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# Blood sealing properties of magnetic fluid seals

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## ABSTRACT

Shaft seals for rotary blood pumps have strong demands for low friction, very little leakage, and long-term use. Magnetic fluid seals have attracted attention as promising candidates for this purpose owing to their properties of having zero leakage, no wear, and relatively small viscous friction at the same time. In this study, the sealing performance including the maximum sealing pressure and the sealing durability under blood sealing is discussed. In addition, hemolysis tests for blood sealed by magnetic fluids are performed from the viewpoint of biological compatibility. The magnetic fluid seals are found to have adequate sealing durability and pressure resistance in the blood. In addition, hemolysis of blood sealed with the organic-solvent magnetic fluid seals is maintained below 0.5%.

## 1. Introduction

Continuous-flow rotary blood pumps have the advantages of a smaller size and the potential for a higher mechanical efficiency when compared to pulsatile blood pumps. In addition, they have greater mechanical reliability because of the simple pumping mechanism. Various types of rotary blood pumps, in which an impeller is supported by magnetic or hydrodynamic bearings, have been investigated. Direct-drive type blood pumps have been also investigated.

Yamazaki et al. [1] have been developing implantable rotary blood pumps since 1990 and put them to the first practical use in Japan. This type of blood pump has one moving part and an impeller, which is directly driven by a motor. The simple structure is expected to provide a long pump life. However, this type of blood pump requires a shaft seal. The design of a clinically viable shaft seal is the most important and difficult subject in the development of the blood pump. The shaft seal for the blood pump must have extremely high sealing performance, low and steady friction characteristics, a long seal life, and anti-wear properties.

Lip seals were used during the early development of the rotary blood pump. It was demonstrated that in an axial-flow pump, no leakage was observed after 1700 h of in vitro testing with a glycerin solution [2]. However, the sealing function was likely to be reduced in the blood because of blood-element infiltration. Blood proteins flowing into the sealing gap were denatured, aggregated, and adhered onto the sealing surfaces by frictional heating [3].

As a practical solution to the shaft-seal problem, Yamazaki et al. [4] and Tomioka et al. [5] developed a miniature mechanical seal with a purge fluid recirculating system. The inside of the seal surfaces was designed to be directly flushed by the purge fluid (sterile pure water) to prevent frictional heat generation, lubricate the seal surfaces, and remove the adsorbed blood protein. Tomioka et al. [6] investigated the effect of the surface roughness of the mechanical seal upon the friction and leakage characteristics under blood sealing. For further understanding of seal properties, Tomioka et al. [7] estimated, under various operating conditions, how blood and purge fluid would flow into the sealing gap and occupy the space. These investigations showed that the mechanical seal possessed viable properties, even under blood sealing. However, shaft seals are the most common sites of thrombus formation and hemolysis in rotary blood pumps. Recently, Kanda et al. [8,9] demonstrated that a denatured protein film was formed on both seal surfaces after friction tests in blood, causing high and unstable friction.

To avoid such difficulty with the shaft seal, a rotary blood pump with a hydrodynamic thrust bearing for supporting an impeller has been developed, in which the impeller is floated in the blood chamber. It is expected that, by optimizing the groove configurations for blood lubrication, it should be possible to sustain the impeller with very low frictional loss [10–12]. However, it has been reported that hydrodynamic bearings seriously damage blood by the high shear stress in very thin bearing gaps, resulting in the destruction of red blood cells and thrombus formation [13]. Magnetic bearings are also non-contact bearings and are expected to have a long life without wear. They allow for a large bearing clearance that can decrease the shear stress in that area, and cause little blood damage [14]. Hence, many researchers have attempted to apply magnetic bearings to centrifugal blood pumps [15–17]. However, a completely passive magnetic bearing is not possible

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and thus at least one degree of freedom must be compensated by an active magnetic bearing. This means that magnetic bearings need many actuators and displacement sensors for stable operation, increasing the system complexity and consumed power. In addition, the bearing stiffness in the radial and axial directions is low for actual use in rotary blood pumps [18].

Recently, magnetic fluid seals have been investigated for rotary blood pumps as another promising candidate for the shaft seal. Magnetic fluid seals were developed in the 1960s as a means of controlling rocket fuel, and their use has been extended to other applications [19]. They function without rubbing contact with the rotating shaft surface, and hence, there is no wear. A magnetic fluid bridges the clearance gap around the shaft and perfectly blocks leakage while still allows the shaft to rotate with relatively small viscous frictional loss. In addition, it does not require high-precision machining like mechanical seals. Therefore, developing a clinically viable magnetic fluid seal is extremely valuable for rotary blood pumps. Mitamura et al. [20] developed a magnetic fluid seal with a shield mechanism. The objective of installing the shield is to minimize contact between the sealed water and the magnetic fluid seal. The gap between the shield and the shaft was set to 50 μm, which is the same as that between the pole piece and the shaft. They installed the seal system in an axial-flow pump and investigated its performance. However, the effect of contact with blood upon the performance of the magnetic fluid seals was not investigated.

