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VIBRATION-TYPE RESONANCE PUMP WITH HIGH EFFICIENCY AND FLOW RATE

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ABSTRACT: Environmentally friendly, high-output, high-efficiency compact pumps are in high demand in industrial fields such as chemical analysis and medical care. The efficiency of many small pumps is rather low, with peak efficiencies on the order of about 2%, even for commercially available pumps. Considering current environmental issues, improving the efficiency of motors and pumps is an important issue for preventing global warming. In this research, a small two-valve pump that can suck and discharge water by converting the energy of electromagnetic-vibration component resonance into kinetic energy was newly developed. In actual machine tests, two types of electromagnetic vibration pumps (I and II) with two-valve structures and different shapes were prototyped, and the shapes were optimized for efficiency. The type II vibration pump with an acrylic rod attached to the type I pump had excellent suction and discharge characteristics. The maximum efficiency was 12.2%, which is exceptional for a small pump. In addition, it was clarified by the actual machine test that the type II pump can stably discharge water at a high head of 2000 mm. The two types of pumps proposed in this paper were shown to be highly useful industrially in terms of performance, simplicity, cost, and operability and can be used selectively according to the application. Furthermore, since these pumps can be manufactured with a small number of parts, this paper shows their potential to contribute to environmental issues.

Keywords: Pump, Vibration, Optimized shape, Pumping head, Efficiency

1. INTRODUCTION

Environmentally friendly, high-output, high-efficiency compact pumps are in high demand in industrial fields. In the medical and welfare fields, in particular, there is a high demand for inexpensive, disposable, small pumps for diagnostic and therapeutic devices, testing and measuring equipment, and other applications. Furthermore, small pumps are needed for the purpose of pumping liquid in microtasks used in biotechnology and chemical analysis. In these fields, the miniaturization of pumps allows for energy and space savings, as well as safety and satellite considerations. For this reason, various designs have been proposed, such as axial flow pumps [1], centrifugal pumps [2-4], diaphragm pumps [5], and rotary pumps [6-8], and their operating principles have been almost completely established. These pumps have a built-in electromagnetic motor, and their flow rate and efficiency mainly depend on the characteristics of this motor. As such, the efficiency of these small pumps is rather low, with peak efficiencies on the order of about 2%, even for commercially available pumps. Pumps without built-in electromagnetic motors have also been proposed, and many pumps using piezoelectric ceramics [9-12] have been developed.

Such pumps can be directly driven and exhibit higher efficiency than pumps with built-in electromagnetic motors. However, the maximum efficiency of commercial piezoelectric pumps is less than 5%. Usually, mechanical vibration and noise are harmful and must be reduced [13-16]. On the other hand, the authors have proposed a small vibration pump that can be directly driven without using an electromagnetic motor [17, 18], and demonstrated its flow rate in an actual machine test.

However, the maximum head capacity of this pump at suction was 500 mm, which was insufficient for an industrial pump. In the present study, in order to significantly increase suction performance, a small two-valve pump that can suck and discharge water by converting the energy of electromagnetic-vibration component resonance into kinetic energy was newly developed. In actual machine tests, two types of electromagnetic vibration pumps (I and II) with two-valve structures and different shapes were prototyped, and the shapes were optimized for efficiency. Considering current environmental issues, improving the efficiency of motors and pumps is an important issue for preventing global warming. It was shown that the small vibration pump having the type I shape has fewer parts, better water suction characteristics, and higher efficiency than commercially available pumps. The type II vibration pump, which uses the inertia effect of acrylic rods, has excellent water suction and discharge characteristics. Its maximum efficiency was 12.2%, which is exceptional for a small pump. In addition, it was clarified by an actual machine test that the type II pump can stably discharge water at a high head of 2000 mm. The two types of pump proposed in this paper were shown to be highly useful industrially in terms of performance, simplicity, cost, and operability, and can be used selectively according to the application.

The pump proposed in this paper has a very simple structure and good controllability and has shown a head capacity of 1000 mm of suction. In addition, by tuning the resonant frequency of the vibration component inserted in the pump to the frequency of the power outlet, the pump can be operated without a drive unit. Therefore, this vibration pump is applicable not only in the fields of medical and chemical analysis but also in a wide range of industrial fields.

Further improvement of efficiency and downsizing should be considered as future tasks. For this purpose, a theoretical analysis that combines vibration and fluid flow is needed, along with a magnetic field analysis of the magnetic circuit of the vibration component proposed by the authors [19].

