Development of Miniaturized Regenerative Pump using Axial Self-Bearing Motor

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Abstract: This paper describes the structure and performance of miniaturized regenerative pumps with an axial self-bearing motor. Two types of pump are introduced: a single-type pump, which has one flow channel on one side of the rotor driven by a single-type axial gap self-bearing motor, and a push-pull-type pump, which has two flow channels on both sides of the rotor driven by a push-pull-type axial gap self-bearing motor. Pump performance and efficiency are evaluated, and the feasibility of the proposed pumps is discussed.

Keywords: Axial Self-Bearing Motor, Regenerative Pump, Canned Pump, Pump Efficiency, Motor Efficiency

Introduction

In recent years, the demand for the development of fuel cells has been increasing. It is expected that the market for small-sized fuel cells for home and mobile devices will grow earlier than that of other applications[1-3]. However, it is important to improve not only the body of the fuel cells but also the peripheral devices involving a fuel supply pump for their widespread use of the fuel cells. In particular, the improvement of reliability and cost of the fuel supply pump is very essential. Several pumps such as electromagnetically driven piston pumps and piezoelectric actuated diaphragm pumps, have been proposed, but these have several disadvantages: low flow rates, pulsatile pressure, high cost and low reliability. In order to solve these problems, we propose a miniaturized regenerative pump.

The regenerative pump is a type of rotary pump[4]. It consists of a casing and an impeller with a number of vanes. Fluid friction caused by the rotating impeller generates fluid pressure. The regenerative pump is considered suitable for the fuel cells, because it produces a large head at comparatively small flows. The impeller is generally driven by the motor installed outside of the casing. The impeller and motor are connected by a shaft that passes through a hole made in the partition. The hole is sealed by a mechanical seal, such as an O-ring, however it has a short-lifespan. Therefore, a driving method without mechanical seals is required. Moreover, non-contact bearings are desirable to extend the life of the pump[5-8]. In order to meet these demands, we have proposed a driving and supporting system that utilizes an axial self-bearing motor (ASBM) [9,10].

The ASBM is a combination of a disc motor and a thrust magnetic bearing, and can simultaneously produce rotating torque and control the axial position of the rotor. Since a single rotating flux performs both functions, the ASBM has a simpler stator structure than the radial-type self-bearing motor, which requires two types of the rotating fluxes. Moreover, the ASBM can support the rotor without mechanical contact by combining the passive magnetic bearing, as the result the control system becomes simple.

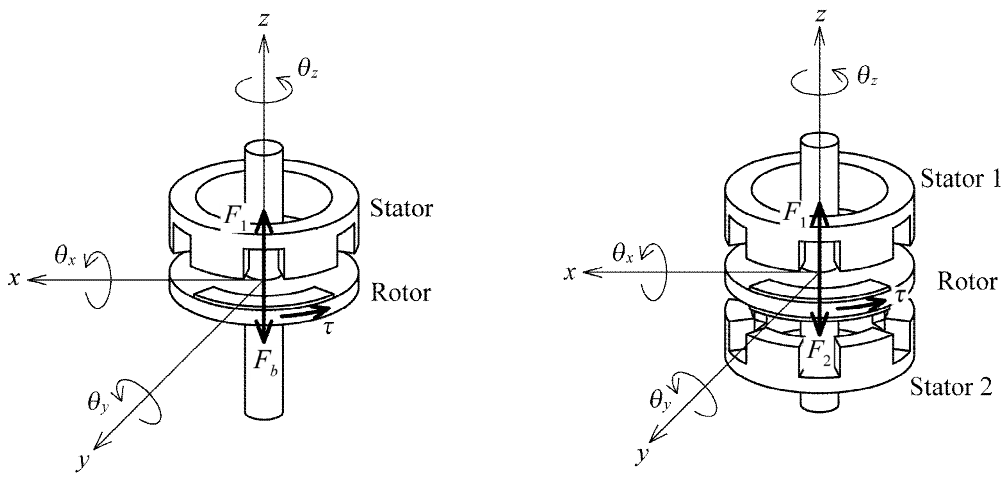
This paper introduces two types of the regenerative pumps that utilize ASBM; one is the single-type pump, which has one flow channel on one side of the impeller, and the other is the push-pull-type pump, which has two flow channels on both sides of the rotor. The pump performance and efficiency are measured and the feasibility of the proposed pumps is discussed.

