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Development of serial-connection piezoelectric pumps

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Abstract

To achieve high output performance at low actuation voltage, serial-connection multi-chamber piezoelectric micropumps (SCMCP micropumps) with cantilever valves were introduced. The SCMCP micropumps, which can be produced using conventional production techniques and materials, have a multi-layer circular planar structure. The border-upon piezoelectric diaphragm actuators (PZT actuators) of a SCMCP micropump work in anti-phase, as a result of which the output performance is equal to that of several single-chamber piezoelectric micropump (SCP micropump) running in series. The theoretic study suggests that pumping performance of a SCMCP micropump depends on not only the characteristic and geometrical parameters of the PZT actuators, but also the number of the pump chambers. Both flowrate and backpressure of a SCMCP micropump can be enhanced to a certain extent in this way. Four piezoelectric micropumps with different chambers were fabricated and tested for comparison. The testing results show that all of the flowrate, backpressure and even optimal frequency of the SCMCP micropumps increase greatly with the rising of the chamber number. Both the maximum flowrate and pressure of the 4-chamber piezoelectric micropump are about four times of those of the SCP micropump at their respective optimal frequencies. The great advantage of a SCMCP micropump over a SCP micropump is that it can achieve high performance at a comparatively low driving voltage, which is helpful for the portable applications such as an implantable drug-delivery system.

Keywords: Micropump; PZT actuator; Multi-chamber; Cantilever valve

1. Introduction

Micropumps are the essential components in micro-fluidic system which has been emerged as a popular area of research with the development of micro-electro-mechanical system (MEMS). Due to their precisely controlled flowrate, micropumps present their promising applications in analytical chemistry, medical treatment, pharmacy, bioengineering, fuel-drop generator for automobile heaters, etc. [1,2]. Since one of the early piezoelectric micropumps for insulin delivery was fabricated [3], more and more efforts have being made in the research of micropumps. Up to now, almost the whole range of microactuation techniques available have been used to design micropumps, such as electromagnetic [4,5], electrostatic [6], shape memory alloy (SMA) [7], thermopneumatic [8,9] and piezoelectric actuation [10–12].

Piezoelectric actuation was the first actuation principle used for micropumps. It is a very attractive concept, as it provides a comparatively high stroke volume, a high actuation force and a fast mechanical response. Nevertheless, the comparatively high actuation voltage was regarded as disadvantages [2]. To achieve higher performance at lower operation voltage, optimization of the geometrical design was done in several places [13–16] in the last decade. Even though, the flowrate and backpressure of piezoelectric pumps are still limited and cannot be applied widely. Higher drive voltages have to be used for most of piezoelectric pump to achieve desired flowrate and backpressure. Typical actuation voltages of the optimized design are in the range of 100 V, which is a significant improvement in comparison to other micropumps that sometimes use commercial piezo buzzers without any optimization [2]. However, the actuation voltage of 100 V is still too high to be used for the medical applications, especially the implantable drug-delivery system. At the same time, a stand-alone driving circuit is necessary for such portable applications, and low actuation voltage is helpful for the design of highly miniaturized electronic drivers which allow low-power operation from a battery [17].

