A study on high-output piezoelectric micropumps for application in DMFC

J.-H. Park · M.-Y. Seo · Y.-B. Ham · S.-N. Yun ·
D.-I. Kim

Abstract In order to supply liquid fuel in DMFC (Direct Methanol Fuel Cell) system, a small but high-output micropump is needed. This study presents a design concept, fabrication and experimental results of the newly devised piezoelectric micropump by using resonance and fluid inertia. The micropump consists of a resonantly-driven pumping unit, an inlet check valve, and a pipeline element with a small diameter employed in an outlet. The resonance mechanism is used to oscillate the pumping chamber. It simply magnifies a small displacement of the used multilayer-piezoelectric actuator. The fluid inertia effect uses a fast flow through a narrow pipeline element employed instead of the outlet check valve. First, an analysis on each element such as a diaphragm and a check valve is performed. Based on the obtained analysis results, a prototype micropump is designed, and fabricated. Then, pumping characteristics such as frequency-dependent displacement, and flow rate without load pressure are experimentally investigated. Finally, a refabrication of the micropump is carried out to improve load characteristics, and the obtained experimental results are presented and discussed.

Keywords Piezoelectric pump · Resonance · Fluid inertia · Check valve · Structural analysis

J.-H. Park (✉) · M.-Y. Seo · Y.-B. Ham · S.-N. Yun
Extreme Mechanical Engineering Research Division,
Korea Institute of Machinery & Materials,
Daejeon 305-343, South Korea
e-mail: jhpark@kimm.re.kr

D.-I. Kim
MFtech Co. Ltd.,
Ansan, Gyeonggi-do 425-866, South Korea

1 Introduction

Direct Methanol Fuel Cell (DMFC) system is an attractive power source for portable electronic devices due to the higher energy density of methanol than it of traditional batteries [1–6]. In such miniaturized DMFC systems, a small but high-output micropump is needed to supply methanol continuously and precisely. Performance levels of the micropump should be needed to have pumping characteristics such as flow rate of a few ml/min and pumping pressure of a few 10 kPa to overcome hydraulic resistance across narrow fluidic channels. A few researches on liquid pumps such as a reciprocating pump using a piezoelectric linear actuator [1] and an electro-osmotic fuel pump [3] were reported. Their performance levels on flow rate are ranging from a few hundreds ml/min to a few ml/min, however, their pressure levels are up to a few kPa with relatively large actuator, or not presented. On the other hand, recently, many micropumps based on various operating principles have been proposed and developed under recent progress in MEMS (Micro Electro Mechanical Systems) technologies [7]. However, their performance levels as fluid power sources are also insufficient because most of the micropumps are fabricated to control the order of a few ml/min.

We have been investigating micropumps using resonance drive [8, 9]or fluid inertia effect [10] to develop micro fluid power sources directly installable to microrobots carrying out power-needed tasks or independently drivable each machine tool inside microfactories. The former is a resonantly-driven piezoelectric micropump. It simply magnifies a displacement of the piezoelectric actuator through a resonance of the pump actuation unit like mass-spring vibration system. The latter is a piezoelectric micropump using narrow pipeline element instead of the
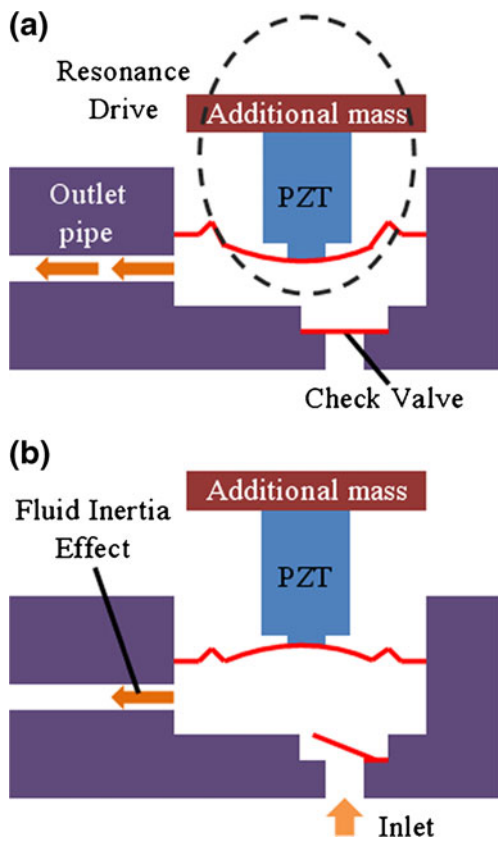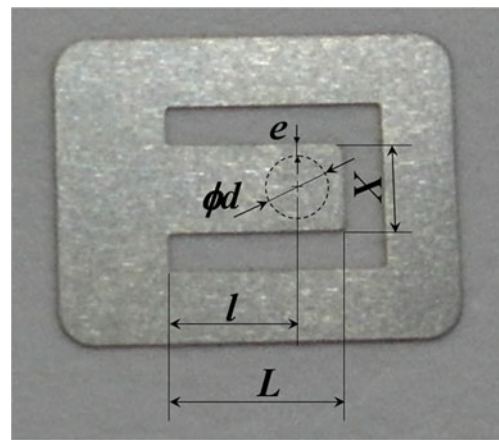
Fig. 1 Construction and working principle of the proposed piezoelectric micropump; (**a**) pumping mode, (**b**) suction mode

