Fundamental Investigation of a Piezoelectric Pump for a Trace Liquid Feed*

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Generally, peristaltic and syringe pumps have been used to feed liquids at about 2(ml/min). However, since continuous and low-fluctuation flow cannot be easily realized simultaneously with either of these two types of pumps, a new type of microquantity pump is required in the field of pharmaceutical manufacturing. Therefore piezoelectric elements were applied to fabricate a 2-dimensional pump suitable for multichannel and multistage pumps. Experiments demonstrated that the pump worked successfully and its maximum head was 18(kPa).

Key Words: Pump, Fluid Machinery, Piezoelement, Microcheck Valve

1. Introduction

Medical treatments and pharmaceutical manufacturing generally require feeding of a liquid, such as medicine, in amounts of a few ml or less. A free-flow electrophoretic apparatus, which can provide separation and analysis of biological samples, requires a pump with 50 or more channels. In addition to the multichannel feature, highly precise flow control is needed. Conventionally, trace liquid has been supplied by two types of pumps, peristaltic and syringe. The former moves the liquid in a tube by squeezing the tube with several rollers. Due to the mechanism, it

can provide a continuous feed; however, it is subject to the adverse effects of pulsation⁽¹⁾ and tube wear. On the other hand, the syringe pump can feed a liquid with no pulsation. However, since the syringe pump cannot suck in and discharge liquid at the same time due to its operating principle, continuous supply cannot be realized unless two or more syringe pumps alternately supply the liquid. Therefore the syringe pump cannot easily be adapted to multichannel uses because of its complexity.

Under these circumstances, we have developed a pump for feeding trace liquids⁽²⁾. Since bimorph-type piezoelectric elements are applied for the pump as the actuator, the pump can easily cope with multichannel uses and provide continuous feed at very low pulsation.

Some prior studies^{(3),(4)} have reported on application of piezoelectric elements for the pump. The pump is characterized by a hardware structure which is adapted to multichannel use by laying channels one after another, in series, and is also adapted to multistage use in order to improve discharge pressure by laying stages one next to another, in parallel.

This paper describes the experimental results on

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the fundamental characteristics of a single-stage, single-channel test model and a three-stage, single-channel test model.

2. Nomenclature

- D : Effective diameter of piezoelectric element
 V : Voltage
 Q : Flow rate
 U : Displacement of piezoelectric element
 d_{31} : Piezoelectric constant
 f : Frequency of piezoelectric element
 h : Height of spherical crown
 k : Constant
 n : Number of piezoelectric elements
 r : Radius of sphere
 t : Thickness of piezoelectric element
 ϵ : Stagnation factor

3. Description of Pump for Trace Liquid Feed

3.1 Structure

Figure 1 shows a schematic of a three-stage, three-channel pump model. In it, the first, the second and the third stages are arranged one after another in the flow direction. In other words, it employs a multistage structure in order to ensure sufficient discharge pressure for its proposed use. Discharge pressure can be easily increased by adding stages. This pump unit per channel with three stages is 50 mm long, 20 mm wide, and 3.5 mm thick. Its flow path has a straight pipe of 1 mm outer diameter and 0.7 mm inner diameter. It has a nozzle with a 0.3 mm diameter opening at the discharge end. Also, each stage has two piezoelectric elements in order to double the flow rate by doubling the displacement volume.

Generally, piezoelectric elements are classified into two types: lamination and bimorph. In order to simplify the structure of the pump, the bimorph-type

Fig. 1 Schematic of 3-stage, 3-channel model (unit: mm)

piezoelectric element (12 mm diameter $\times$ 0.4 mm thickness) is employed. This allows the element to obtain sufficient displacement even without any displacement scale-up mechanism. These two upper and lower piezoelectric elements in a stage are driven against each other to squeeze out the liquid between them, and at the same time, the elements in each stage are operated in different phases from those in the other stages so as to continuously transfer the liquid from the suction stage to the discharge stage.

Furthermore, in order to obtain an inner volume of the pump chamber close to the displacement volume of the piezoelectric elements, a convex silicone rubber liner is attached to the surface of the elements. This ensures that the liquid flow will achieve sufficient pressure against the flow path resistance. Also, it can prevent the element performance from being degraded due to direct contact with the liquid. Moreover, a fluorocarbon polymer film is coated on the rubber liner surface to prevent sticking where the rubber liners touch each other and to provide good waterproofing.

If the single-channel pumps thus structured are laid one on top of another, the intermediate piezoelectric element can be shared by two channels, and therefore a micro-pump suitable for multichannel use can be created.