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Presently, most of piezoelectric micropumps are developed with single pump chamber. Further enhancement of their output performance with optimization design and rising voltage are limited. It is well known that the flowrate and backpressure of a SCP micropump cannot be improved simultaneously by changing diameter and thickness of the PZT actuator at a given operation voltage. With the rising of the actuator diameter, the flowrate increases, while the pressure decreases. In this situation, another effective method to obtain desirable flowrate and backpressure without increasing voltage is to construct multi-chamber pumps. Owing to its simple planar structure, the PZT actuators are appropriate to multi-chamber micropump. Double-chamber valveless piezoelectric micropumps were developed successively by Ullmann [18] and Kim [19]. Investigation results show that a series-connection valveless piezoelectric micropump is usually advantageous to a parallel one even for the purpose of increasing the flowrate. Large double-chamber check-valve piezoelectric pumps were developed for performance comparison by Kan [20]. Experiments were carried out at the same voltage and frequency. The results suggest that the parallel-connection pump enhance flowrate, while the series-connection one enhance both of the flowrate and backpressure greatly compared with a SCP pump. Another type of piezoelectric pumps consisting of three series-connection chambers is called peristaltic micropumps [16,17,21], in which the first and third PZT actuators functioned as the check-valve actually and make no additional contribution to improving performance. Thus, the peristaltic micropump doses not belong to the so-called multi-chamber pumps. The above researches on the double-chamber piezoelectric pumps indicate an alternative method to obtain high performance. In contrast with the valveless piezoelectric micropumps [18,19,22], the check-valve piezoelectric micropumps [23–25] are high flowrate, high backpressure, precise and without back-flow. Thus, the multi-chamber check-valve micropumps will enhance pumping performance remarkably. However, the researches on check-valve micropumps with more chambers have not been widely explored to the author's best knowledge.

In this work, cantilever-valve piezoelectric micropumps with 1-, 2-, 3- and 4-chamber were developed. The influence of chamber number on pump performance in terms of flowrate, backpressure and even optimal frequency was studied experimentally at a low voltage of 40 V. The previous investigations [26,27] show that a membrane-actuator-driven pump are able not only to pump liquid, but also to actuate/control a cylinder system. Thus, a multi-chamber pump using large PZT actuator and high voltage is more suitable for such an application.

2. Structure and working principle of the cantilever-valve piezoelectric micropumps

A piezoelectric micropump can transfer mechanical energy into fluid movement when the PZT actuator is operating in bending vibration mode. This vibration mode shows its advantage of lower natural frequency than that of radial and width mode with the same dimensions. With a PZT actuator, kinds of micropumps have been investigated, such as valveless, check-valve and peristaltic piezoelectric micropumps. Because of the difference of structure and principle, they present different performance of flowrate, backpressure and optimal frequency. This work focuses on the multi-chamber cantilever-valve piezoelectric micropumps.

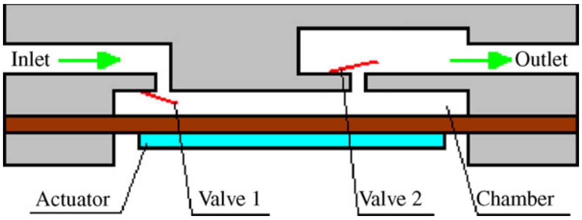


Fig. 1. Schematic cross-section of 1-chamber PZT pump.

2.1. A SCP micropump

A SCP micropump (Fig. 1) consists of pump body, a PZT actuator and two cantilever valves, from which a pump chamber forms. When the PZT actuator is operating in bending vibration mode, the pressured liquid in the chamber opens and closes the valves alternately. As a result of this, the liquid moves from the inlet to outlet continuously. If the PZT actuators are operated at a frequency well below its natural frequency, its central displacement and generated pressure are expressed as [3]

$$\delta = \frac{3}{8} d_{31} \frac{d^2}{t^2} U \tag{1}$$

$$P_g = \frac{12\pi Y_{11}^D d_{31}}{4.5\pi Y_{11}^D g_{31} d_{31} + 1} \frac{t}{d^2} U \tag{2}$$

where d and t are the diameter and thickness of the PZT actuator, d_{31} and g_{31} are the piezoelectric constant, Y_{11}^D is the elastic modulus of piezoelectric material, U is driving voltage. When a voltage is applied, the PZT actuator is assumed to have a spherical displacement, and the volume displaced per stroke is given by [3]

$$\Delta V = \frac{\pi d^2}{8} \delta = \frac{3\pi}{64} d_{31} \frac{d^4}{t^2} U. \tag{3}$$