Fig. 3 Shape and design parameters of the inlet check valve

outlet check valve. It utilizes a fluid inertia effect caused by a fast flow of the pipeline element. From the experiments on pumping characteristics, the validity of the proposed micropumps was verified through comparisons of maximum power density among conventional micropumps [8, 10].

In this study, the newly devised piezoelectric micropump using resonance and fluid inertia effect at the same time is presented to obtain higher performance levels. The micropump consists of a resonantly-driven pumping unit, an inlet check valve, and an outlet pipe with small diameter. First, an analysis on each element such as a diaphragm and an inlet check valve is performed. A
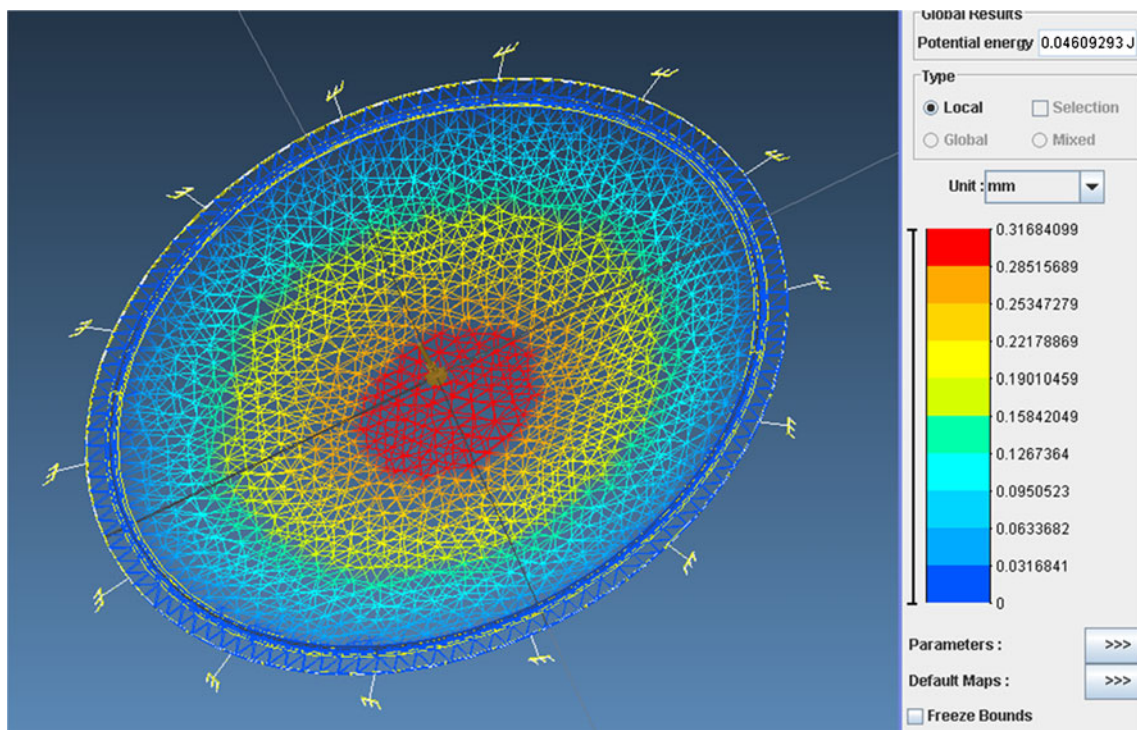
Fig. 2 Analysis result of the diaphragm