Figure 2 shows a photograph of the three-stage, single-channel test model, one of the test models made so far. In the upper and lower parts of the pump, six piezoelectric elements are provided. Only the upper three can be seen through the acrylic resin plates, which are marked with a "+" on their surface. The direction of liquid flow in the pump is from right to left, and the nozzle at the tip of the outlet can be seen.

Figure 3 shows a schematic of the float-type micro-check valve used in this test model pump. This micro-check valve controls the flow direction by means of the movement of a polycarbonate float inside. In order to miniaturize the entire pump, the

Fig. 2 Photo of 3-stage, 3-channel model

Fig. 3 Schematic of micro-check valve

Fig. 4 Control method of piezoelectric elements in test model

micro-check valve is constructed so that it can be mounted in the flow path of the pump. This micro-check valve works as follows: the liquid flows through the slit in the rear part of the float in the forward direction while the flow in the reverse direction is blocked by the float. The micro-check valves were installed at two positions, on the suction and discharge sides.

3.2 Driving method

Figure 4 shows the driving control method for the piezoelectric elements. As described above, the elements in the same stage are driven at a phase difference of 180° , and the phase differences in the stages are defined from an upper element in the first stage; that is, the phase differences are controlled so that the second stage is delayed by $\Delta\theta_{12}$ after the first stage, and the third stage is delayed by $\Delta\theta_{23}$ after the second stage. In this way, the water in the pump chamber is continuously discharged in the direction of the flow.

Table 1 Element driving unit specifications

Wave Shape	Rectangular
Number of Channels	10
Voltage (V)	0–60
Frequency (Hz)	0–9.99
Phase Difference ($^\circ$)	0–359

Fig. 5 Experimental apparatus

4. Experimental Apparatus and Method

4.1 Experimental apparatus

Figure 5 shows an outline of the experimental apparatus. Driving of each piezoelectric element of the test pump can be controlled independently with the piezoelectric element driving device. Table 1 lists specifications of the driving unit. The output waveform is rectangular, and a maximum voltage of 60 V can be generated. The rectangular waveform for element driving reflects the fact that it takes a shorter time to obtain the maximum voltage application than with sine wave driving; this means the flow rate can be increased. The structure is arranged so that the water in the water level tank is always circulated to maintain a constant water level, and at the same time, the center of the pump is adjustable according to the water level to eliminate the effect of the suction head. A system is adopted in which the liquid flow from the tank is continuously supplied into the test pump, and the amount discharged from the pump is measured by weighing with an electronic balance which transmits the data to a personal computer.

4.2 Experimental method

For the basic characteristics of the pump, the effects of the driving frequency and phase difference of the piezoelectric element on the flow rate and the discharging pressure are considered. The flow rate of the pump was measured by a gravimetric method, and was obtained from the average value for two minutes. The measuring time of two minutes was chosen since no flow rate fluctuation was recognized during that time. Also, in order to determine the pump

discharging pressure, a fluorocarbon polymer tube was installed vertically at the tip of the test pump outlet, and the height of the liquid level in the tube was measured. In this experiment, it was confirmed beforehand that the effect of the surface tension on the liquid level was negligibly small. In addition, purified water was used in the experiment.

5. Experimental Result and Consideration

5.1 Shape of the interior of the pump chamber

Before the basic characteristic experiment, we investigated fundamental aspects of the shape of a convex rubber liner inside the pump chamber. In particular, we studied the effects of the interior volume per element displacement on the pumping performance. In the experiment, we tested three types of models which differed in curvature radii. Two of them are shown in Fig. 6. The third type was a model for $R=\infty$. The model in Fig. 6(a) was designed so that the curvature radius was 25 mm, and the top of the rubber was at the same height as the center of the inlet and outlet. In order to classify the inner volumes of the models, the dimensionless average gap G defined by Eq.(1) was introduced. According to Eq.(1), the dimensionless average gap G of this model was 15.

$$G = \frac{\text{(Average gap between upper and lower rubber liners)}}{\text{(Displacement of piezoelectric element)}} \quad (1)$$

In other words, the average gap between the upper and the lower silicone rubber liners was 15 times the displacement (on the basis of 60 V, and a no-load condition) of the piezoelectric element. On the other hand, the model in Fig. 6(b) had a curvature radius of 13 mm, about half the previous one, and

Fig. 6 Shapes of rubber liners inside pump chambers

consequently the dimensionless average gap was $G=35$. The $R=\infty$ model had a curvature radius of ∞ ; that is, it was made flat, and therefore $G=0$.

