1A2-1

Proceedings of the 6th JFPS International
Symposium on Fluid Power, TSUKUBA 2005
November 7-10, 2005

FUNDAMENTAL STUDY ON A PZT JET PUMP

Hidetoshi OHUCHI*, Tetsuya WADASAKO**,
Tomohiro HOSAKA** and Tasuku OSADA*

* Graduate School of Medical and Engineering Science Department of Research
University of Yamanashi
4-3-11, Kofu, Yamanashi, 400-8511 Japan
(E-mail: ohuchi@yamanashi.ac.jp)
** Graduate School of Medical and Engineering Science Department of Education
University of Yamanashi
4-3-11, Kofu, Yamanashi, 400-8511 Japan

ABSTRACT

In this paper we propose a delivery method for a PZT jet pump driven by repeated impulsive force of the actuator. The pump is simple in construction being composed of only a piston-cylinder and a receiving hole, and it has no check valves. The multilayer PZT actuator pushes the piston impulsively and the fluid in the cylinder is ejected out through the nozzle forming a jet flow. The receiving hole that is placed facing the nozzle catches the jet flow and one way flow can be obtained. Experimental works indicated that the driving frequency as well as the dimensions such as the diameters of the nozzle and receiving hole was important to improve the pump performance. Moreover it was recognized that while air bubbles were apt to be generated in the cylinder during the suction stroke they were exhausted out of the cylinder at under a certain driving frequency.

KEY WORDS

Jet pump, PZT pump, Nozzle, Receiving hole, Air bubble

NOMENCLATURE

d_1 : Diameter of the nozzle
d_2 : Diameter of the receiving hole
D : Distance between the nozzle and the receiving hole
p : Pressure in the cylinder chamber
Q_{out} : Output flow rate
Q_{leak} : Leakage flow rate
H : Output head
f : Driving frequency of the PZT actuator

INTRODUCTION

In this paper we propose a delivery method for a PZT jet pump driven by repeated impulsive force of the actuator. The principle of delivery is the same as a water pistol. The pump is simple in construction being composed of a piston-cylinder and a receiving hole. The multilayer PZT actuator pushes the piston impulsively and the fluid in the cylinder is forced to flow out through the nozzle forming a jet. The receiving hole is placed facing the nozzle and catches the jet flow. In this pump, the one way flow is obtained using the difference of flow patterns between the jet flow out of the nozzle and the