As mentioned above, many small pumps that operate on various principles have been developed, but their efficiency is very low. The purpose of this study is to propose a new small vibration pump with excellent suction and discharge characteristics and an efficiency exceeding 10% at low head. Actual machine tests have shown that the pump exhibits twice the efficiency of commercial products.

2. RESEARCH SIGNIFICANCE

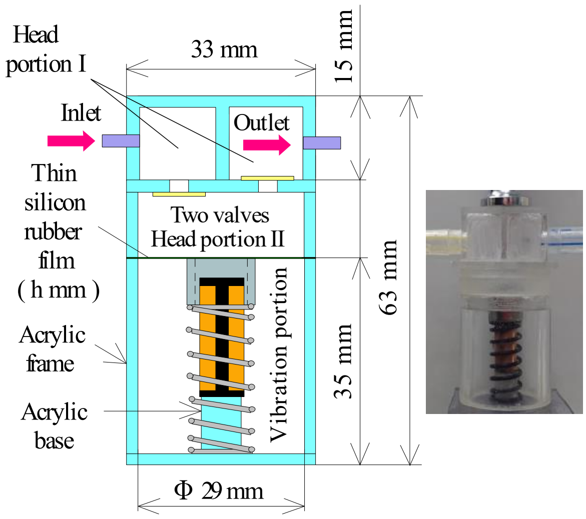
Flow and efficiency characteristics in commercial pumps depend almost exclusively on the characteristics of the electromagnetic motor. For this reason, the efficiency of small pumps is quite low, with a maximum efficiency of about 2%. Considering the current global environment, the development of high-efficiency pumps is one of the most important issues. The significance of this research is to establish a new high-efficiency pump operating principle and it is to solve the needs of industry.

3. STRUCTURE OF TYPE I VIBRATION PUMP

Fig. 1 shows a schematic of a small electromagnetic vibration pump with the type I shape that was prototyped for pumping water. This vibration pump consists of a vibration component, an electromagnet, an acrylic casing, a thin silicone rubber film, and suction and discharge valves, and has a very simple structure. To prevent contact between the water and the vibration components, this pump has a thin silicone rubber film with a thickness of h [mm] installed on top of the vibration components. In this figure, the area above the thin rubber film is defined as the head portion, and the area below the thin film is defined as the vibration portion. The head portion is defined as head portions I and II, with the valve part as the boundary. Water flows into the head portion, and only air is injected into the vibration portion. Since the vibration component vibrates in air, the viscous damping of water does not work on the vibration component. The valve is a two-valve system for suction and discharge. In the head portion, I have holes 6 mm in diameter for the water inlet and outlet.

As shown in Fig. 2, the vibration component consists of a permanent magnet and a compressed coil spring. The permanent magnet is a NdFeB ring-shaped magnet with two poles magnetized on both sides. It has an outer diameter of 12 mm, an inner diameter of 9 mm, and a height of 5 mm. The surface magnetic flux density is 384 mT. A coil spring with a free length of 25 mm, an outer diameter of 12 mm, and a spring constant of k = 1,836 N/m was used. An iron core with a bobbin shape (Fig. 2) is used for the excitation electromagnet. The iron core is wound with 1200 turns of copper wire 0.2 mm in diameter to form an electromagnet. Combining a ring-shaped permanent magnet and a bobbin-shaped permanent magnet efficiently converts the electromagnetic force into an excitation force [19]. The bobbin-shaped electromagnet is inserted into the vibration component. In the type I pump, the specifications of the vibration components and electromagnets are the same as those in our previous study [17].

The structure and dimensions of the suction and discharge valves are shown in Fig. 3. At these valves, triangular acrylic supports are attached to acrylic square plates with a side length of 30 mm. The plate is drilled with suction and discharge holes with a diameter of d [mm]. By preliminary experiments regarding pump specifications, the dimensions of the rubber sheet for the two valves are a width of 8 mm, a length of 10.5 mm, and a thickness of 0.05 mm. Fig. 3(c) shows the flow pattern of water due to



(a) Schematic cross-section (b) Photograph
Fig. 1. Structure of type I vibration pump