Thus the flowrate against zero pressure head can be roughly estimated by [28]

$$Q_g = \Delta V f = \frac{3\pi}{64} d_{31} \frac{d^4}{t^2} U f. \tag{4}$$

It should be noted that Eqs. (2) and (4) indicate only the performance of a piezoelectric pump without considering the influence of valve style, inlet/outlet diameter, chamber volume and so on. It is well known that all of the flowrate, backpressure and optimal frequency of a check-valve pump are different from those of a valveless pump. Thus, the check efficiency of the valves should be introduced, and the output flowrate and backpressure of a 1-chamber pump should be expressed as

$$Q_{\text{one}} = Q_g \eta_Q \tag{5}$$

$$P_{\text{one}} = P_g \eta_P \tag{6}$$

where η_Q and η_P are the check efficiency of the check valves.

For the movement of the check valves in piezoelectric micropumps is a driven harmonic oscillation, the actions (open/close) of the passive check valves are always lag behind the vibration of the PZT actuator. Therefore, both the valve opening (defined as frequency-dependence amplitude) and the phase shift (φ, between the movement of the actuator and the valve) exert great influence on the check efficiency. When the driving frequency is much lower than the natural frequencies of both the check-valve and the actuator, the valve opening and the actuator deflection can be considered as constant. In this case, the flowrate of the pumps depends mainly on the check efficiency of the valve, which decreases with the increasing of the phase shift ($\eta_Q \propto 1/\varphi$). Thus, the there will be a lower frequency (f_0) for the product of η_Q and f_0 to reach maximum. Consequently, the output flowrate is not linear with the working frequency, and there is an optimal working frequency f_0 (well below the resonant frequency in the air), at which the maximal output flowrate can be achieved. Eq. (5) is valid only for the case of $f \leq f_0$. The relationship among η_Q, f_0 and φ was presented [25].

There are many factors exerting effect on the output value of a piezoelectric micropump such as working parameters (voltage and frequency) and geometrical parameters of the PZT actuator. In the case of a given pump diameter, we can rise flowrate with decreasing the actuator thickness; or heighten backpressure by increasing the actuator thickness. For the limited maximum driving voltage, it is difficult to increase the flowrate and pressure simultaneously with changing the geometrical parameters of the PZT actuator. In this condition, the introduction of multi-chamber structure is necessary to enhance pump performance further.

2.2. A SCMCP micropump

With planar PZT actuators, series/parallel-connection and peristaltic micropumps can be developed. Nevertheless, serial-connection micropumps are helpful to improve both of flowrate and back-pressure. A SCMCP micropump is that the inlet and outlet of SCP micropumps are connected serially one by one. Taking the 4-chamber piezoelectric micropump for example, the structure and working principle are presented in Figs. 2 and 3, respectively. In the figures, A_i, V_i and C_i ($i = 1, 2, 3, 4$) denote the actuators, valves and chambers, respectively.

As shown in Fig. 3, the PZT actuators of the border-upon chambers work in anti-phase. When an alternating voltage is applied, bending displacement occurs on the PZT actuators, accordingly, the chamber volume changes alternately. At the first half-cycle (shown in Fig. 3(a)), C1 and C3 enlarge and underpressure occurs in them. Meanwhile, the decreasing volume of C2 and C4 leads to overpressure. The changing liquid pressure makes V1/V3/V5 open and V2/V4 close. As a result, liquid moves from inlet to C1, C2 to C3, and C4 to outlet. Likewise, at the second half-cycle (Fig. 3(b)), liquid moves from C1 to C2, and C3 to C4. Apparently, no liquid is sucked in or discharged out at the second half-cycle of the 4-chamber pump, but the pressure is enhanced.