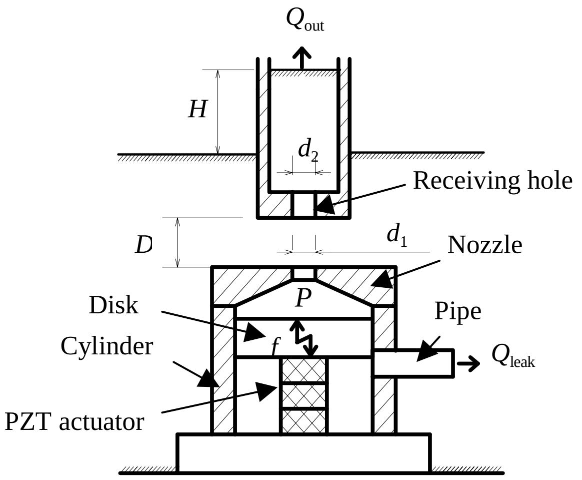

Figure 1 Fabrication of the jet pump

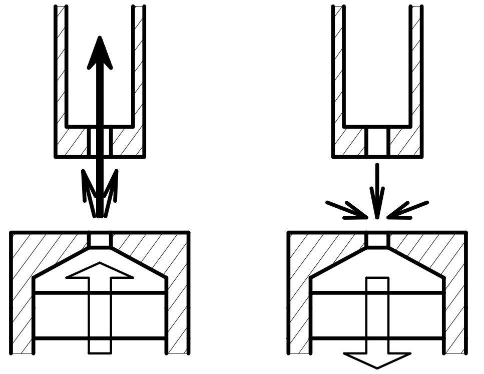
(a)Delivery (b)Suction

Figure 2 Basic principle of jet pump

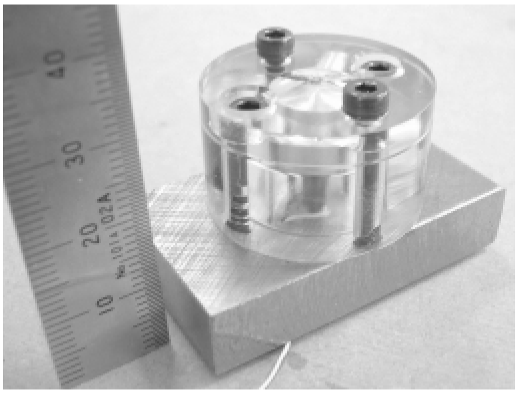

Figure 3 External view of the jet pump

suction flow into the same nozzle. The delivery pressure of the pump is not high because it has no check valves. It is the feature that this pump does not have a valve, while most of the pumps developed before have check valves[1].

The functions of the pump are to eject small amount of fluid intermittently, to stir fluid in a narrow region, and to make a continuous flow with high-frequent ejection. Then the valve will be used to select small particles in a flow or to convey fluid substances in low pressure. In this paper, we are going to obtain a quasi continuous flow for transportation.

The piston is 12mm in diameter. The multilayer piezo-electric actuator has a small size of 2x3x9mm and is driven by rectangle wave voltage. Experimental works on the parameters that determine the pump characteristics indicated that the dimensions such as the diameter of the nozzle and receiving hole and the driving frequency were important to improve the pump performance.

Since the developed pump is not a positive displacement one, its delivery flow rate is changed according to the load pressure even if the driving frequency of the pump is constant. On the other hand, under a no-load condition the flow rate more than the calculated value was obtained. Moreover it was recognized that while air bubbles were apt to be generated in the cylinder during the suction stroke they were exhausted out of the cylinder at under a certain driving frequency.

WORKING PRINCIPLE OF THE JET PUMP

Fabrication of the jet pump

Fig.1 shows the fabrication of the jet pump proposed in this paper. A PZT actuator is bonded on the base, and a disk is also bonded on the upper side of the actuator. The disk acts as a piston. These are set into the cylinder, which is covered by a lid with a nozzle hole. The pump is in simple construction as shown.

To obtain the output flow, a receiving hole is installed at the position facing to the nozzle, and a pipe is connected to the receiving hole. The jet that flows out from the cylinder chamber and flows into the receiving hole is an output of the pump. In the cylinder wall under the piston there is a small hole that makes the fluid go in and out freely. This pump with the receiving hole is submerged a little below the surface of the liquid.

Working principle

The working principle of the jet pump is as follows. The PZT actuator expands rapidly when a rectangle wave voltage is applied to it, and the fluid is gushed by the piston through the nozzle. When the actuator is shrunk, the fluid is inhaled through the same nozzle. When the expansion and the shrinkage of the PZT actuator are repeated at a high frequency, the flow through the nozzle seems like a continuous flow. This is because the aspect of the inlet flow is different from the outlet jet flow.

Then, a receiving hole is set at the position facing the nozzle. One side of a pipe was shut and a small receiving hole was made as shown in Fig.2. Fig.2 (a) shows that