Axial Self-bearing Motor

The ASBM can be using a permanent magnet motor, an induction motor and a reluctance motor. The permanent magnet ASBM is used in regenerative pump because it generates a large torque and has high efficiency as compared to the other types of motors. Fig. 1 (a) shows the structure of a single-type ASBM, and Fig. 1 (b) a push-pull-type ASBM. The single-type ASBM consists of a permanent magnet rotor and a stator, which has 3-phase winding, whereas the push-pull-type ASBM consists of a rotor and two stators. In the single-type ASBM, since the stator can produce only attractive force, a bias force, which is opposite directional force to the attractive force, is required. The single-type ASBM has a simpler structure and control system than that of the push-pull ASBM, however, the rotating torque is limited by the magnitude of the bias force. In the push-pull-type ASBM, the stator can produce bidirectional force, hence, it does not require a bias force.

Both the ASBMs control the axial force and rotating torque through single rotating magnetic flux. Hence, the stator structure is similar to a conventional disc motor. The rotating torque is controlled by the phase difference between the angular position of the rotor and the stator current or quadrature axis current, whereas the axial force is controlled by the amplitude of the rotating magnetic flux or direct axis current. The rotating torque and axial force can be independently controlled using vector control method. In this paper, two regenerative pumps having single- and push-pull-type ASBMs have been introduced and compared.

Note that the ASBM controls only axial direction, and cannot control other directions, radial displacement or tilt motions. In this paper, the radial directions are supported by passive bearings.



(a) Single-type ASBM (b) Pusu-pull type ASBM

Fig. 1 Structures of axial self-bearing motors

Pump Structure

Single-type Pump. Fig. 2 shows the single-type pump structure, which has one flow channel on one side of the rotor. The impeller is supported by two permanent magnet bearings (PMBs) and a single-type ASBM. The ASBM produces a rotating torque and an attractive force between the rotor and the stator. The PMBs produce a restoring force in the radial directions and a bias force in the axial direction. The rotor rotates while balancing the bias force as well as the attractive force.

The PMBs are placed on the upper and lower sides of the rotor. The PMB consists of two cylindrical neodymium iron magnets which are magnetized along the axial direction. Dimensions of the rotor magnet are $\phi 3 \times 5$, and those of the stator magnet are $\phi 8 \times \phi 4 \times 3$.

The stator of the ASBM was made from laminated silicon steal. It has an outer diameter of 21 mm, inner diameter of 13 mm and six concentrated wound poles of copper wire, each having 60 turns of ϕ0.26 mm of copper wire. The rotor is a flat disc which has a diameter of 21 mm and two neodymium iron magnets, each having a thickness of 1mm, to create two poles. In order to measure the axial position of the rotor, three eddy-current-type displacement sensors have been installed.

Fig. 3 shows the geometry of the flow channel of the single-type pump. The impeller has 16 vanes on the side opposite the ASBM. The air gap between the pump housing and the impeller was set at 0.02 mm.