Table 1 Obtained design parameters of the inlet check valve

| $\phi\,d$ (mm)	e (mm)	X (mm)	l (mm)	L (mm)	f (kHz)
1.0	0.12	1.24	1.75	2.37	3.0

prototype micropump is fabricated, and then pumping characteristics with no load pressure are experimentally investigated. Finally, a refabrication of the micropump is carried out to improve load characteristics, and the obtained experimental results are presented and discussed.

2 Design and fabrication

### 2.1 Construction and working principle

There are two driving methods generally to increase pumping performance levels of a positive-displacement-type micropump that is strongly dependent upon the used actuator displacement. One is directly to magnify the displacements and the other is to increase the driving frequency. However, both of methods have some problems such as an additional magnification unit, and a small valve opening and low durability of the check valve unit caused by high stiffness, respectively.

In this study, therefore, a simple mechanism that magnifies a displacement of the piezoelectric actuator through a resonance drive of the pump actuation unit like mass-spring vibration system is proposed and investigated. Figure 1 shows a schematic and working principle of the proposed piezoelectric micropump using resonance drive and fluid inertia at the same time. It consists of a resonantly-driven pumping unit, an inlet check valve, and a pipeline element with small diameter employed in outlet. Here, an additional mass is attached to the free end of the piezoelectric actuator to obtain
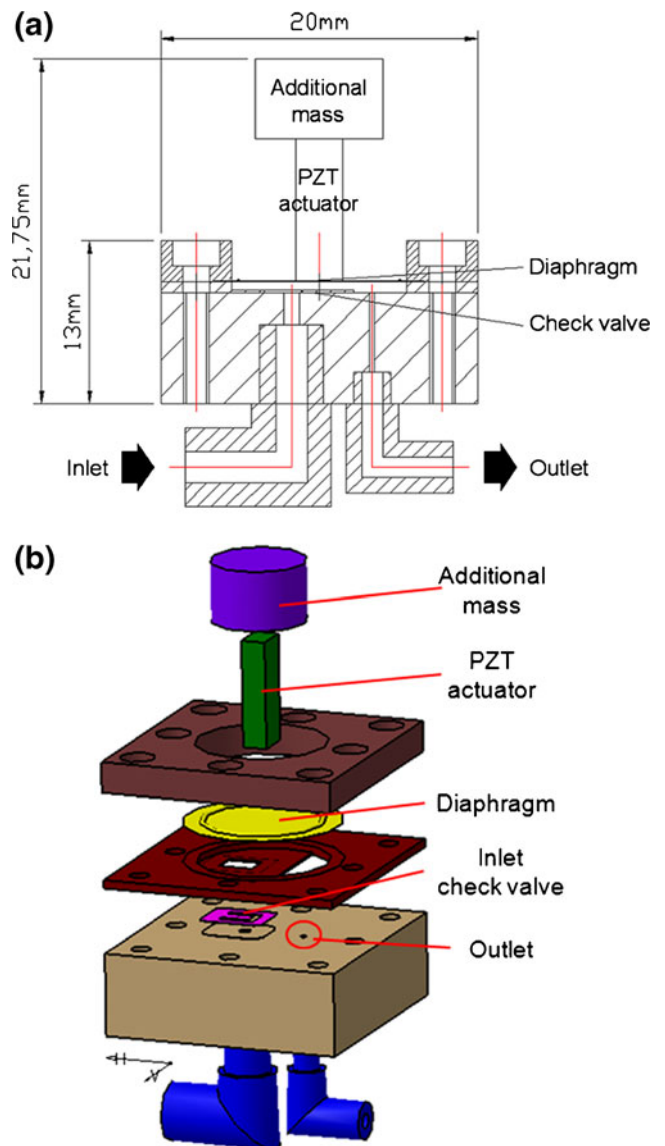
Fig. 5 Schematics of the fabricated prototype micropump; (**a**) 2-D view, (**b**) 3-D view