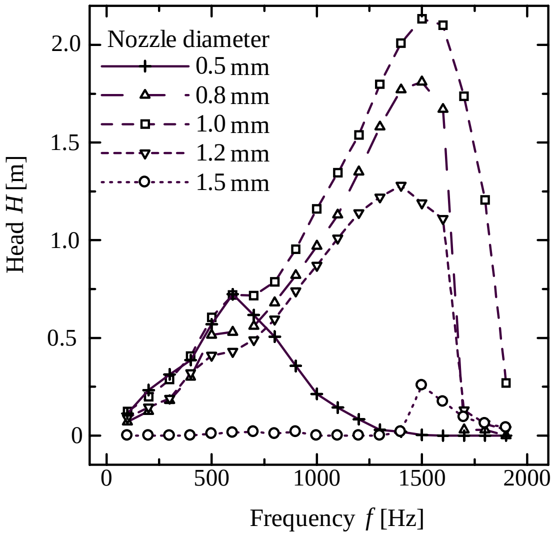

Figure 4 Variations of output head with the driving frequency of various nozzle diameters

when the PZT actuator rapidly expands the fluid goes out of the nozzle forming a jet flow and passing into the receiving hole. Fig.2 (b) shows the appearance that the fluid in the vicinity of the nozzle exit flows toward the nozzle when the PZT actuator shrinks. At this time, though there is a backflow out of the receiving hole, the total flow is directed to the output pipe, because the inlet flow rate is more than the back flow rate. In a word, the one way flow is obtained by using the difference between how to flow through out or into the nozzle. As a result, a pump without a check valve is realized unlike a conventional diaphragm pump.

The tested jet pump

Fig.3 shows external view of the tested jet pump. The parameters of this pump are as follows. The PZT actuator has a size of 2×3×9mm, and it reveals an elongation of 7.5 μm in a long direction when the voltage of 150V is applied. The aluminum disk bonded onto the actuator is of 12mm in diameter and 4mm in thickness, and it acts as a piston. The nozzle, the cylinder and the receiving pipe were made of acrylics to make it easy to observe the situation inside the cylinder. The hydraulic oil was used as a working fluid. Different size of nozzles (0.5, 0.8, 1.0, 1.2, 1.5 and 2.0mm in diameter) and receiving holes (0.8, 1.0, 1.2, 1.5 and 2.0mm in diameter) were prepared for experiments.

Although the pumping action is performed by the disk, it is not sealed and there is a gap of about 0.05mm between the disk and the cylinder. When the bubbles are generated in the cylinder chamber and remain there, they become obstructions of the pump operation. However, these bubbles are apt to be exhausted outside the cylinder chamber through the gap, and the continuous pumping action becomes possible.

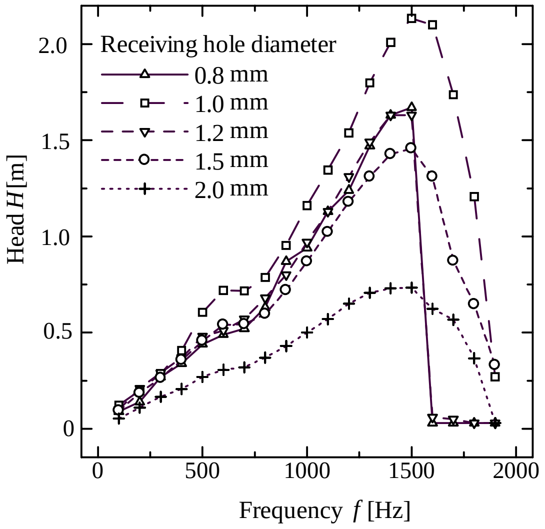

Figure 5 Variations of output head with the driving frequency of various receiving dole diameters

EXPERIMENTS

When the PZT actuator is driven successively by a high frequency rectangle wave voltage, a quasi continuous flow occurs in the outlet pipe through the receiving hole as shown in Fig.2 (a). Then this pipe was extended upwards, and the height H of the oil column that rose up in the pipe was measured. We changed the nozzle diameter, the receiving hole diameter and the distance between the nozzle and the receiving hole as parameters of the pump, and also varied the driving frequency and the duty ratio of the rectangle wave as parameters of the driving condition. Then, we examined the relationship between the output head and each parameter. The piston diameter was 12mm and the driving frequency was varied from 100 Hz to 1900 Hz by 100 Hz.

A high frequency piezo driver was used for driving the actuator. The specifications of the drover are as follows; maximum output voltage of 150 V, rated current of 200 mA and peak current of 600 mA.