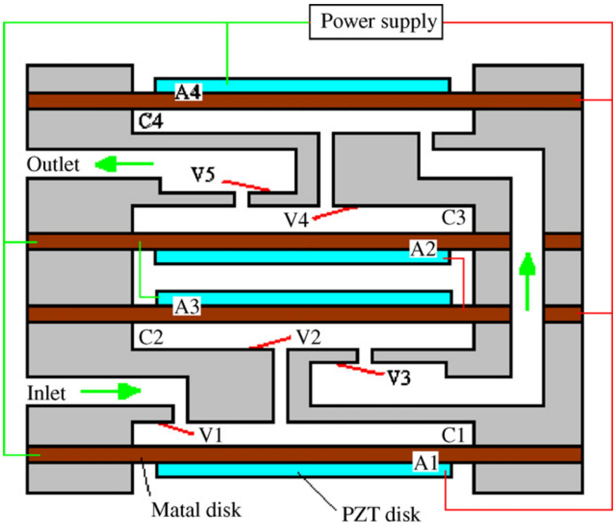


Fig. 2. Schematic cross-section of serial-connection 4-chamber PZT pump.

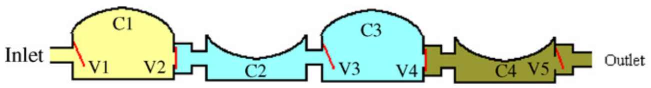
The working principle of the diaphragm pump can be described as a periodic process. In this operation mode, the output performance of a SCMCP micropump is equivalent to that of some SCP micropumps operating in series. Theoretically speaking, the backpressure of a SCMCP micropump should be the sum of that of all chambers running solely, i.e. $P_{\text{multi}} = \mathrm{P}_1 + \mathrm{P}_2 + \cdots, P_n$, where n is the chamber number. Give all chamber share the same check efficiency (η_P), there will be $P_i = P_g \eta_P = P_{\text{one}}$. Thus, the backpressure of a SCMCP micropump can be expressed as roughly

$$P_{\text{multi}} = n P_{\text{one}}. \tag{7}$$

For a SCMCP micropump, the flowrate cannot be expressed in the form of Eq. (5). According to the relationship between the flowrate and pressure, there will be [19]

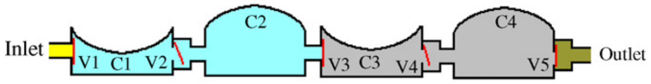
$$Q = C_v A \sqrt{2 \Delta P / \rho} \tag{8}$$

where C_v is the velocity coefficient, A the area of the valve orifice, ρ the liquid density, and ΔP is the pressure difference from inlet to outlet. In case of zero output pressure, there will be $\Delta P = P_{\text{one}}$ for a SCP micropump, and $\Delta P = P_{\text{multi}}$ for a SCMCP micropump. Give all chambers share the same the check efficiency (η_Q), the flowrate against zero pressure head of a SCMCP



Liquid movement: Inlet to C1; C2 to C3; C4 to Outlet

(a) First half-cycle



Liquid movement: C1to C2; C3 to C4
(b) Second half-cycle

Fig. 3. Working principle of the serial-connection 4-chamber PZT pump.

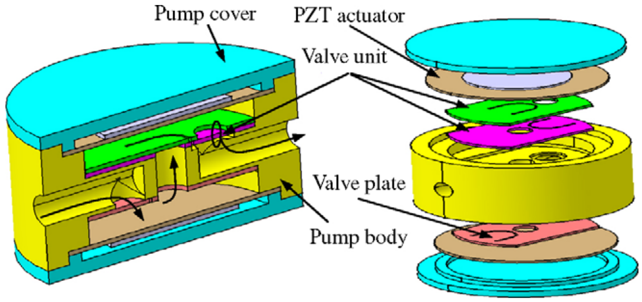


Fig. 4. Assembly structure of the 2-chamber piezoelectric pump.

micropump can be deduced as

$$Q_{\text{multi}} = C_v A\sqrt{\frac{2nP_{\text{one}}}{\rho}} = \sqrt{n}\,Q_{\text{one}}. \tag{9}$$

Eqs. (7) and (9) suggest that both back-pressure and flowrate can be improved with increasing the number of the serial-connection chambers. It should be well noted that the piezoelectric pumps discharges unsteady-flow liquid. Therefore, the above equations indicate only the enhancement trend of pump performance roughly. At present, it is difficult or impossible to build an effective analytical model for accurate calculation. The improving extent of performance of a SCMCP micropump can be obtained only with experiments finally.