**Fig. 4** Analysis results of the inlet check valve; (**a**) deformation, (**b**) stress
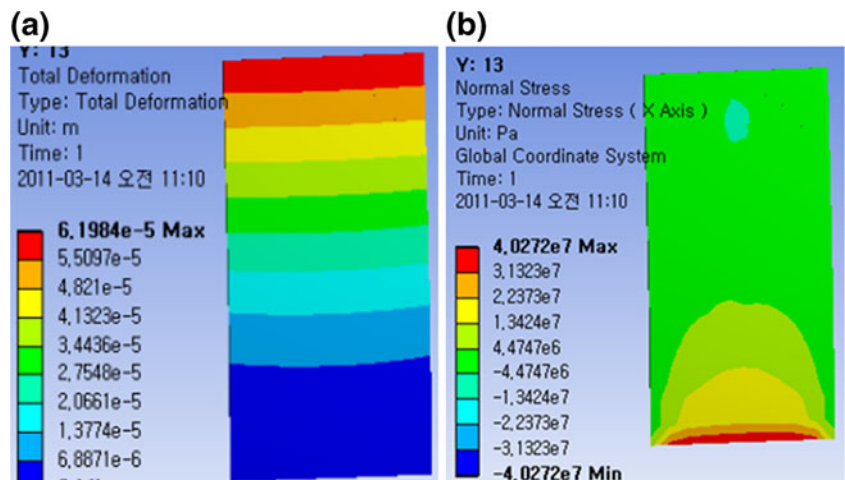
Table 2 Specification of the used piezoelectric actuator

| Multilayered Piezoelectric Actuator PSt 150/2 × 3/7 (Piezomechanik Gmbh)	
Maximum displacement	13 μm at 150 V
Blocking force	300 N
Stiffness	25 N/μm
Resonance frequency	100 KHz
Mass	0.62 g

even higher performance by enlarging the amplitude of the displacement at the resonant point. The fluid inertia effect uses a fast flow through a narrow pipeline element employed instead of the outlet check valve. In a pumping mode as shown in Fig. 1(a), the inlet check vale is closed with the increased chamber pressure and the working fluid flows through the outlet pipe. In a suction mode as shown in Fig. 1(b), the fluid flows through the inlet check valve into the chamber. At the same time, in the outlet pipe, the flow is going to maintain due to fluid inertia caused by a fast flow with high driving frequency. Thus, the micropump flows out the fluid in not only pumping but also suction modes with the magnified volumetric change by the resonance drive.