Nozzle diameter d_1

First, we carried out fundamental experiments varying d_1 on condition of the receiving hole diameter d_2 of 1.0mm, the distance between the nozzle and receiving hole D of 2.0 mm and the duty ratio of 50 %. Fig.4 shows the results, in which the highest value H of 2.2m was obtained at f=1.5 kHz and d_1=1.0 mm.

Then, another experiment was performed, where the pressure sensor was installed facing the nozzle instead of the receiving pipe. The strongest jet or propellant force was recorded also at d_1=1.0mm. It was thought that an effective jet flow for the pump action was formed by the nozzle of 1.0mm in diameter in case of the piston of 12mm in diameter.

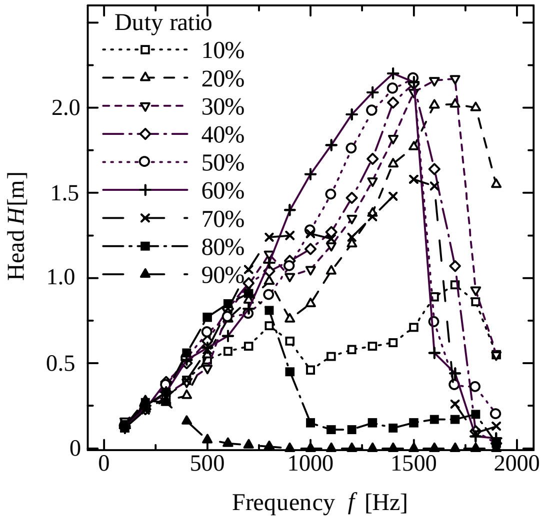

Figure 6 Variations of output head with the driving frequency of various duty ratios

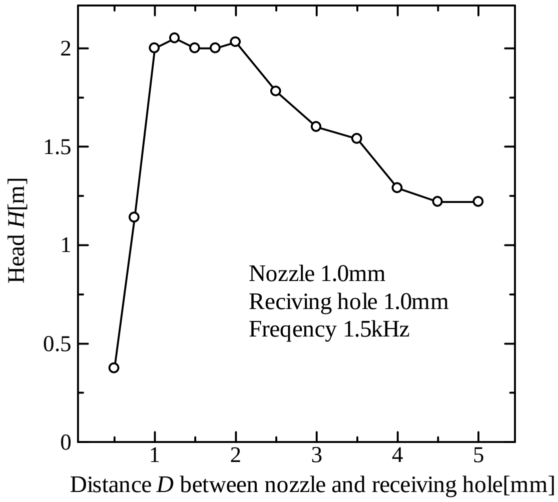

Figure 7 Variations of output head with the driving frequency of various distances between nozzle and receiving hole

Receiving hole diameter d_2

Next experiment was to vary d_2 on condition that d_1=1.0mm, D=2.0mm and the duty ratio of 50%. As shown in Fig.5, the maximum H of 2.2 mm was obtained at the same value of f=1.5 kHz and d_2=1.0mm. Moreover, the peak values of H appeared at the same frequency f=1.5 kHz for any values of d_2. The best receiving hole diameter was the same as the nozzle diameter of 1.0mm. In this experiment, however, there was no output flow. It seems that the receiving hole diameter influences not only the output head but also the flow rate. So, the value of d_2 should be chosen after examining the characteristics between the load and flow rate.

