of 160 to 175 mmHg. The tests were continued until seal failure. Three types of magnetic fluid seal were used (Table 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 liquid level. Seal "C" was a seal with a shield. The results are shown in Table 1. In the pumps with Seal "A", the magnetic fluid seal failed after 6 days and 11 days. Seal "B" showed better results (20 days and 73 days). Seal "C" with a shield showed long-term durability. The magnetic fluid seal remained in perfect condition for 217 days and 275 days.

The purpose of this study was to investigate mechanisms of long-term durability in water of a magnetic fluid seal with a shield. Behaviors of magnetic fluids in a magnetic fluid seal were studied both experimentally and computationally.

II. Methods

The magnetic fluid seal consisted of a magnet (Nd-Fe-B magnet, H_c: 1.14 MA/m, Br: 1.26 T, ID: 3.6 mm, OD: 8 mm, L: 1 mm) sandwiched by pole pieces (SUS420, ID: 3.1 mm, OD: 8 mm OD, L: 1 mm) (Fig. 1). The magnetic fluid seal was installed on a rotating shaft (3.0 mmϕ) of a centrifugal pump. The gap between the pole piece and the shaft was 50 μm. The gap was filled with two microliters of magnetic fluid (Ferrotec Exp. 03045, Saturated magnetization: 47.9 kA/m, Viscosity: 0.568 Pas, Density: 1.621 g/cm^3). The shield was made of a non-magnetic material (SUS303). The thickness was 1 mm,

Y. Mitamura was with the Graduate School of Information Science and Technology, Hokkaido University, Sapporo 005-0005, Japan. He is now an Emeritus Professor (phone: +81-11-812-3690; fax: +81-11-812-3690; e-mail: ymitamura@ par.odn.ne.jp).

T. Yano is with the Department of Machine Intelligence and Systems Engineering, Faculty of Systems Science and Technology, Akita Prefectural University, Yuri-Honjo 015-0055, Japan (e-mail: yano@akita-pu.ac.jp).

E. Okamoto is with the Department of Human Science and Informatics, School of Biological Science and Engineering, Tokai University, Sapporo 005-8601, Japan (e-mail: okamoto@tspirit.tokai-u.jp).

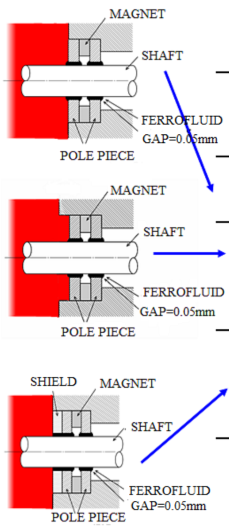

Table 1 Results of long-term tests in water

Seal	Shield	Position of megnetic fluid	Life (Day)	Motor Speed (rpm)	Outlet Pressure (mmHg)	Flow Rate (L/min)
Seal A	No	Water level	6	5248	161	4.0
	No	Water level	11	5104	164	4.2
Seal B	No	One mm below water level	20	5142	167	3.9
	No	One mm below water level	73	5172	171	5.0
Seal C	Yes	One mm below water level	275	4243	150	4.0
	Yes	One mm below water level	217*	5049	175	3.9

* Inlet and outlet tubes were mistakenly kinked.

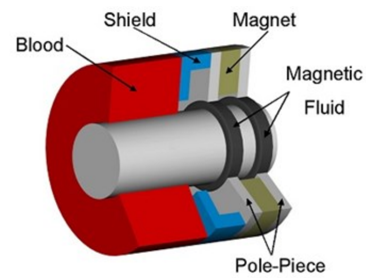

Fig. 1 Magnetic fluid seal with a shield.

and the gap between the shield and the shaft was 50 µm. The objective of installing the shield was to minimize the influence of pump flow on the magnetic fluid.