Table 2 lists specifications of the silicone rubber used as a liner. This silicone rubber is mainly used for medical equipment and food product manufacturing equipment. Since the working temperature range is from -55 to 200°C , the rubber can withstand sterilization, such as in an autoclave. There is no problem even if it is applied to a pump for biological samples. Also, since it has a high bridge formation density, and small plastic deformation due to mechanical impact, stable feeding of trace liquid can be conducted even for a long time.

These convex rubber liners were installed in a single-stage, single-channel model for a preliminary experiment in which element driving frequency was used as a parameter. As a result, the $G=15$ -type pump exhibited good pump performance over a wide frequency range. However, the $G=0$ -type pump did not operate as a pump. The $G=35$ -type pump did operate as a pump, but had too low a flow rate, about 0.2 ml/min at a frequency of 100 Hz , and did not discharge at all in other frequency regions. These results are considered to be brought about by the interrelation between the volume of the pump chamber and the displacement of the element. In other words, if G is small, the movement of the element is blocked, and if G is large, no pressure sufficient to induce flow is delivered by the element. Therefore, only the results for the $G=15$ -type pump are described hereafter.

5.2 Performance of single-stage, single-channel model

Figure 7 shows the relationship between the flow rate of the single-stage model and the driving frequency of the piezoelectric element. In the experiment, the elements were driven at 60 V to evaluate the validity of the micro-check valve, using the model with and without the valve. Both cases, with and without the valve, showed good pump performance at a high frequency. When the valve was used, the dischargeable frequency region was narrowed by about 100 Hz because of the increased resistance due to the valve presence, but the flow rate was increased

Table 2 Rubber specifications

Use in Medical Equipment	Pasteurization
Temperature ($^{\circ}\text{C}$)	$-55 - 200$
Specific Gravity	1.07
Rubber Hardness	20

Fig. 7 Relationship between flow rate and frequency of single-stage model

Fig. 8 Effects of voltage of single-stage model

by about 1.5 times at all frequencies of 250 Hz or less, which indicated that the float-type test micro-check valve functioned effectively. Also, the maximum flow rate was increased from 0.7 ml/min to 1.2 ml/min (about 1.7-fold). Figure 8 shows the relationship between the flow rate of the single-stage model with the micro-check valve and the driving voltage of the piezoelectric element. Here, three driving frequencies were used for the piezoelectric element: 50, 100 and 200 Hz. At any of these, the relationship between the voltage and flow rate was linear. This was because the displacement U of the piezoelectric element was proportional to the driving voltage V , as expressed in Eq. (2). In other words, the pump flow rate was subject to the voltage control.

$$U = k \cdot d_{31} \cdot (D/t)^2 \cdot V \quad (2)$$

Also, this pump does not function as a pump in a region of driving voltage of 25 V or less because of flow resistance at the nozzle.

Then we calculated the pump flow rate on the basis of a simple theoretical model. First, the volume S of the silicone rubber liner installed on the surface

Fig. 9 Relationship between stagnation coefficient and frequency

of the piezoelectric element can be approximated by the formula of a spherical crown.

$$S = 1/3 \cdot \pi \cdot h^2 \cdot (3r - h) \quad (3)$$

When a fixed voltage is applied to this piezoelectric element, the element and the silicone rubber are deformed to increase or decrease the volume of the liquid in the pump chamber. First, the volume S' of the silicone rubber is found when the piezoelectric element is deformed in such a direction as to discharge the liquid. For simplicity, if the rubber is assumed to be uniformly deformed,

$$S' = 1/3 \cdot \pi \cdot (h')^2 \cdot (3r' - h') \quad (4)$$

where $h' = h + U$, and $r' = r + U$.

This difference ($S' - S$) in the volume of the silicone rubber liner is a unit of volume discharged by one stroke of the piezoelectric element. The displacement U of the test element is 16.6 μm when the element is free from a load and not rigidly fixed.

Since, however, the element is fixed and supported over the entire periphery in this pump, the deformation is markedly reduced. When, for simplicity, the element is assumed to be a beam fixed rigidly at both ends, the deformation becomes $U = 3.3 \mu\text{m}$, 1/5 of that of the nonfixed beam model. Since all the surfaces of the upper and lower silicone rubber liners cannot touch each other at all points because of their convex-shape, all the liquid that flows into the pump chamber is not sent out. Assuming the stagnation factor of the liquid to be ϵ , the flow rate can be represented by the following expression:

$$Q = \epsilon \cdot n \cdot f \cdot (S' - S) \quad (5)$$

Figure 9 shows the relationship between the driving frequency of the piezoelectric element and the stagnation factor ϵ . As can be seen also from Fig. 9, only 1/4 or less of the liquid flowing into the pump can be sent out, and yet the stagnation factor decreases as the frequency is increased. The reasons for the above are considered to be neglect of the flow resistance and

the silicone rubber elasticity in the simple theoretical model.