2.2 Component analysis

In this study, a driving frequency of the pumping unit using resonance drive is set up to be about 300 Hz in case of without working fluid and check valve. Therefore, to get optimized design parameters, structural analysis of components such as a diaphragm and an inlet check valve is performed by using commercially available tool. Figure 2 shows an example of the obtained analysis results on a displacement of diaphragm with 10 N. The diaphragm is designed to have a wrinkle structure along circumferential direction. Based on the analysis results, a stiffness of the designed diaphragm is 7,200 N/mm. Figure 3 presents a shape and parameters of the inlet
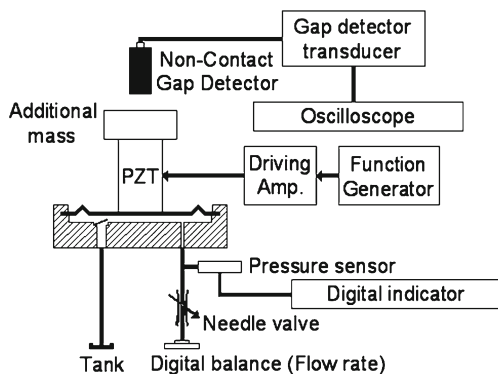
Fig. 6 Experimental apparatus for the fabricated micropump
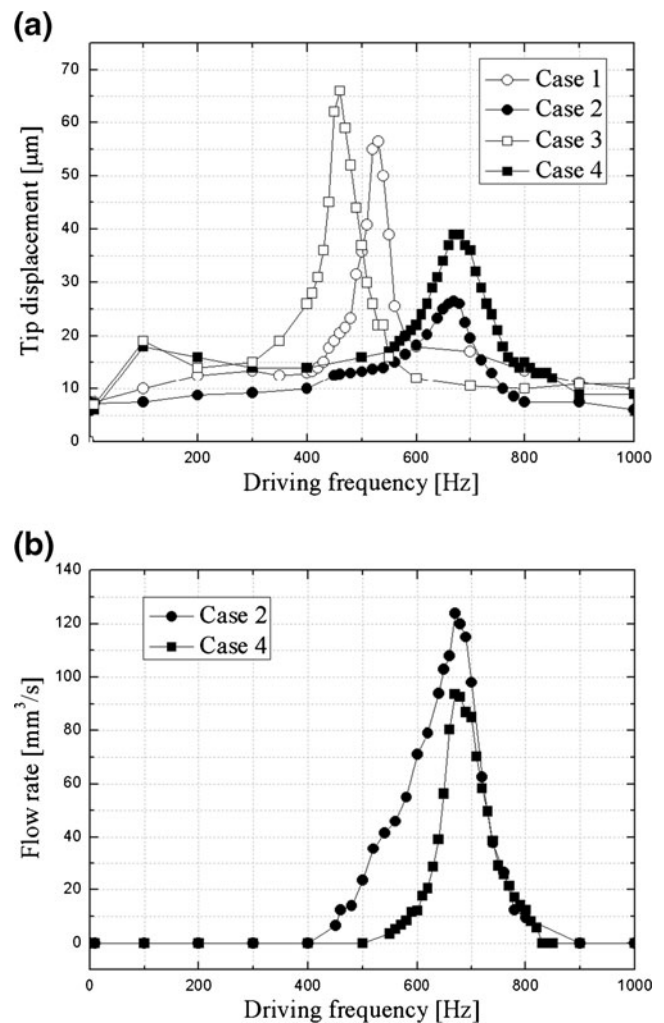

Fig. 7 Experimental results with no load pressure; (a) frequency-dependent displacement, (b) frequency-dependent flow rate

check valve. In the resonance drive, the resonance frequency of the check valve is very significant. The resonance frequency of the valve must be higher than that of the pumping unit [9]. Therefore, the cantilever-type check valve is designed to have sufficient stiffness like a natural frequency of 3 kHz. Table 1 presents the obtained parameters of the inlet check valve with the flow rate of 200 mm³/s and internal leakage rate

Table 3 Experimental conditions of the fabricated prototype micropump

|	Outlet diameter [mm]	Working fluid	Resonance frequency [Hz]	Displacement [μm]
Case 1	Φ0.4	Without	530	56.5
Case 2	Φ0.4	With	670	26.5
Case 3	Φ0.5	Without	440	66
Case 4	Φ0.5	With	660	39
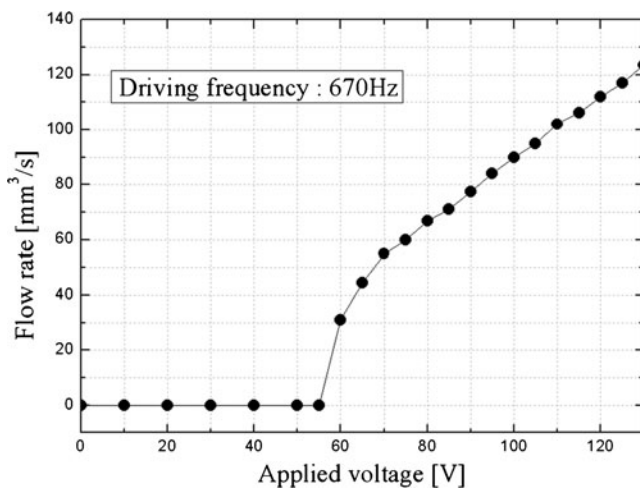
Fig. 8 Voltage-dependent flow rate characteristics

of 2 %. Figure 4 illustrates an example on the structural analysis of the check valve with the applied pressure of 5 kPa.