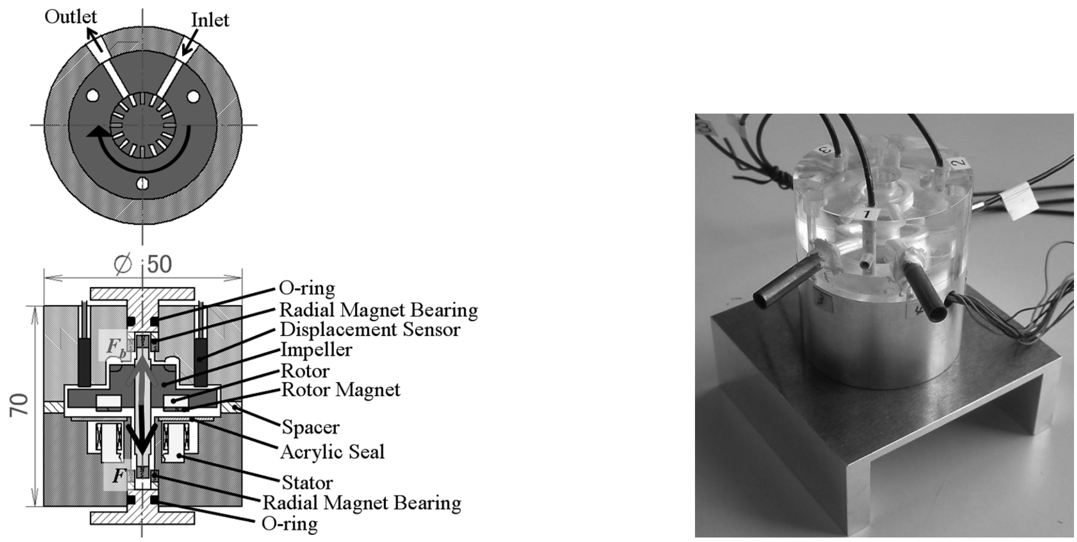


Fig. 2 Structure of single-type pump

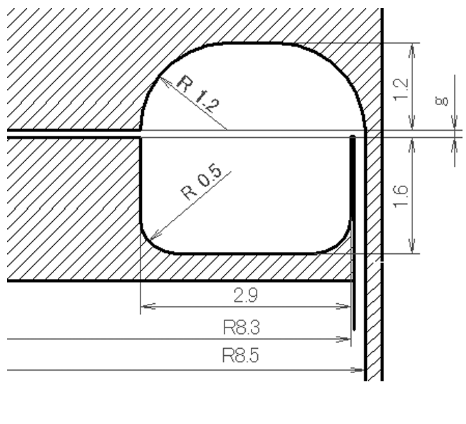


Fig. 3 Schematic of flow channel geometry of single-type pump

Push-pull-type Pump. Fig. 4 shows the structure of the push-pull-type pump, which has two flow channels on both side of the rotor. The rotor is supported by the push-pull-type

ASBM and a fluid bearing. The stator and rotor are of the same type as those in the single-type pump. A plastic slide bearing, which has larger tolerance as compared to a conventional one has been used for the fluid bearing.

Fig. 5 shows the geometry of the flow channel of the push-pull-type pump. The impeller has 18 vanes and a diameter of 42 mm. The air gap between the pump housing and the impeller is 0.1 mm.