Table 1 Combination of parameters that gives a high output pressure

Nozzle diameter d_1 [mm]	1.0
Receiving hole diameter d_2 [mm]	1.0
Distance between the nozzle and receiving hole D[mm]	2.0
Duty ratio [%]	60
Driving frequency f[kHz]	1.5

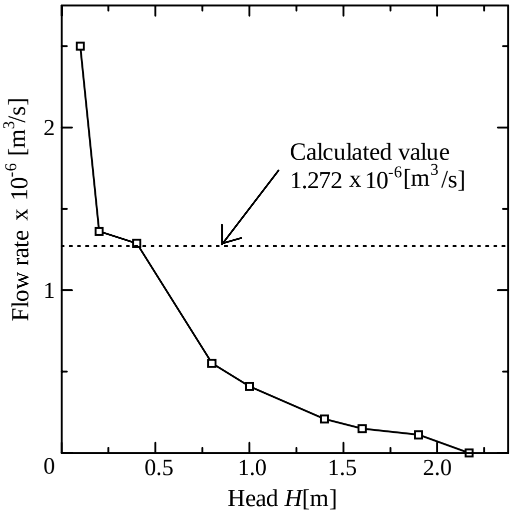

Figure 8 Delivery flow rate

Duty ratio

We examined the height H varying the duty ratio of rectangle wave on condition of d_1=1.0 mm, d_2=1.0 mm and D=2.0 mm. The results are shown in Fig.6. Within the duty ratio range from 20 to 60 %, the height H reached 2m or more though there were a few differences in the peak driving frequency.

The peak frequency tends to decrease when the duty ratio increases. Because the suction time decreases as the duty ratio increases, the result shows it is necessary to set the ratio below 60 % and to keep a sufficient suction time.

Distance D between the nozzle and receiving hole

Finally we examined the head H with varying D on condition of d_1=1.0mm, d_2=1.0mm, the duty ratio 50 % and the driving frequency f=1.5 kHz. Fig.7 shows the result. H reached 2 m or more when D is from 1.0 to 2.0 mm. The H decreased little by little when D parted from the range. Moreover, when the receiving hole is located near the nozzle, for example less than 1 mm, it becomes an obstruction of the inhalation of the fluid.

The result in Fig.7 indicates that the output did not change so much when D is from 1.0 to 2.0mm. That means the accuracy is not necessary for positioning the receiving hole. Therefore, the assembly of the pump can be performed easily.

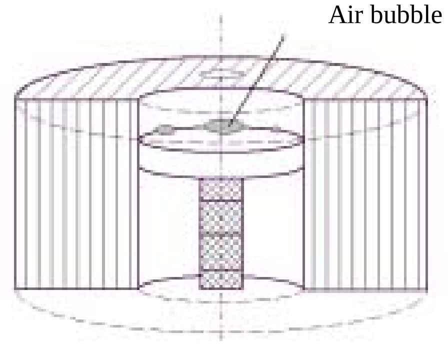

Figure 9 Generation of air bubbles

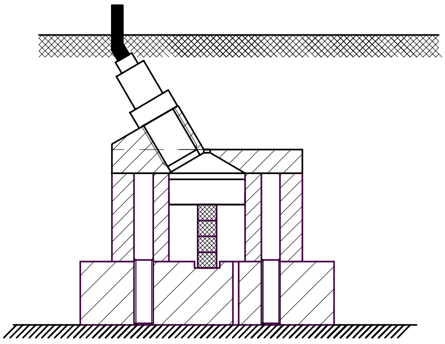

Figure 10 Measuring of the nozzle back pressure

Considering these results, the combination of parameters that gives a high output head was obtained as described in Table 1. In the following experiment the relationship between the head and flow rate was measured on these conditions varying the maximum height of the output pipe. Fig.8 is the obtained characteristics and shows the maximum flow rate Q_{out} was 2.5×10^{-6} m^3/s.

The broken line drawn in Fig.8 shows a value of the flow rate without load (H=0m) calculated from the piston stroke, the area of the disk and the driving frequency. As a result of the experiment, the flow rate more than the calculated value was obtained when H was 0.4 m or less. It is thought that the fluid around the jet flow in addition to the jet flow itself from the nozzle might flow into the receiving hole. Therefore, the flow rate more than the piston displacement can be obtained when the load is small.