2.3 Prototype fabrication

Based on the obtained analysis results, a prototype piezoelectric micropump is fabricated. Figure 5(a) and (b) show the schematics of the fabricated prototype pump. Table 2 shows a specification of the used piezoelectric actuator. The commercially available piezoelectric actuator has the maximum blocking force of 300 N with no displacement and the maximum displacement of 13 μm with no restraint when 150 V is applied. A mass of the actuator is 0.62 g and an additional mass is 2 g and has a value of 320 % mass of the piezoelectric actuator. The effectiveness of the additional 330 % mass in resonance drive was verified in the previous researches [8]. The inlet check valve made of stainless steel is
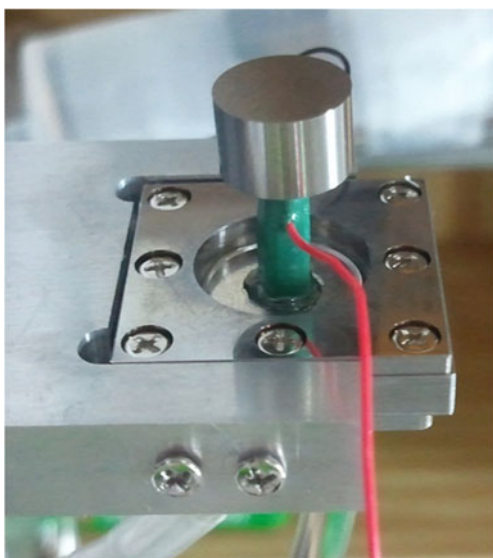
Fig. 9 Photocopy of the refabricated piezoelectric micropump
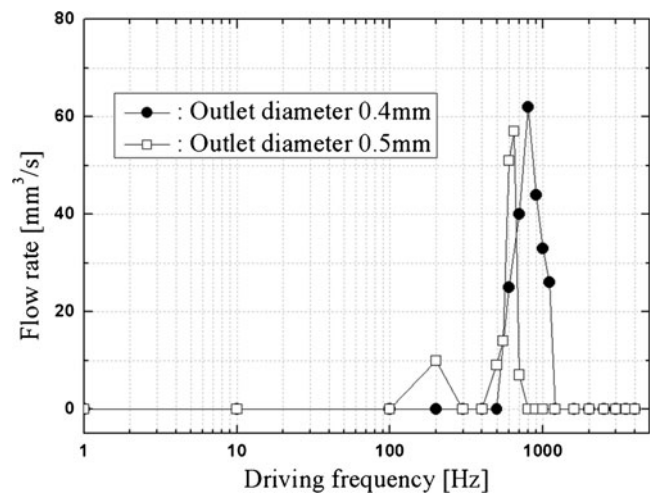
Fig. 10 Frequency-dependent flow rate characteristics

fabricated by using etching process to ensure sufficient accuracy. A length of the outlet pipe element is 5 mm, and a diameter is set to be 0.5 mm or 0.4 mm.
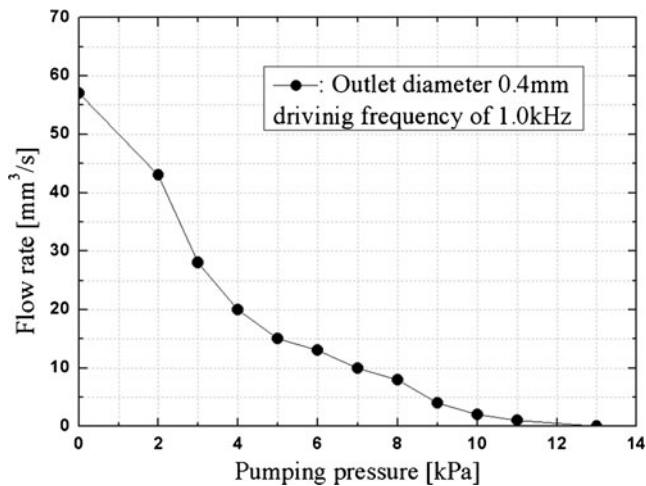
3 Experiments