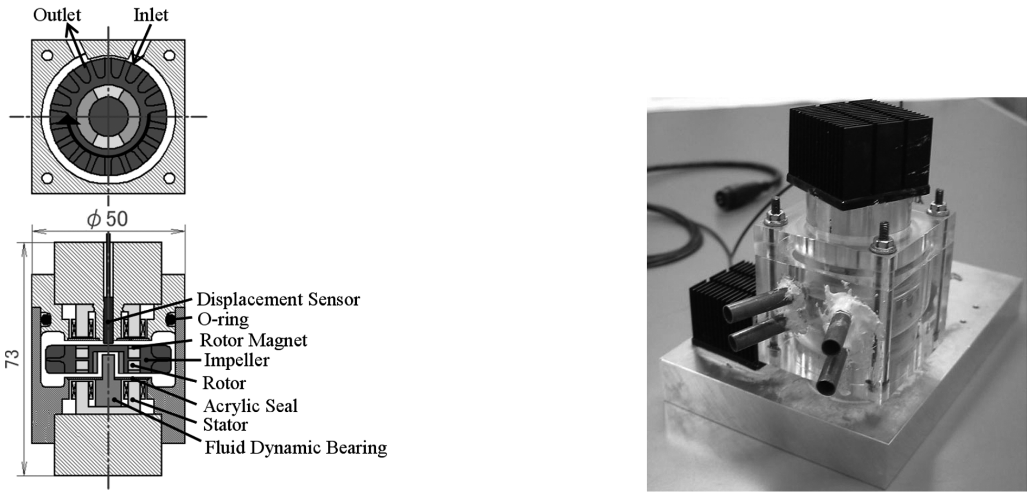


Fig. 4 Structure of push-pull-type pump

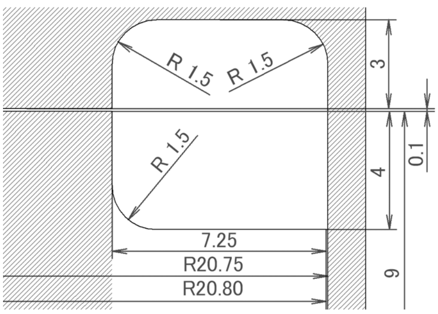
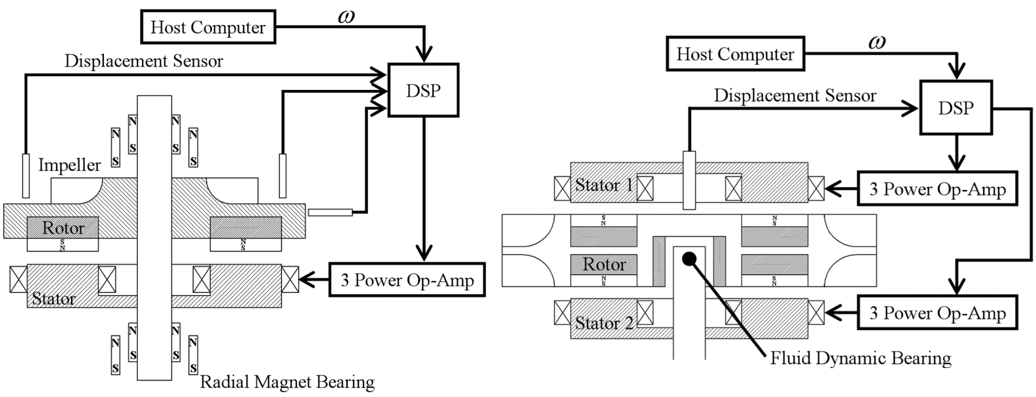


Fig. 5 Schematic of flow channel geometry of push-pull type pump



(a) Single-type pump (b) Push-pull-type pump

Fig. 6 Control system

Control System. Fig. 6 shows the control system. A digital signal processor (DSP) was used for the motor control. The DSP obtained the displacement signals via A/D converters, and then calculated the motor currents. Motor currents were derived from the motor controller and the axial position controller. In these pumps, in order to make the system simple, an open loop torque controller, which uses three-phase current with constant amplitude and frequency, was used for motor control. This controller does not require rotor angular position data, and therefore the system becomes simple. A digital PID controller was used for the position control. The transfer function of the digital PID controller is

$$G(z) = K_p + \frac{K_d(z-1)}{T_d(z - e^{-\tau/T_d})} + \frac{K_i \tau z}{z-1} \tag{1}$$

where K_p is proportional gain, K_d is derivative gain, K_i is integral gain, T_d is a derivative time constant, and τ is the sampling interval, respectively. The control current I_c is calculated by the PID controller. The stator currents for the single type pump were calculated using

$$\begin{aligned} i_u &= (I_m + I_c)\cos(\omega t) \\ i_v &= (I_m + I_c)\cos(\omega t - 2\pi/3) \\ i_w &= (I_m + I_c)\cos(\omega t - 4\pi/3) \end{aligned} \tag{2}$$