A. Behaviors of magnetic fluids in a magnetic fluid seal

Behaviors of magnetic fluids were observed in three different conditions: (a) magnetic fluid in air (Fig. 2(a)), a condition in which the magnetic fluid seal was used in air without a shield, (b) magnetic fluid in water (Fig. 2(b)), a condition in which the magnetic fluid seal was used in water without a shield, and (c) magnetic fluid in water covered with an acrylic plate (substitute for a shield) (Fig. 2(c)), a condition in which the magnetic fluid seal was used in water covered with an acrylic plate. Behaviors of magnetic fluids were observed by using a stereoscopic microscope (Nikon, SMZ-10) and a video camera (Sony, DCR-TRV70) and were recorded on videotape (30 frames/sec). Rotational speed of the shaft was changed from 3610 rpm to 5868 rpm. High-speed images of behaviors of magnetic fluids were also captured by a high-speed microscope (Keyence, VW-9000) at a frame rate of 4000 frames/s. Rotational speed of the shaft was changed from 4186 rpm to 5862 rpm. Images on the videotape were captured into a computer in MPEG format. Images for 2 seconds were trimmed and stored in AVI format. The dynamic images were converted into static BMP images. Each image size was 720 pixels times 480 pixels. The BMP images were converted into raw image formats. A region of interest (ROI) was set on a line crossing over the magnetic fluids. RGB color values at each pixel on the line were read and the brightness was calculated by (R value + G value + B value) / 3. Mean brightness of images was calculated for each pixel. Magnetic fluids were identified by pixels having a brightness of less than the threshold that was determined beforehand by identifying the magnetic fluid on the static BMP images.

B. Computational fluid dynamics (CFD) analysis of a magnetic fluid seal

A magnetic fluid seal was modeled to analyze flow in a shield chamber (Fig. 3). One side of the shield chamber was closed with a pole piece and magnetic fluid. The other side was open to a pump chamber through a narrow doughnut-shaped channel with a clearance of 0.05 mm and a length of 0.5 mm. A pump chamber was modeled by a reservoir of 10 mm in diameter and 3 mm in height.

For CFD analysis the magnetic fluid seal model was divided into 10 blocks. Each block was divided into 30×18×30 hexahedral elements. CFD analysis was conducted using CFX 11.0 (ANSYS). Unsteady incompressible Navier-Stokes equations were solved with a finite volume method. The calculations were performed up to 1.0 s with a time step of 0.1 msec. The density and viscosity of fluid were set to be 997 kg/m^3 and 0.8899 mPas, respectively. Boundary conditions were as follows. The shaft surface rotated at 7000 rpm. Opening pressure of 0 Pa, and radial, circumferential and axial velocity components (u_r,u_θ,u_z) of 0 m/s were applied to the upper surface of the pump chamber. A non-slip condition was applied to all other surfaces. Initial conditions were as follows. Initial velocities (r-, θ- and z-directions) were zero and initial pressure was zero.

III. Results

A. Behaviors of magnetic fluids in a magnetic fluid seal

Behaviors of a magnetic fluid in air are shown in Fig. 4. Sixty pixels in the horizontal axis correspond to nearly one mm. The magnetic fluid rotated stably in air. The locus of the

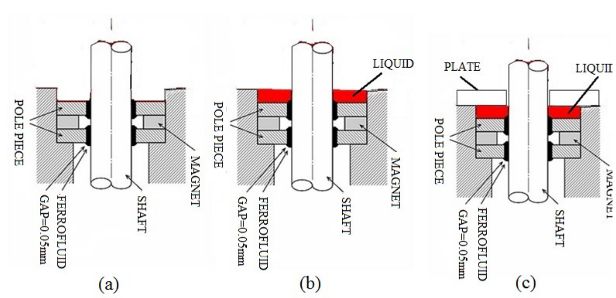

Fig. 2 Magnetic fluid seals (a) in air, (b) in water and (c) in water covered with a plate.