3. Fabrication and experiments

As aforementioned, piezoelectric micropumps have applications in analytical chemistry and medical treatment. Therefore, appropriate fabrication methods, materials, and assembly method should be selected to satisfy the requirements of mass production so as to make the price as reasonable as possible. Taking a serial double-chamber micropump for example, the fabrication process is introduced here.

The assembly structure of the 2-chamber pump is shown in Fig. 4. At present, both the pump body and pump covers are made of PMMA and manufactured by a precision-carving machine. In the case of mass production, they can be fabricated by cast plastic. The two important components of such a piezoelectric micropump are the PZT actuators and cantilever valves. To obtain repeatability of the micropump, all of the components should be fabricated and located carefully. The cantilever valves were made of beryllium bronze membrane 0.05 mm in thickness and fabricated also by the precision-carving machine to obtain sufficient accuracy. The valve size of cantilever type was designed to be 4 mm × 1.35 mm. The valve orifices and the inlet/outlet orifices are 0.5 and 0.8 mm in diameter, respectively. The finished valve parts were adhered to the surfaces of the pump body. The actuator consists of a circular piezoelectric membrane (Ø 8 mm × 0.15 mm) glued on nickel membrane. The thickness and diameter ratio of the two materials are designed to be 1 and 0.8, respectively, so as to achieve the largest displacement of the PZT actuators [13]. After the valve unit and the actuators were assembled, a pump chamber (Ø 10 mm × 0.2 mm) was set up. Serial piezoelectric micropumps with 1-, 2-, 3- and 4-chamber were fabricated using the same materials and method to contrast with each other. The finished pumps are shown in Fig. 5.

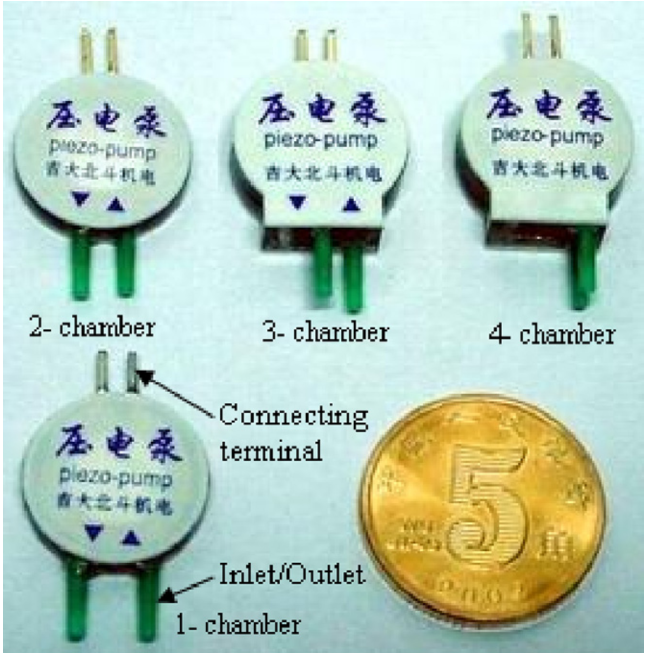


Fig. 5. Photo of the fabricated piezoelectric pumps.

The fabricated pumps were tested with water as working medium at the driving voltage of 40 V, which is close to the secure voltage. The AG1200 Arbitrary Waveform Generator and the 7058 Power Amplifier were used as the source of the micropumps. The driving force was a double-channel voltage signals. In this work, a series of experiments were conducted to find out the performance of the SCMCP micropumps.