3.1 Experimental apparatus

Figure 6 shows the experimental apparatus for investigating basic characteristics of the fabricated prototype micropump. To measure the tip displacement of the additional mass without affecting the state of resonance, a capacitance-type noncontact gap detector (LION Corp., measuring range: 500 μm, sensitivity: 0.04 V/μm, resolution: 24 nm) is used. A semiconductor-type pressure transducer (Sensys, measuring range: 0~500 kPa) is installed to measure the pumping pressure at the outlet. In this study, the flow rate is measured as an average of the outflow mass in a constant time by using a
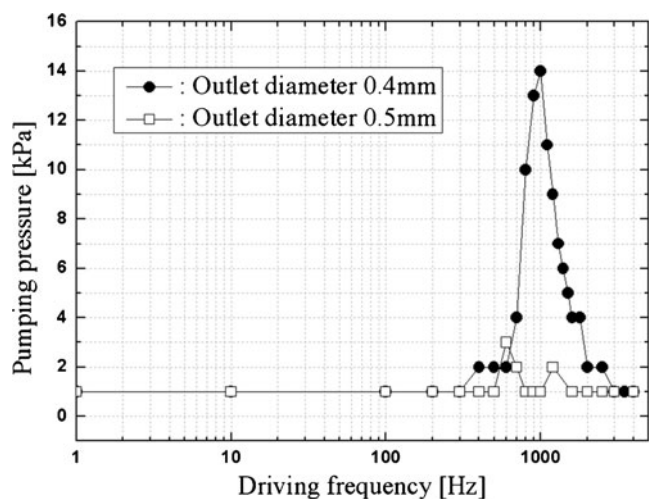
Fig. 11 Frequency-dependent pressure characteristics

Fig. 12 Load characteristics of the piezoelectric micropump

digital balance (resolution: 0.01 g). De-ionized water is used as a working fluid.

3.2 Experiments and discussions

Frequency-dependent displacement and frequency-dependent flow rate characteristics are experimentally investigated and the results are shown in Fig. 7(a) and (b), respectively. Table 3 shows experimental conditions performed with no load pressure. From the results as shown in Fig. 7(a), it is ascertained that the decrease of the displacement is thought to be due to the damping effect caused by an existence of the working fluid and difference diameter of the outlet pipe. It is also confirmed that the maximum flow rate at a resonance frequency of the displacement as shown in Fig. 7(b). Figure 8 shows applied voltage-dependent flow rate characteristics tested at 670 Hz. It is ascertained that the outflow in lower voltage range is not obtained due to the residual bubbles in pumping chamber and the flow rate in higher voltage range is almost linear along to the applied voltage. Then, frequency-dependent pressure characteristics were experimentally investigated but the satisfactory performance was not obtained.

Therefore, a refabrication of the micropump was performed to improve load characteristics. Figure 9 shows a photocopy of the refabricated piezoelectric micropump. A length of the outlet pipeline element is modified from 5 mm to 10 mm for effectiveness of the fluid inertia effect. Figures 10 and 11 show the obtained frequency-dependent flow rate and frequency-

dependent pressure characteristics. Then, Load characteristics of the piezoelectric micropump using resonance drive and fluid inertia are shown in Fig. 12. As a result, maximum flow rate of 62 mm^3/s (3.7 ml/min) at 800 Hz and maximum pumping pressure of 14 kPa at 1.0 kHz were obtained. In next work, an application in DMFC by using the micropump will be tested.

4 Conclusions

As a fluid power source to supply liquid fuel in DMFC (Direct Methanol Fuel Cell) system, in this study, a piezoelectric micropump using resonance drive and fluid inertia was newly designed, fabricated and experimentally investigated. First, to get optimized design parameters, structural analysis on diaphragm and inlet check valve was performed. Second, a prototype micropump was designed, and fabricated based on the obtained analysis results. Then, pumping characteristics were experimentally investigated with the structural improvement of the outlet pipe. As a result, it was ascertained that maximum flow rate is 62 mm^3/s and maximum pumping pressure is 14 kPa.

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