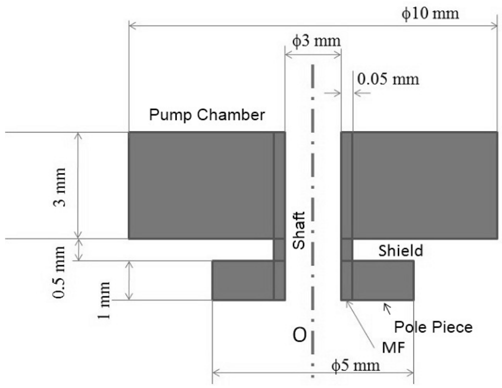

Fig. 3 Model of a magnetic fluid seal for CFD analysis.

magnetic fluid differed slightly at each speed. The widths of the magnetic fluid, however, were almost the same.

Behaviors of a magnetic fluid in water are shown in Fig. 5. The outer position of the magnetic fluid changed with increase of speed. When more water was poured on the pole piece and motor speed was increased, the surface of the water waved.

Behaviors of a magnetic fluid in water covered with an acrylic plate are shown in Fig. 6. The locus of the magnetic fluid was more stable than that in water without an acrylic plate. The surface of the water was stable even at high motor speeds because the water was covered with an acrylic plate.

Behaviors of a magnetic fluid in water covered with a plate during one revolution of the shaft are shown in Fig. 7. The locus of the magnetic fluid during one revolution was stable. High-speed images also showed that water adjacent to the magnetic fluid rotated together with the magnetic fluid.

B. CFD analysis of a magnetic fluid seal

At 60 msec after the start of rotation of the shaft, flow in the shield chamber became stationary and a secondary flow pattern (Taylor vortex) was observed. No flow was observed between the shield chamber and the pump chamber. The velocity vector on a horizontal cross section at 0.1 mm from the pole piece-magnetic fluid surface is shown in Fig. 8. Velocity near the shaft was almost tangential to the shaft. Velocity decreased rapidly in a region of 0.172 mm from the shaft. Circumferential velocities were 0.647 m/s at 0.034 mm from the shaft and 0.342 m/s at 0.069 mm from the shaft.

IV. Discussion

The life of a magnetic fluid seal has been reported to decrease in liquids. It has been reported that the reason for the short life is the instability of the two liquids (magnetic fluid and water in this study) [3, 4]. Influence of pump flow on a magnetic fluid was thought to be a factor causing the instability of a magnetic fluid. In our previous study [7, 8], CFD analyses disclosed velocity profiles in magnetic fluid seals (Seal "B" and Seal "A" in Table 1) installed in an axial

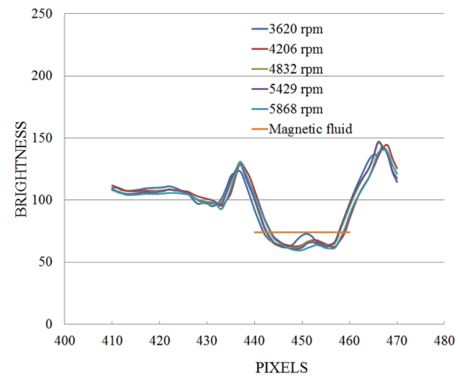

Fig. 4 Behaviors of magnetic fluids in a magnetic fluid seal in air.

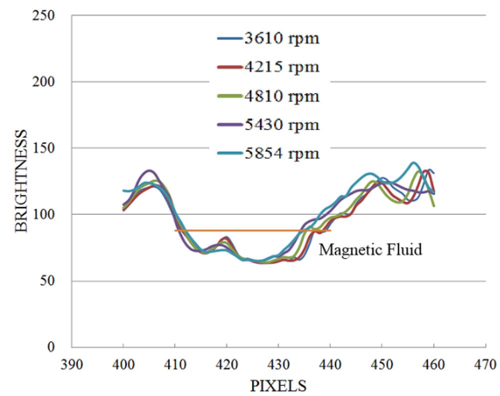

Fig. 5 Behaviors of magnetic fluids in a magnetic fluid seal in water.