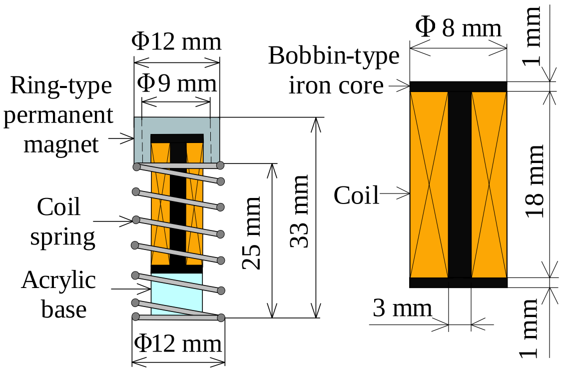


Fig. 2. Vibration component and electromagnet

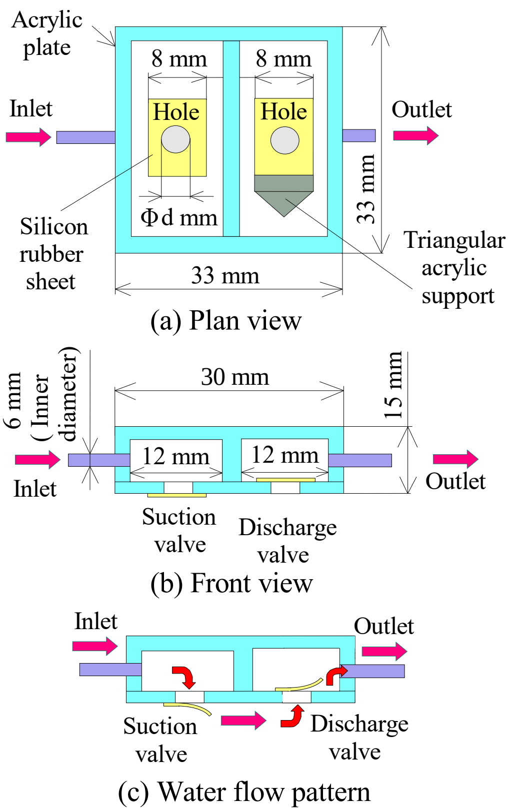


Fig. 3. Structure of head portion I

opening and closing of the two valves. Fig. 4 shows details of the triangular acrylic support.

This type I pump is installed as a suction-only pump and AC power is input to the bobbin-type electromagnet to drive the vibration component in resonance. In Fig. 1, when the vibration component is displaced upwards, the pressure in head portion II increases. This closes the suction valve made of the silicone rubber sheet, and the discharge valve is pushed up to discharge the water. When the vibration component is displaced downward, the pressure in head portion II decreases so that the suction valve opens and the discharge valve closes to prevent the backflow of water. In this case, because the pressure inside the head portion becomes negative, water is drawn in. Water is expelled intermittently by repeatedly increasing and decreasing the pressure over one vibration cycle. As shown in Fig. 1, the pump has a height of 63 mm and an outer diameter of 33 mm.

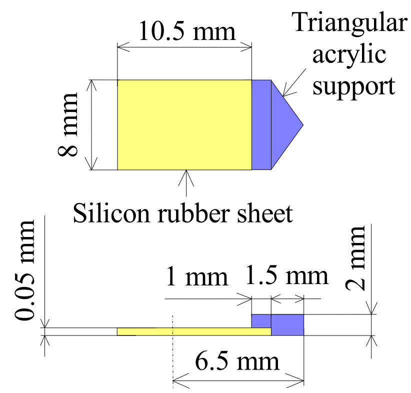


Fig. 4. Details of the triangular acrylic support

4. OPTIMUM DESIGN FOR THE SHAPE OF TYPE I VIBRATION PUMP

As shown in Fig. 5, optimization of the shape for the type I pump was performed for two items.

(1) Thickness of thin silicone rubber film: h [mm]

(2) Dimensions of suction and discharge ports in valve: d [mm]

The prototype pump was mounted on an acrylic tank base 350 mm wide, 250 mm long, and 350 mm high. As shown in Fig. 5, the pumping head was fixed at L = 200 mm, and the flow rate and

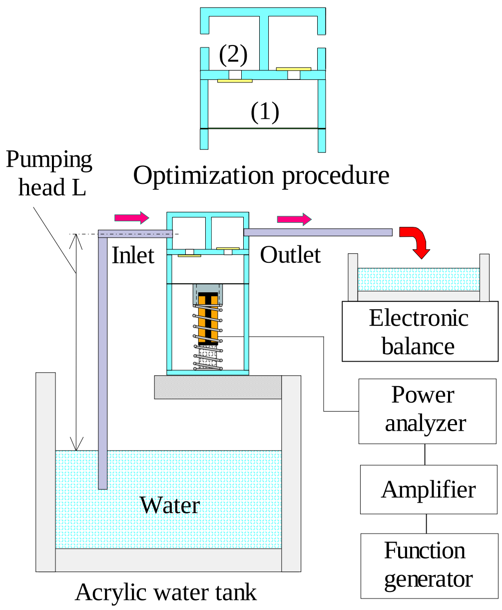


Fig. 5. Experimental apparatus and optimization procedure for type I pump

efficiency of water suction, which are important characteristics of the pump, were measured. Tap water at 20°C was used for the measurement. Acrylic pipes with an inner diameter of 6 mm were used as pipes for the water inlets and outlets. The vibration component was driven resonantly at a resonant frequency of 70 Hz using a function generator and amplifier. The input voltage, current, and power to the electromagnet were measured using a power analyzer. The efficiency η of the vibration pump is expressed as follows:

$$\eta = 100\, M_f\, G\, (L / t) / P \tag{1}$$

where M_f [kg] is the mass flow, G [m/s^2] is the acceleration due to gravity, L [m] is the pumping head, t [s] is the measurement time, and P [W] is the input power. The mass flow was measured with an electronic balance for 30 s.

Figs. 6 and 7 show the dependence of the flow rate and efficiency, respectively, on the input power (pumping head L = 200 mm for suction, hole diameter d = 4 mm for suction and discharge ports, and silicone film thickness h of 0.1, 0.3 and 0.5 mm). The figures show that the thin silicone rubber film with a thickness of 0.3 mm yields excellent flow characteristics and the highest efficiency. The thinner the thin rubber film, the lower its stiffness and the smaller the effect on the movement of the vibration component. However, if the thin rubber film is thin, it is likely to be deformed by the vibration component. Therefore, when the pressure in the head II portion increases due to vibration, the thin rubber film with low rigidity swells and inhibits the pressure increase. In contrast, a thicker rubber film inhibits the vibration of the component. For these reasons, the best flow characteristics are obtained with a silicone rubber film thickness of 0.3 mm, which has a relatively high stiffness.

Figs. 8 and 9 show the relationship between the power input to the electromagnet and the flow rate and efficiency, respectively, for L = 200 mm for

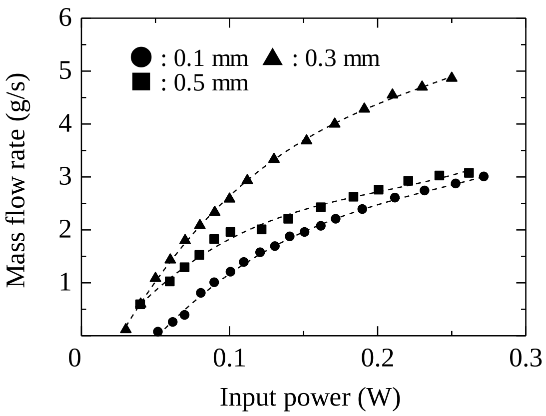


Fig. 6 Relationship between input power and mass flow rate for type I pump with three silicone film thicknesses h

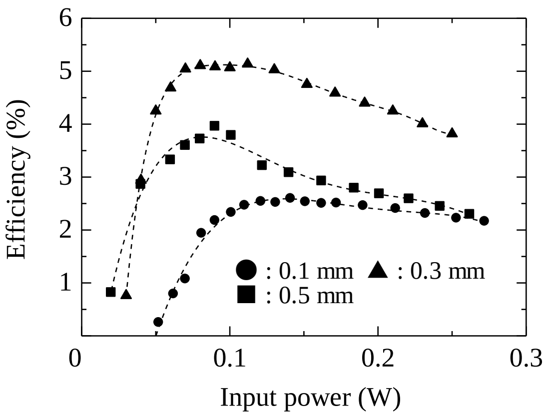


Fig. 7. Relationship between input power and efficiency for type I pump with three silicone film thicknesses h

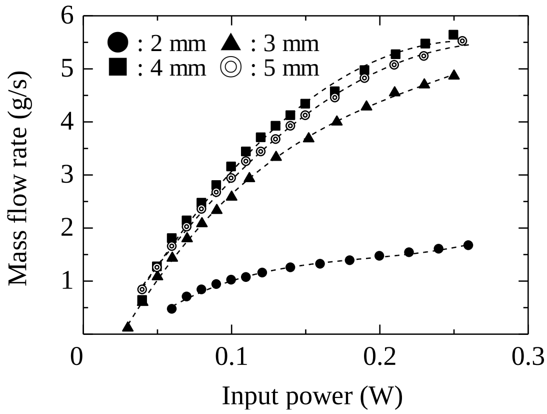


Fig. 8. Relationship between input power and mass flow rate for type I pump with four port diameters