At first, the flowrate against zero pressure and pressure against zero flowrate were tested at different operating frequencies. Figs. 6 and 7 present the influence of the number of the pump chambers on the output flowrate and pressure, respectively. The curves indicate that both the flowrate and back-

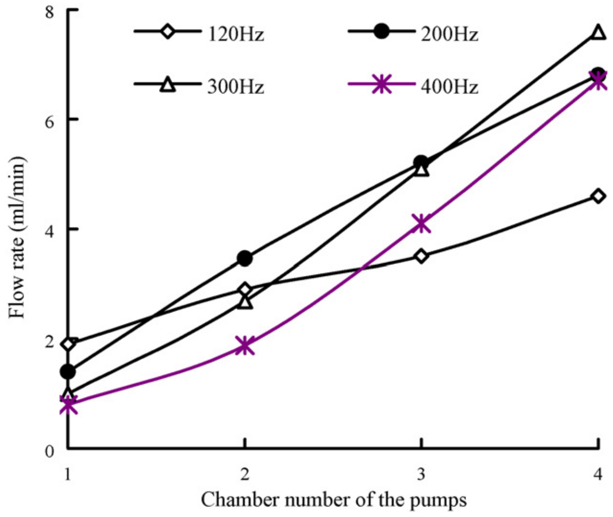


Fig. 6. Flowrate vs. the number of chambers of the micropumps.

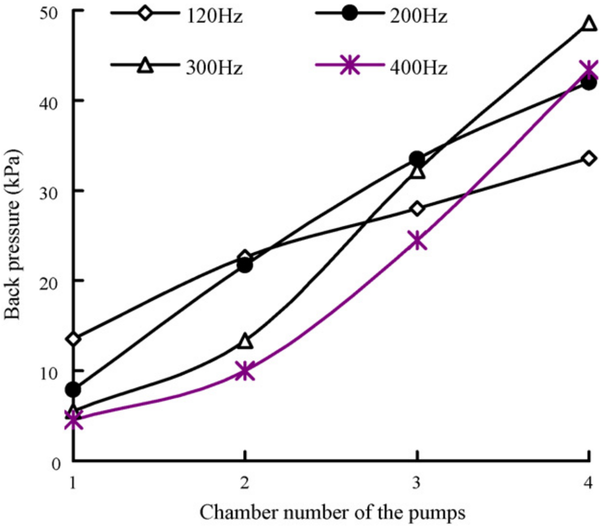


Fig. 7. Backpressure vs. the number of chambers of the micropumps.

pressure rise with the increasing of chamber number at the same driving frequency. The 4-chamber micropump achieve its maximal flowrate of 7.6 ml/min and backpressure of 48.6 kPa at 300 Hz, respectively, which are 7.5 and 10.6 times those of the 1-chamber micropump under the same operating conditions. The curves show also that the changing regular of output flowrate and backpressure is not all the same at different frequencies. This suggests that the micropumps should have different frequency-dependence flowrate and backpressure, i.e. perhaps they have their respective optimal frequencies. It was proved with farther experiments.

Figs. 8 and 9 present the change of the flowrate and backpressure with driving frequency. From the figures, we can find that the optimal frequencies are not constant, but rise slowly with the increasing of the chamber number. The possible reason for this is that the check efficiency increases with the rising of the chamber number. Previous investigation shows that the optimal frequency of a passive check-valve piezoelectric micropump depends mainly on the check efficiency of check valves (η_Q), which increases with the decreasing of the phase shift (φ) between the PZT actuator and check valves [25]. For the SCMCP micropumps, the opening/closing movement of the shared valves (V2, V3 and V4, in Fig. 3) are caused by the changing liquid pressure of the two border-upon chambers together (one chamber pushes and the other pulls). Thus, lesser "resting liquid" before the valves obstructs them from motion. That is to say, the liquid reaction force against the motion of the valves decreases. The liquid resistance is usually represented as an added-damping contribution to the dynamic response of the valves [29]. Therefore, the phase shift between the check valves and PZT actuators decreases, and the check efficiency of valves increases. Correspondingly, the driving frequency for $\eta_Q f$ to achieve maximum is the optimal frequency, which increases also with the decreasing of the phase shift. At the same time, the decreasing liquid resistance is helpful for the cantilever valves to achieve large opening, which allow more liquid to pass through. Based on the above analysis, a conclusion can be drawn that the check efficiency and optimal frequency of a SCMCP micropump increase with the rising of chamber number.