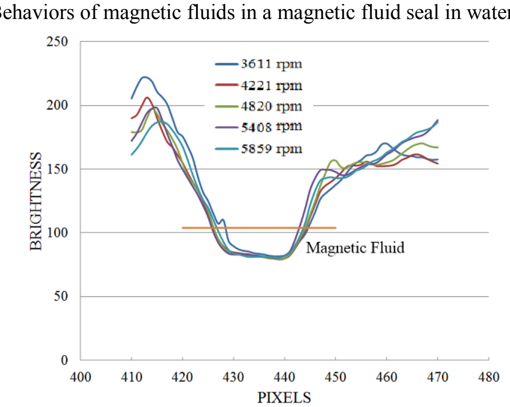

Fig. 6 Behaviors of magnetic fluids in a magnetic fluid seal in water covered with a plate.

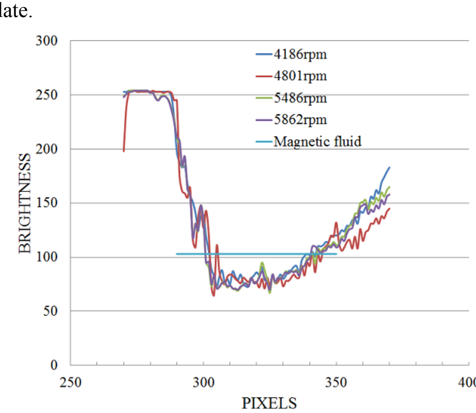

Fig. 7 Behaviors of magnetic fluids in a magnetic fluid seal in water covered with a plate during one revolution of the shaft.

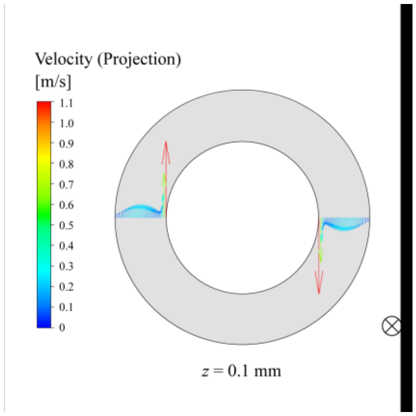

Fig. 8 Velocity vector on a horizontal cross section at 0.1 mm from the pole piece-magnetic fluid surface.

flow pump. Velocity difference between liquid and magnetic fluid was less in Seal "B" than in Seal "A". This decreased velocity difference was thought to contribute to the longer life of Seal "B". In our previous study, however, a magnetic fluid with a shield (Seal "C") was not analyzed. In the present study, the behavior of a plane between moving fluid layers (magnetic fluid and water) in Seal type "C" was investigated both experimentally and computationally.

Magnetic fluid is kept in a gap between a shaft and pole piece by magnetic force. Magnetic fluid rotates with a rotating shaft in a gap. The shape of magnetic fluid in the gap changes due to centrifugal force when rotational speed increases. If centrifugal force exceeds magnetic force, magnetic fluid splashes. Fig. 4 shows that behaviors of a magnetic fluid in air were stable at increased rotational speeds. These results indicate that magnetic force is strong enough for holding the magnetic fluid in the seal. As shown in Fig. 5, the outer position of magnetic fluids, however, changed in water with increase of speed. Water flow near the magnetic fluid in a seal seemed to change the behavior of the magnetic fluid. Moreover, when motor speed was increased, the surface of the water waved. These results suggested that behaviors of magnetic fluids were affected by flow in the seal. In contrast, behaviors of magnetic fluids in water covered with an acrylic plate were stable even at high motor speeds as shown in Fig. 6. Since the shield chamber is almost a closed space, flow in the shield chamber is stable as shown by CFD analyses (Fig. 8). Behaviors of magnetic fluids are not greatly influenced by water flow surrounding the magnetic fluid.