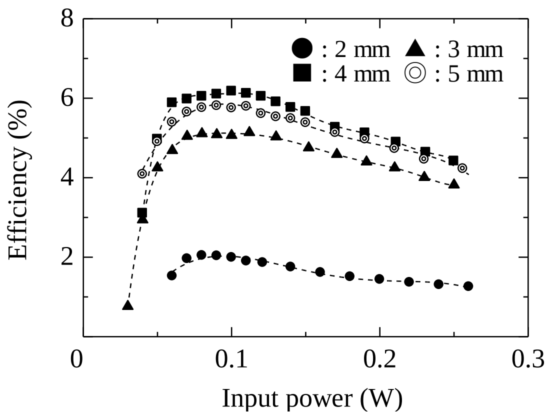


Fig. 9. Relationship between input power and efficiency for type I pump with four port diameters

suction, h = 0.3 mm, and d = 2–5 mm. It can be seen that the highest efficiency was obtained for d = 4 mm. When the pumping head was relatively low, the highest flow rate was obtained for d = 4 mm. A thin silicone rubber film thickness of 0.3 mm and a hole diameter of 4 mm at the suction and discharge ports were shown to be the optimal values for a type I pump. The vibration pump showed a maximum efficiency of 6.2%, which is superior to that of commercially manufactured pumps, as shown by tests on actual machines. However, type I pumps have the disadvantage of having a high capacity to suck in water but little capacity to push it up.

5. OPTIMUM DESIGN FOR SHAPE OF TYPE II VIBRATION PUMP

The type I pump was shown to be simple and relatively efficient, with excellent performance in terms of suction characteristics. However, the flow characteristics are slightly lower than the pump reported in a previous paper [17]. A prototype type II vibration pump with an acrylic rod attached to the top of the vibration component was built for the purpose of generating the inertial effect shown in Fig. 10. In the type II pump, head portions I and II are defined as being above the thin silicone rubber film, and the vibration portion is defined as being below the film. The dimensions of the vibration portion and head portion I, the vibration components, and electromagnets are identical to those for the type I pump. Based on the results of a previous study [17], the dimensions of the acrylic rod were set to a length of 25 mm and a diameter of 20 mm. The clearance between the acrylic casing of the pump and the rod was therefore set at 1.5 mm. As shown in Fig. 10, Dimensional optimization was performed for the Type II pump. The variables were the pump and the rod was therefore set at 1.5 mm.

As shown in Fig. 10, Dimensional optimization was performed for the Type II pump. The variables were the thickness of the thin silicone rubber film, and the dimensions of the suction and discharge ports. The prototype type II pump was attached to the acrylic tank and its flow rate and efficiency were measured as shown in Fig. 11.

Figs. 12 and 13 show the relationship between the power input to the electromagnet and the flow rate and efficiency, respectively (L_2 = 200 mm, L_1 = 0 mm, d = 4 mm for suction and discharge ports, h = 0.01–0.3 mm). It can be seen that the flow rate increases with increasing input power. The thinner the rubber film, the better the flow characteristics this pump exhibits. The reason may be that as the thickness of the rubber film increases, it causes more viscous damping of the vibration component. In the type II pump, it is expected that the water pushing up effect (inertia effect) will be exerted by attaching