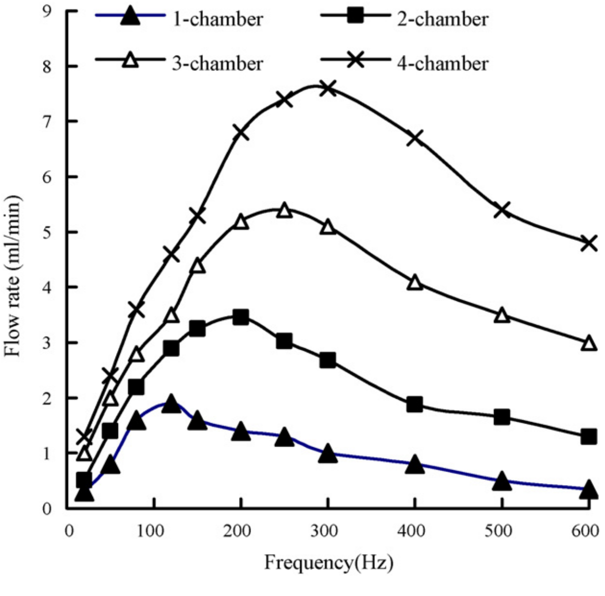


Fig. 8. Relationship between the flowrate and driving frequency.

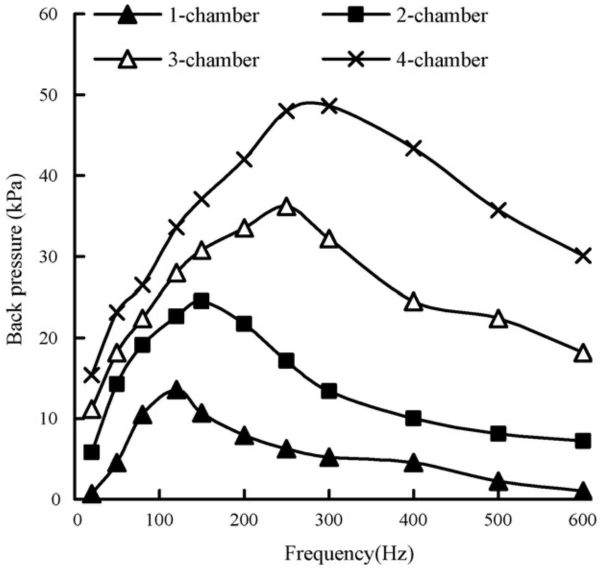


Fig. 9. Relationship between the backpressure and driving frequency.

Since the SCMCP micropumps have their respective optimal frequencies for them to achieve the maximal output capability, the improving extent of pump performance is not the constant at different operating frequencies. The enhancing degree of the maximal flowrate and backpressure of the SCMCP micropumps at the respective optimal frequencies are presented in Figs. 10 and 11, respectively. In the figures, real lines denote test results, and broken lines express the theoretical calculation with substituting the test data of the 1-chamber pump into Eqs. (7) and (8). Clearly, both the maximal flowrate and backpressure achieved from the 4-chamber micropump are about 4 times those from the SCP micropump. It is in great agreement with the theoretical calculation for the backpressure (as shown in Fig. 11). Nevertheless, there is a great discrepancy between the test results