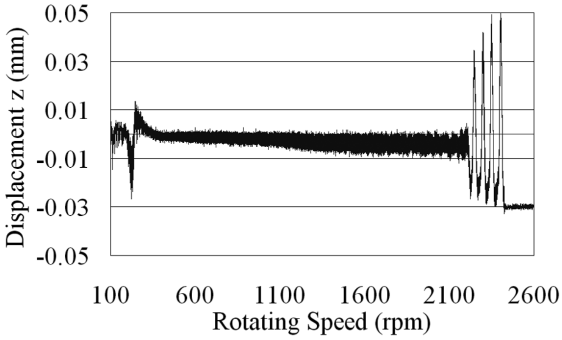
where I_m is amplitude of motor current, ω is angular velocity, and t is time, respectively. The stator currents for the push-pull type pump were calculated using the following equations.

$$\begin{aligned} i_{1u} &= (I_m + I_c)\cos(\omega t) \\ i_{1v} &= (I_m + I_c)\cos(\omega t - 2\pi/3) \\ i_{1w} &= (I_m + I_c)\cos(\omega t - 4\pi/3) \\ i_{2u} &= (I_m - I_c)\cos(\omega t) \\ i_{2v} &= (I_m - I_c)\cos(\omega t - 2\pi/3) \\ i_{2w} &= (I_m - I_c)\cos(\omega t - 4\pi/3) \end{aligned} \tag{3}$$

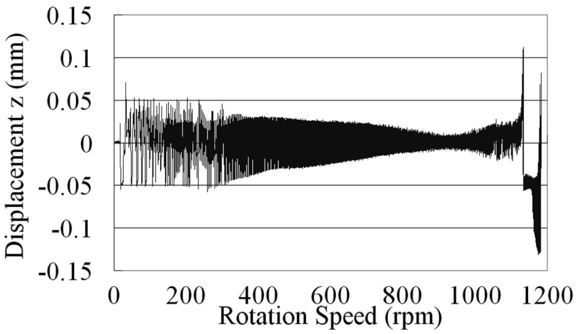
Then the DSP outputs current signals to power amplifiers through D/A converters. Power operational amplifiers were used to supply the stator currents to each winding.

Results

Levitation Tests. Fig. 7 shows the results of the acceleration test when the pump outputs the maximum pressure. Fig. 7 (a) shows the results of the single-type pump. The single-type pump rotated up to 2200 rpm; however, the maximum rotation speed was limited due to current saturation. The rotor position stayed at 0 mm, and the amplitude of the vibrations was less than 0.01mm, except around 300 rpm. Fig. 7 (b) shows the results of the push-pull-type pump. The rotor speed was 1100 rpm. The maximum rotation speed of push-pull-type pump was also limited by the current saturation. The amplitude of the vibrations was larger than that of the single-type pump. Since the stator had slots and the air gap flux was not ideal, the attractive force between the stator and the rotor was affected by the rotor angular position. The push-pull-type ASBM has two pairs of stators and rotors, hence it is assumed that the push-pull type ASBM was more affected than the single type ASBM.



(a) Single-type pump



(b) Push-pull-type pump

Fig. 7 Axial displacement during acceleration test

Pump Performance. Water pumping tests were performed. Fig. 8 shows the flow-pressure properties of the single- and push-pull-type pumps. The maximum water head discharged by the single-type pump was about 7.5 kPa, whereas it was 10 kPa for the push-pull-type pump. The maximum flow-rates of the single- and push-pull-type pumps were 150 and 450 ml/min, respectively. The push-pull-type pump had a higher water head and flow rate because its impeller had a larger diameter. In order to compare the performance of the two types pf pumps, water head and flow rate were transformed into dimensionless values using following equations:

$$\psi = \frac{2gH}{U^2}, \quad \phi = \frac{Q}{AU} \tag{4}$$

where ψ is head coefficient, ϕ is flow coefficient, g is the acceleration due to gravity, H is the head, U is circumferential velocity, Q is flow rate, and A is the cross-sectional area of the flow channel, respectively. Fig. 9 shows the dimensionless flow-pressure property of both pumps. This result shows that the push-pull-type pump had lower flow coefficient and head coefficients than the single-type pump. One of the reasons for this is that the geometry of the flow channel of the push-pull-type pump was not appropriate. It had a particularly large air gap between the housing and impeller.