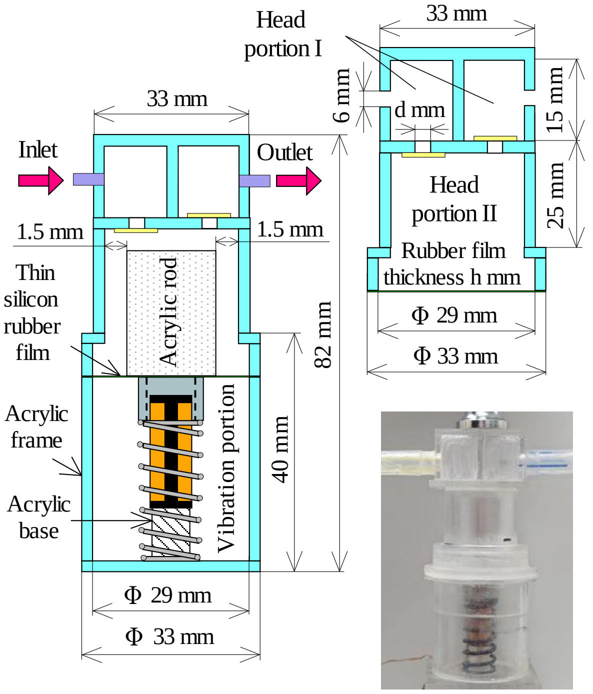


Fig. 10. Structure of type II vibration pump

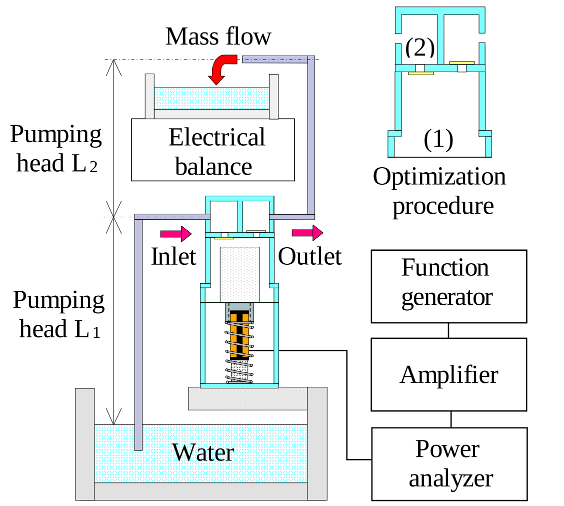


Fig. 11. Experimental apparatus and optimization procedure for type II pump

the acrylic rod. For this reason, the pump exhibits a different behavior than that the type I pump.

Figs. 14 and 15 show the relationship between the power input to the electromagnet and the flow rate and efficiency, respectively (L_2 = 200 mm, L_1 = 0 mm, h = 0.01 mm, d = 3–5 mm). The highest efficiency was found for d = 4 mm, which is the same result as for the type I pump. The effect of the hole diameter in the valve section on the flow characteristics is considered to be dominated by the pumping head. The above results indicate that the

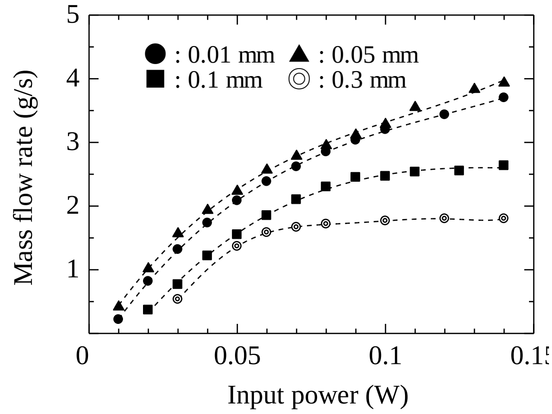


Fig. 12. Relationship between input power and mass flow rate for type II pump with four silicone film thicknesses

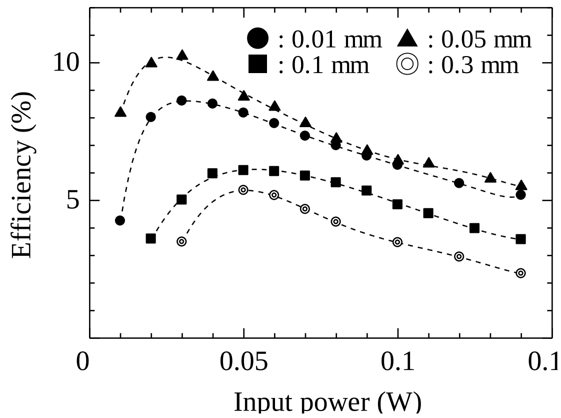


Fig. 13. Relationship between input power and efficiency for type II pump with four silicone film thicknesses

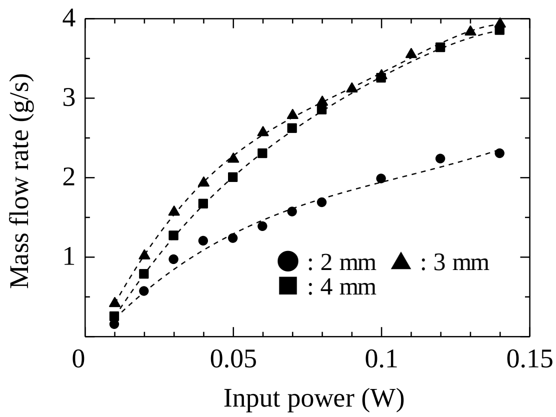


Fig. 14. Relationship between input power and mass flow rate for type II pump with three valve diameters

optimal values are h = 0.01 mm and d = 4 mm. The height and outer diameter of the pump in the optimized design are 82 and 33 mm, respectively.