Figure 10 shows the relationship between the discharging pressure of the single-stage model and the driving frequency of the piezoelectric element. Only the discharge pressure of about 0.2 - 0.3 kPa was given in the entire frequency region for the pump without any micro-check valve. On the other hand, the pump with a micro-check valve had a discharging pressure of about 9 kPa at frequencies of 50 Hz or less, so it could be confirmed that the discharging pressure was effectively improved by the micro-check valve. However, it was found that hardly any discharge pressure was generated in a region of frequency of 100 Hz or more. This was because the float in the micro-check valve was pushed by the water column in the discharge pressure measuring tube. In other words, due to the water column blockage, eventually the movement of the float could not follow the driving frequency of the piezoelectric element. As a result, the movements of the water column and the float were out of phase, which caused the water to increase the flow stagnation. From these results, it was presumed that the optimal frequency of the float-type test micro-check valve at the maximum discharge pressure would be gained in the vicinity of 50 Hz.

5.3 Performance of a three-stage, single-channel model

Figure 11 shows the relationship between the driving frequency and the flow rate of the three-stage model without the micro-check valve. Here, the phase differences between each stage of the pump were parameters, and phase difference $\Delta\theta_{12}$ between the first and the second stages and phase difference

Fig. 10 Relationship between discharge pressure and frequency of single-stage model

$\Delta\theta_{23}$ between the second and the third stages were set as the same value in the experiment. Consequently, it turned out that the larger the phase difference, the higher the flow rate became; pumpability was demonstrated even in the higher frequency region. The maximum flow rate at a phase difference of 90° was 1.2 ml/min, and the pump had the same flow rate as the single-stage model with the micro-check valve. However, although it was effective to reduce the pump pulsation when it was driven at a higher frequency, vibration noise and wear of the element were significantly increased. Therefore it would be preferable to drive the pump at a lower frequency as long as the low pulsation could be maintained regarding the above, along with the response characteristics of the rubber liner, the pump, and the valve. From the viewpoint of cost, 50 to 60 Hz power frequency is preferable since it is commercially and inexpensively available.

Fig. 11 Relationship between flow rate and frequency of 3-stage model

Fig. 12 Relationship between flow rate and phase difference of 3-stage model (With micro-check valve)

Fig. 13 Relationship between flow rate and discharge pressure of 3-stage model (With micro-check valve)

Figure 12 shows the relationship between the flow rate of the three-stage model with the micro-check valve and the phase differences between of the stages. Here, the frequency was set at the low region of 50 and 100 Hz in the experiment. At either frequency, although there was a slight peak at a phase difference of 10° , generally the flow rate tended to decrease when the phase difference was increased. However, the absolute flow rate was markedly increased as compared with the single-stage model. For example, the maximum flow rate at a frequency of 100 Hz was 2.5 ml/min, about double that of the single-stage model, and the multistage effect of the pump was also recognized to be valid in order to increase the flow rate.

Figure 13 shows the Q - H characteristics of the three-stage model with the micro-check valve. The smaller the driving frequency of the element, the higher the discharge pressure of the pump became. The maximum discharge pressure at a frequency of 10 Hz was 18 kPa. This value was about double that of the single-stage model, and it could be confirmed that the discharge pressure was effectively improved by adding stage after stage. In this respect, we believe that it will be feasible to further improve the discharge pressure by installing a micro-check valve between the pump stages.

6. Conclusions

As a pump able to easily cope with multichannel

and continuous low-pulsation supply, we developed a microquantity pump which applies piezoelectric elements in a specific way. Two types of test models were investigated experimentally for their basic characteristics. The results are summarized below.

(1) The shape of the rubber liner on the piezoelectric elements inside the pump chamber was one of the factors determining the pump performance, and among the tested shapes, the one with an average gap between the rubber liners 15 times larger than the displacement of the element had a good performance.

(2) The increase in the number of stages of the pump was an effective way to increase the flow rate and discharge pressure, and the three-stage, single-channel model had double the performance of the single-stage, single-channel model.

(3) The three-stage, single-channel model achieved a maximum flow rate of 2.5 ml/min and a maximum discharge pressure of 18 kPa.

(4) The three-stage, single-channel model clarified that the multi-stage structure of the pump, where the element controls were almost in phase, was effective in increasing the flow rate in addition to the discharge pressure, which was expected beforehand.

(5) Since the pump flow rate depended linearly on the driving voltage of the piezoelectric element, the flow rate was easily adjusted by changing the voltage.

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