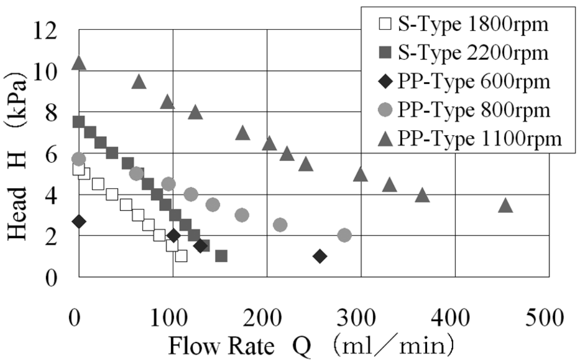


Fig. 8 Flow-Pressure Property

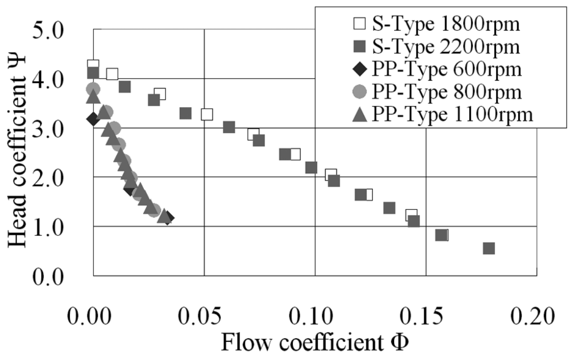


Fig. 9 Flow-Pressure Property (Dimensionless)

Water Power and Input Power. Water power of the pump was calculated using

$$L_w = \left(\frac{\rho g}{1000}\right)\left(\frac{Q}{60}\right)H \tag{5}$$

where ρ is the density of water (998 kg/m^3). Fig. 10 shows the water power property. The water power increased with an increase in the rotating speed. The water power of the push-pull-type pump was 4.8 times larger than the single-type pump. This is because the impeller of the push-pull-type pump had a diameter 2.5 times that of the single-type pump. Fig. 11 shows the input power. It was calculated from the measured coil voltage and current. In the single-type pump, the input power decreased with an increase in flow rate, whereas the input power of the push-pull-type pump did not change. In the single-type pump, the bias force increased with an increase in the water pressure. Hence, the control current increased to balance the attractive force and bias force. On the other hand, in the push-pull-type pump, the control current was not affected by the flow rate because water pressure was generated on both sides of the rotor. Hence, the motor currents were almost constant.