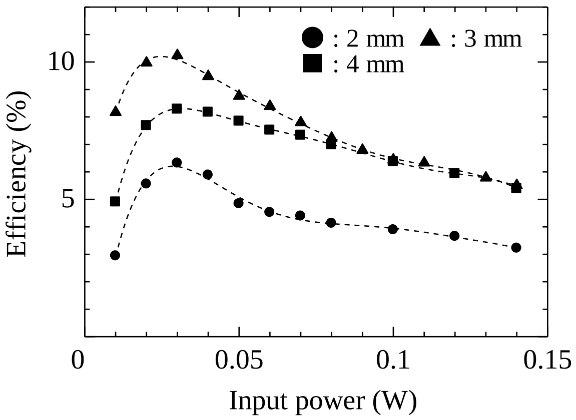


Fig. 15. Relationship between input power and mass efficiency for type II pump with three valve diameters

6. FLOW CHARACTERISTICS OF OPTIMIZED TYPE II VIBRATION PUMP

A prototype type II vibration pump with optimized dimensions was built. The flow characteristics were measured using the experimental apparatus shown in Fig. 11. The driving frequency of the vibration component was 70 Hz.

Figs. 16 and 17 show the relationship between he power input to the electromagnet and the flow rate and efficiency, respectively (L_2 = 0 mm, L_1 = 100–500 mm). When L_1 = 500 mm and the input power is 0.18 W, the type II pump can discharge 2.4 g/s of water. In contrast, when 0.03 W of power is input, the pump shows a maximum efficiency of 10.24% for L_2 = 200 mm.

Figs. 18 and 19 show the relationship between the power input to the electromagnet and the flow rate and efficiency, respectively (L_1 = 200 mm, L_2 =0–500 mm). A maximum efficiency of about12.2% was obtained at an input power of 0.04 W for L_1= 200 mm and L_2=100 mm. The maximum

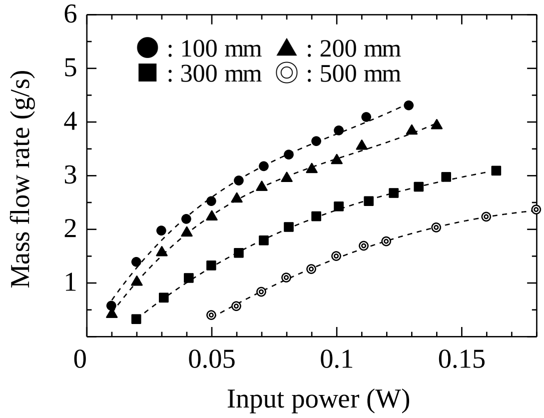


Fig. 16. Relationship between input power and mass flow rate for four L_1 values (L_2 = 0 mm)

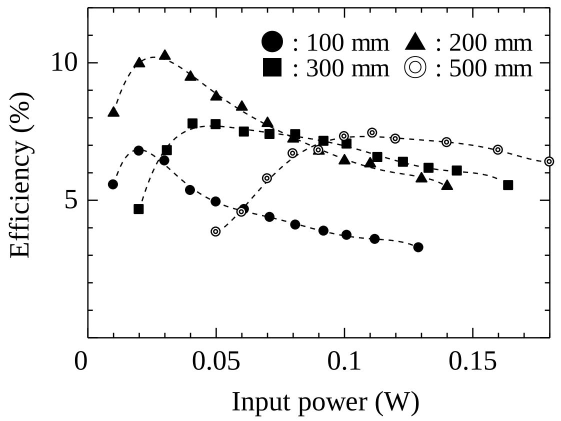


Fig. 17. Relationship between input power and efficiency for four L_1 values (L_2 = 0 mm)

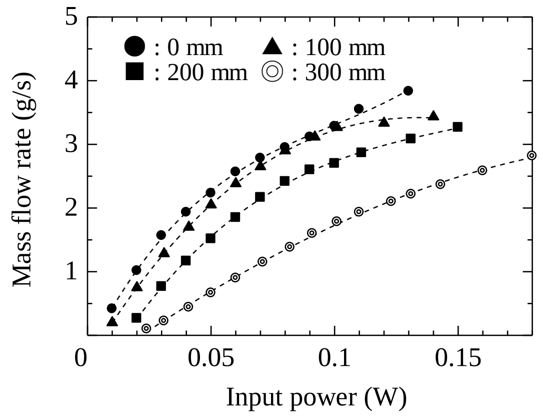


Fig. 18. Relationship between input power and mass flow rate for L_2 values (L_1 = 200 mm)