In this study, the blood sealing properties of magnetic fluid seals are investigated for rotary blood pumps. The shield mechanism was not applied in this investigation in order to perform acceleration tests and to clarify the effect of blood upon the seal performance. The pressure resistance and sealing durability are experimentally examined under blood sealing, and compared with the results obtained using water. In addition, hemolysis tests for blood sealed by magnetic fluids are performed after the sealing tests from the viewpoint of biological compatibility.

## 2. Experiment

### 2.1. Experimental apparatus

Fig. 1 shows a schematic of the experimental apparatus designed for this study. Blood is sealed in a chamber by a magnetic fluid seal. The pressure of the sealed blood is controlled by a compressor and a pressure tank. The pressure-time history is memorized by a computer. A conventional magnetic fluid seal is installed in this apparatus. As shown in Fig. 2, a samarium-cobalt magnet (residual magnetic-flux density: 0.92–1.05 T) is sandwiched between two pole pieces (SUS630, magnetic permeability: $4.02\times10^{-4}$ H/m). The radial clearance between the pole piece and the shaft is set to 400 μm, which is larger than the conventional setting (50 μm) because of the performance of acceleration tests. For the same reason, the magnetic fluid seal is built for only one side of the pole pieces. As shown in Table 1, four kinds of magnetic fluids are used in this study: a water-solvent (W-40) and organic-solvent (N-504, HC-50, and A-400) magnetic fluids.

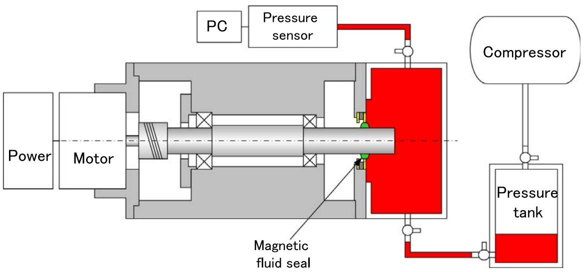

**Fig. 1.** Schematic of the experimental apparatus.

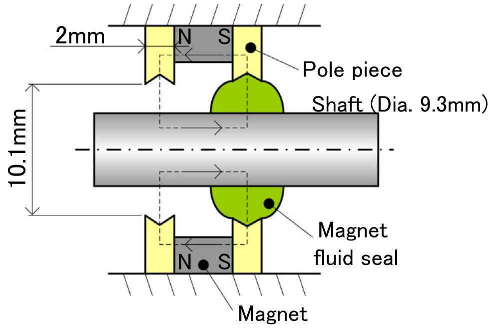

**Fig. 2.** Schematic of the magnetic fluid seal.

**Table 1**
Magnetic fluid data.

| Magnetic fluid | Solvent | Saturation magnetization T | Viscosity Pa s (298 K) | Specific gravity |
|---|---|---|---|---|
| W-40 | Water | 0.038 | 0.025 | 1.40 |
| HC-50 | Kerosene | 0.048 | 0.022 | 1.39 |
| N-504 | Isoparaffin | 0.055 | 0.022 | 1.40 |
| A-400 | Alkyl-naphthalene | 0.040 | 0.370 | 1.34 |

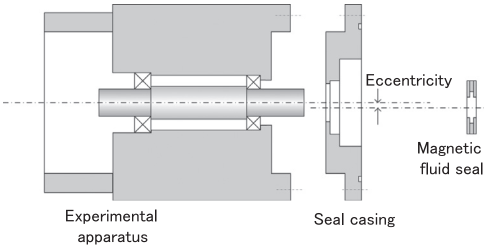

**Fig. 3.** The method of setting eccentricity.

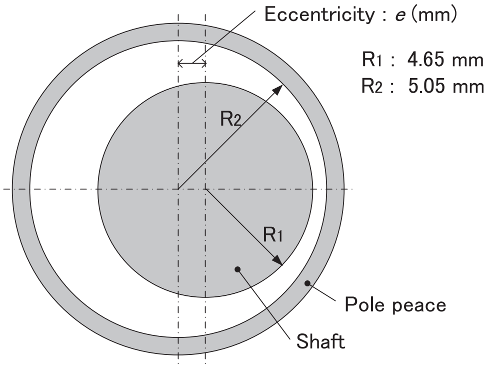

**Fig. 4.** Eccentricity of the shaft.

The magnetic fluid seal is held on the seal casing with eccentricity $e$, as shown in Figs. 3 and 4. The eccentricity ratio is defined as shown in Eq. (1):

$$\varepsilon = \frac{e}{C} \tag{1}$$

where $C$ ($C=R_2-R_1$) is the radial clearance and $e$ is the eccentricity of the shaft with respect to the seal casing. Four kinds of seal casings ($\varepsilon$=0, 0.25, 0.50, 0.75) are used in this study.

### 2.2. Pressure resistance tests

The pressure resistance in blood is an important performance for the shaft seals used in rotary blood pumps. In this study, the maximum sealing pressure, which is the pressure just before the loss of the sealing function, is obtained by continuously increasing the sealing pressure