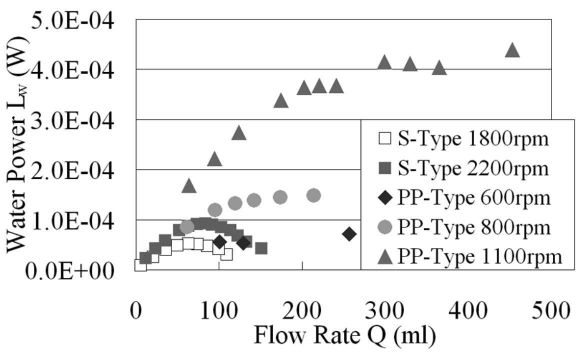


Fig. 10 Water Power Property

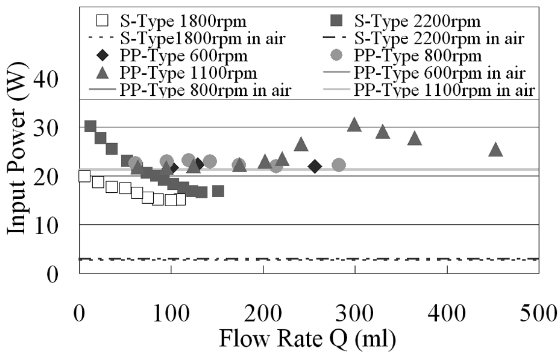


Fig. 11 Input power Property

Pump Efficiency. Fig. 12 shows the overall efficiency of the pumps. The overall efficiency of the single-type pump was about 4×10^{-4} %, wheseas the overall efficiency of push-pull-type pump was about 1.8×10^{-3} %. These values were calculated from the water and input power. The overall efficiencies were quite low. In order to determine the reason for this, pump and motor efficiency were estimated. The motor output power L was estimated from

$$L = P_{all} - P_c - P_b \tag{6}$$

where P_{all} is the input power, P_c is copper loss in the coil, and P_b is the bearing loss. P_b was estimated from the input power of the rotational test in the air. Figs. 13 and 14 show the pump and motor efficiency, respectively. Efficiencies of both types of pump were quite low as compared to the motor efficiencies, therefore, it was confirmed that the problems of these pumps were due to the pomp efficiency. The motor efficiencies were also not good, however, they can be improved by using vector control method. Hence, in order to improve the overall efficiency, it is necessary to improve the pump efficiency. The pump efficiency of the push-pull-type pump was 16.5 times as larger than the single-type pump. Therefore, it is considered that the push-pull-type pump is appropriate to be used as a regenerative pump.

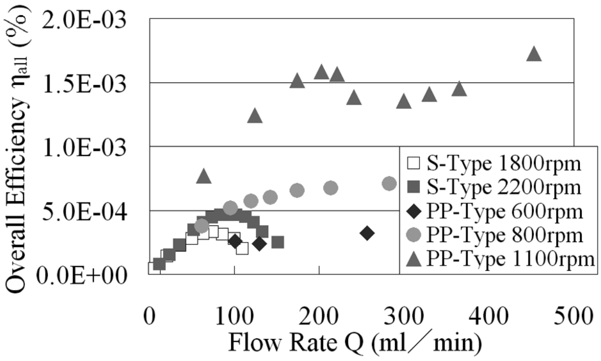


Fig. 12 Overall efficiency

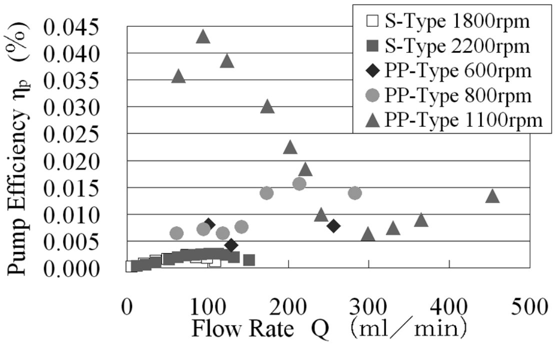


Fig. 13 Pump efficiency

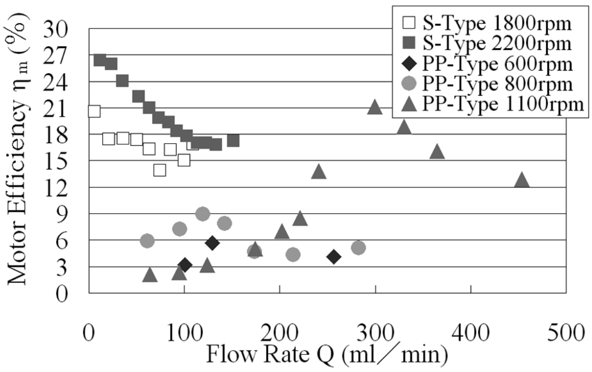


Fig. 14 Motor efficiency

Summary

This paper has introduced two types of regenerative pumps. These pumps could discharge water without leakage. However, pump performance and efficiency were quite low. The major reason for this is considered to be inappropriate flow channel geometry. The development of a low-cost miniaturized regenerative pump with high reliability by improving the flow channel geometry is proposed.

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