The CFD analyses disclosed that a stable secondary flow pattern appeared in the shield chamber. No flow was observed between the shield chamber and the pump chamber. Flow in the shield chamber was not influenced by the flow in the pump chamber. Velocity near the shaft on a horizontal cross section at 0.1 mm from the pole piece-magnetic fluid surface was almost tangential to the shaft. Magnetic fluid in a gap of 0.05 mm showed a Couette flow. The circumferential velocity of magnetic fluid was 0.352 m/s at 0.034 mm from the shaft. Velocity difference between magnetic fluid and water at the same position was 0.295 m/s. The velocity difference affects instability of the magnetic fluid. The Kelvin-Helmholtz instability condition is given by the following equation [9].

$$(u_b - u_a)^2 > \frac{\rho_b + \rho_a}{\rho_b \rho_a}\left(2(g(\rho_b - \rho_a)\sigma)^{\frac{1}{2}} + \frac{(\mu_a - \mu_b)^2 H_y^2}{\mu_a + \mu_b}\right) \quad (1)$$

where u_a: velocity of water (0.647 m/s), u_b: velocity of magnetic fluid (0.352 m/s), ρ_a: density of water (1×10^3 kg/m^3), ρ_b: density of magnetic fluid (1.621×10^3 kg/m^3), μ_a: permeability of water (1.26×10^{-6} H/m), μ_b: permeability of magnetic fluid (1.32×10^{-6} H/m), Hy: intensity of magnetic field parallel to magnetic fluid-water interface (1 MA/m), σ: interface tension between magnetic fluid and water (0.0466 N/m) and g: gravitational acceleration (9.8 m/s^2). Substituting the above values into (1), we obtain the left hand side of the equation of 8.70×10^{-2} m^2/s^2 and right hand side of the equation of 2.32 m^2/s^2. The instability condition was not satisfied.

The magnetic fluid seal was incorporated into an axial flow blood pump and the pump was implanted in a goat for an acute experiment. However further study is required for long-term test in blood.

V. Conclusion

Both observations of the behaviors of magnetic fluids and CFD analyses of flow in a magnetic fluid seal with a shield disclosed that the interface between magnetic fluids and water is stable. A shield is effective for stabilizing the behavior of a magnetic fluid in water and this prolongs the life of a magnetic fluid seal with a shield in water.

References

[1] F.D. Pagani, L.W. Miller, S.D. Russel, K.D. Aaronson, et al., "Extended mechanical circulatory support with a continuous-flow rotary left ventricular assist device", *J Am Coll Cardiol*, vol. 54, pp. 312-321, Jul 2009.

[2] T. Kitahora, J. Kurokawa, Y. Miyazoe and M. Hayashi, "Seal pressure characteristics of a magnetic fluid seal and an application to a turbopump", *Trans. Japan Soc. Mech. Eng. B*. vol. 60, pp. 3086-3092, Mar 1994.

[3] J. Kurfess. and H.K. Muller, "Sealing liquids with magnetic liquids", *J. Magn. Magn. Mater*, vol. 85, pp. 246-252, Apr 1990.

[4] T. Liu, Y. Cheng and Z. Yang, "Design optimization of seal structure for sealing liquid by magnetic fluids", *J. Magn. Magn. Mater*, vol. 289, pp. 411-414, Mar 2005.

[5] K. Sekine, Y. Mitamura, S. Murabayashi, I. Nishimura, R. Yozu, D.W. Kim, "Development of a magnetic fluid shaft seal for an axial-flow blood pump", *Artificial Organs*, vol. 27, pp. 892-896, Oct 2003.

[6] Y. Mitamura, S. Arioka, D. Sakoto, K. Sekine, M. Azegami, "Application of a magnetic fluid seal to rotary blood pumps", *J. Phys.: Condens. Matter,* vol. 20, pp. 204145(5 pp), May 2008.

[7] Y. Mitamura, S. Takahashi, S. Amari, E. Okamoto, S. Murabayashi, I. Nishimura, "A magnetic fluid seal for rotary blood pumps: Long-term performance in liquid", *Physics Procedia*, vol. 9, pp. 229-233, 2010.

[8] Y. Mitamura, S. Takahashi, S. Amari, E. Okamoto, S. Murabayashi, I. Nishimura, "A magnetic fluid seal for rotary blood pumps: effects of seal structure on long-term performance in liquid", *J Artif Organs*, vol. 14 , pp. 23-30, Mar 2011.

[9] R.E. Rosensweig, *Ferrohydrodynamics*, Mineola, N Y: Dover Publications, 1997, pp.202.