The total efficiency of this jet pump was 0.12 %, which was calculated using the input electric power of 7.35 W and the measured values in Fig.8. Moreover, the leakage flow rate $Q_{leak}=0.03\times10^{-6}$m^3/s was measured through the discharge pipe at H= 0 m. It was about 1 % of Q_{out}.

IMPROVEMENT OF THE PUMP CHARACTERISTICS

Generation of air bubbles

As shown in Fig.9, air bubbles were generated mostly at the disk edge inside the cylinder. The movement of the bubbles was observed and the following fact was found. The generated bubbles were exhausted not through the nozzle but through the gap between the disk and the cylinder. When the characteristics of the pump were measured in the preceding chapter, there was a feature that height H decreased rapidly when the driving frequency was raised higher than f=1.5 kHz. At a lower frequency than that, even if bubbles were generated, they were exhausted and the pumping action was kept stable. On the other hand when the driving frequency was increased, the bubbles did not pass through the gap between the disk and the cylinder. The bubbles stayed inside the cylinder and the pressure p could not increase. Therefore the jet flow could not occur any more.

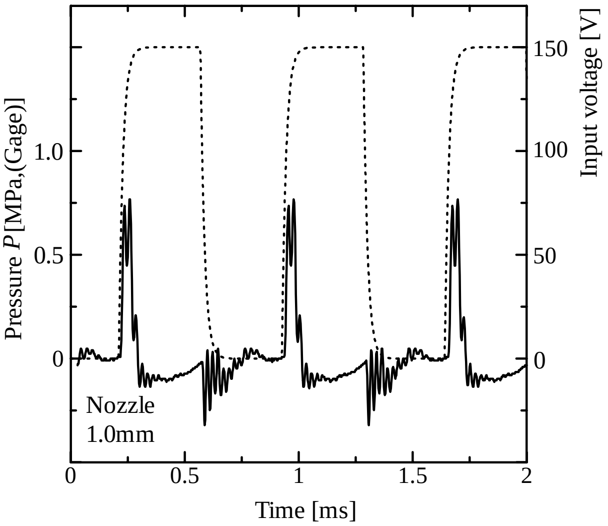

Figure 11 Pressure in the cylinder chamber without air bubbles

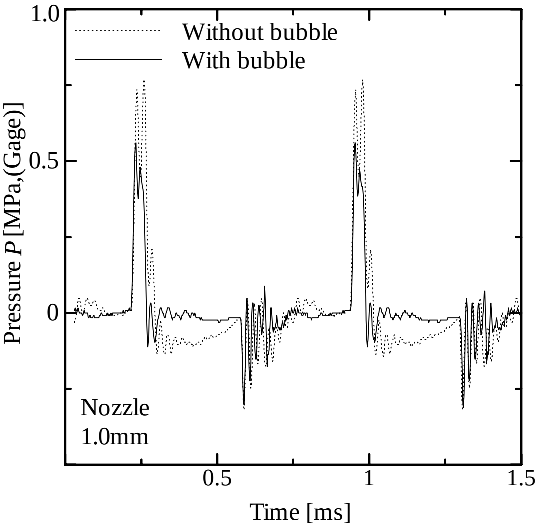

Figure 12 Pressure in the cylinder chamber with and without air bubbles

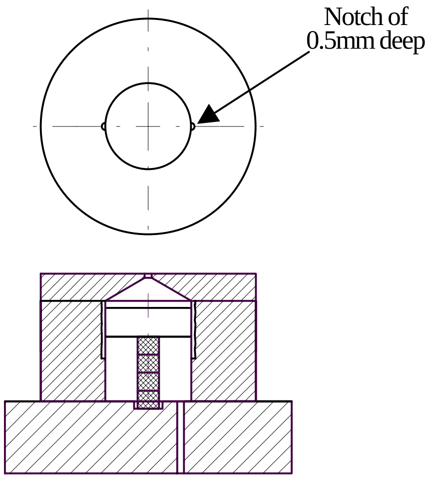

Figure 13 Disk with two notches

Pressure in the cylinder chamber

The semiconductor pressure sensor was installed to measure the nozzle back pressure as shown in Fig.10. Fig.11, in which the pressure values represent the gage pressure, shows the recorded result in case of the nozzle diameter of 1.0 mm. The pressure reached the maximum value of 0.7 MPa in 0.036 ms from the start of the actuator, and the pump ejected the fluid during about 0.1 ms. After that, the pressure decreased to -0.1MPa. The suction process started before the actuator began to shrink. Moreover, the pump continued to inhale and finished it in about 0.17ms. The pressure decreased to -0.1MPa once when the actuator shrunk. The recorded pressure waveform reveals high frequency vibrations and absolutely negative value. It is not a real pressure but a vibration of the diaphragm of the semiconductor pressure sensor.