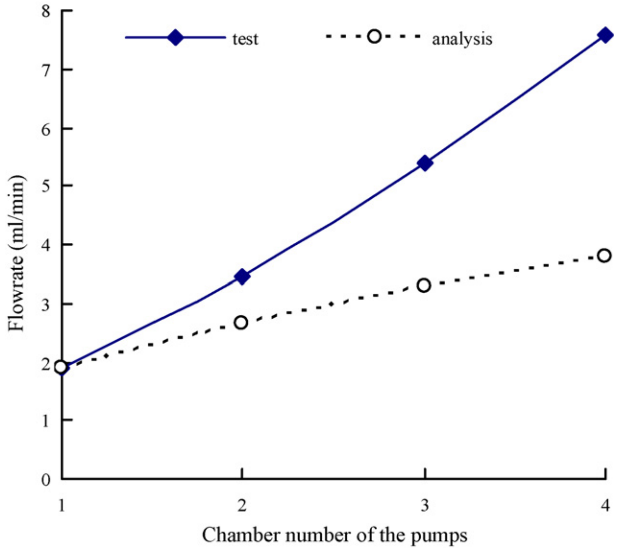


Fig. 10. The maximal flowrate vs. the number of chambers of the SCMCP micropumps.

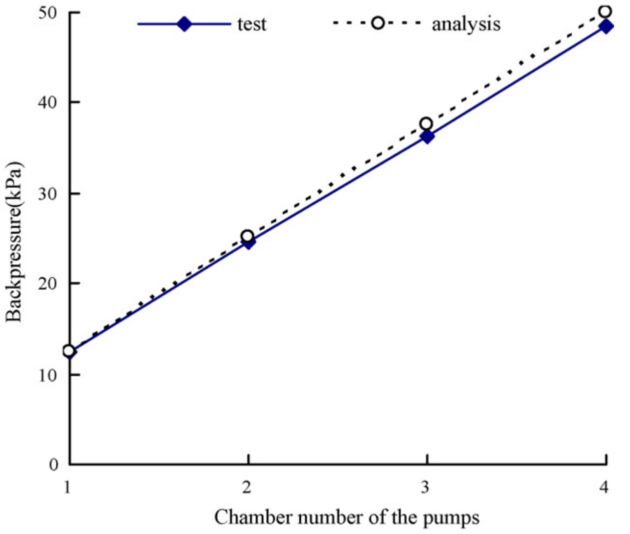


Fig. 11. The maximal backpressure vs. the number of chambers of the SCMCP micropumps.

and theoretical analysis of the flowrate (as shown in Fig. 10). The 4-chamber micropump should obtain 2 times flowrate of the SCP micropump in theory. The possible reasons for such a discrepancy are the followings: (i) the check efficiency of cantilever valves in the SCMCP micropump is higher than that in the SCP micropump, which was not taken into account theoretically; (ii) Eq. (9) was deduced in the case of continuous flow, and is not completely suitable for the pulsating flow of the piezoelectric micropumps.

4. Conclusions

The dependence of piezoelectric pumps on high driving voltage will become a bottleneck of portable applications. In order to obtain desirable flowrate and backpressure of piezoelectric micropumps at lower secure voltage, the SCMCP micropumps were investigated theoretically and experimentally.

The theoretic study shows that the capability and geometrical parameters of the PZT actuator exert great influence on the output performance of a piezoelectric micropump, i.e. decreasing the thickness or increasing the diameter of the PZT actuator is helpful for the improvement of the flowrate. While, decreasing the diameter or increasing the thickness is advantageous for the augment of the backpressure. Moreover, the serial-connection of multi-chambers can significantly enhance flowrate as well as backpressure.

Four SCMCP micropumps with 1-, 2-, 3- and 4r-chamber were fabricated and tested with water as the working medium. The test results show that both flowrate and backpressure of the SCMCP micropumps rise with the increasing of the number of pump chambers. At the same time, the SCMCP micropumps have their respective optimal frequency, which also increase slowly with the rising of chamber number. Both flowrate and backpressure of the SCMCP micropumps are in direct proportion to the chamber number at the optimal frequency. At a low voltage of 40 V, the maximum flowrate and pressure of the 4-chamber micropump are 7.6 ml/min and 48.6 kPa respectively, which are about 4 times those of the SCP micropump. Apparently, the achieved performance of the 4-chamber micropump and the working voltage can satisfy the need of medical applications even for implantable system. On the other hand, a large SCMCP pump can be used to drive a cylinder system. A linear actuator driven by a 9-chamber PZT pump was developed in the author's laboratory presently.

Acknowledgements

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