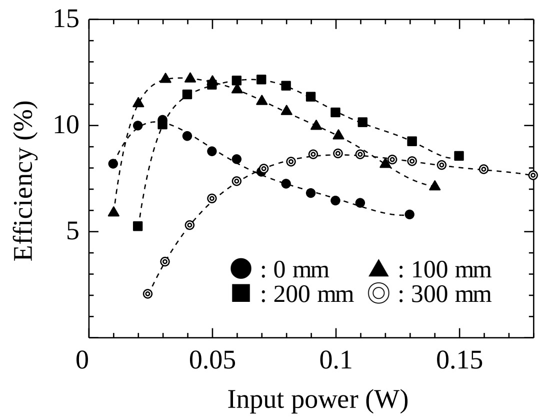


Fig. 19. Relationship between input power and efficiency for four L_2 values (L_1 = 200 mm)

efficiency reported in the previous paper [17] with the same suction and discharge pumping heads was 6.06%. The two-valve pump proposed in the present study shows an efficiency more than twice as high.

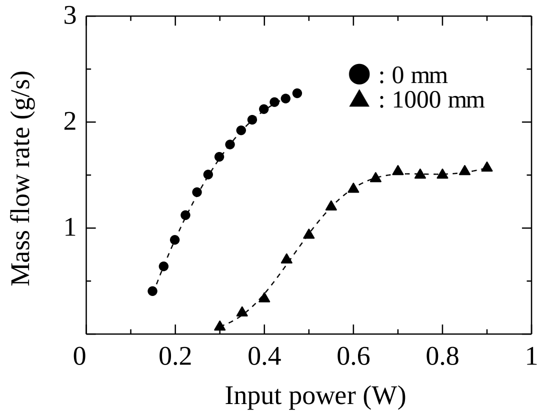


Fig. 20. Relationship between input power and mass flow rate for two L_2 values (L_1 = 1000 mm)

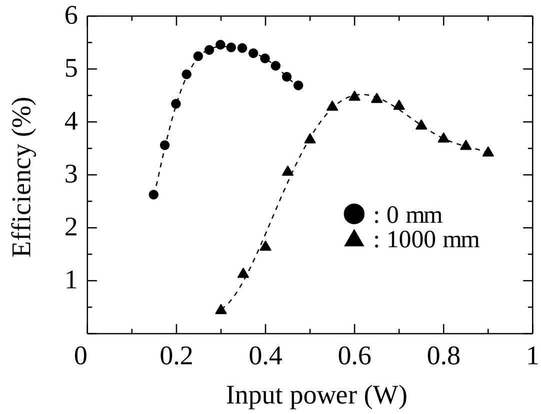


Fig. 21. Relationship between input power and efficiency for four L_2 values (L_1 = 1000 mm)

By applying the two-valve system, the type II pump exhibited a much higher suction capacity than the previous paper [17]. The result is a significant improvement in performance as the pump relative to suction head while maintaining discharge performance. Furthermore, compared to the type I pump, the type II pump has more parts, but the maximum efficiency was shown to be considerably higher.

Figs. 20 and 21 show the relationship between the power input to the electromagnet and the flow rate and efficiency, respectively (L_1 = 1000 mm, L_2 = 0–1000 mm). The prototype type II pump can discharge water at 1.53 g/s at a total pumping head of 2000 mm and an electromagnet input power of 0.7 W. The maximum efficiency of this pump at a total pumping head of 2000 mm is approximately 4.5% for an input power of 0.6 W. This performance is comparable to that of commercially available piezoelectric pumps, although the maximum efficiency is reduced under adverse conditions, such as an increased pumping head.

7. CONCLUSIONS

Two types of two-valve electromagnetic-vibration pumps combining electromagnetic force and mechanical vibration were proposed and optimized. The type I vibration pump, which has a very simple structure, showed a maximum efficiency of 6.2% when used in a water suction application, indicating that it is more efficient than commercially available pumps.

A prototype type II vibration pump that uses the inertial effect of water was also developed. This pump had excellent water suction and discharge characteristics and showed a maximum efficiency of 12.2% for a total pumping head of 300 mm. It was also shown that with a total pumping head of 2000 mm and an electromagnet power input of 0.7 W, 1.53 g/s of water was discharged.

The two environmentally friendly pumps proposed in this paper can be directly powered by an ordinary power outlet by tuning the resonance frequency of the vibration component, and were shown to be industrially useful by actual machine tests. These pumps consist of inexpensive and simple components that satisfy the requirements of disposable pumps demanded by their respective applications. The operation of an engineering useful pump is newly established by this paper. Based on the results of actual machine tests, a new industrially useful pump is proposed in this paper.

8. ACKNOWLEDGMENTS

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