Next, Fig.12 shows the pressure recorded in case that the air bubbles stayed in the chamber. The ejecting pressure decreased to about 60 %. When the bubbles were not seen, the pressure has decreased to a negative level before the actuator started to shrink. On the other hand, in case that there exist air bubbles, the pressure decreased only to 0 MPa. When the actuator shrunk, the pressure became negative; however, the level was higher than that measured without air bubbles. Therefore, when a big air bubble is generated, it seems that not only the jet flow but also the suction flow decrease. In other words, the output flow vanishes because the internal air bubbles repeat growth and disappearance. As a result, how to exhaust the air bubbles inside the cylinder becomes an important problem to improve the characteristics of this type of pump.

Exhaust of the air bubbles

It seems that the gap between the piston and cylinder should be small to obtain a strong jet flow. However, considering the bubble generation and exhaust, it seems also that a small gap is necessary there. Then, other experiments were carried out for comparison. One was a pump with two notches of about 0.5mm carved on the cylinder wall as shown in Fig.13 to make the bubble exhaust easily. The other was a pump with an O-ring to seal the piston gap.

The results are shown in Fig.14. The output head of the pump with the notch decreased by about 20% compared with the pump without the notch. The air bubbles appeared and stayed in the chamber as before at the frequency higher than 1.6 kHz. In this method, it was noticed that the pump was kept stable while the output decreased a little. On the other hand, the output of the pump with an O-ring decreased remarkably. It has been understood that the existence of the gap was important.

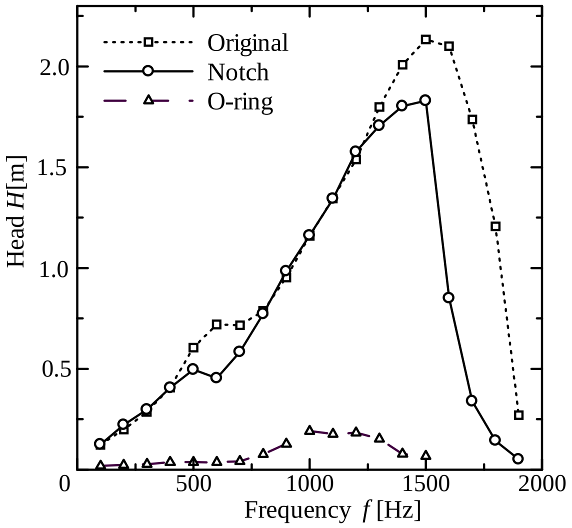

Figure 14 Influence of the gap seal

CONCLUSIONS

In this paper, a jet pump driven by impulsive force of a PZT actuator was proposed. The pump has no check valves and so it is simple in construction. Basic characteristics of the pump were studied experimentally concerning the pump parameters and the driving conditions. The air bubbles generated in the cylinder chamber considerably affected the performance of the pump. Future research will involve a design to easily exhaust air bubbles and also to improve the efficiency.

REFERENCE

1. Park, J. H., Yokota, S. and Yoshida, K., Piezoelectric Micropump Using Resonance Drive, Proc. Fifth Triennial Int. Symp. On Fluid Control, Measurement and Visualization (FLUCOME'97), Hayama, Japan, 1997, pp.319-324