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To cite this article: Yiwen Fan *et al* 2022 *J. Micromech. Microeng.* **32** 055004

IOP Publishing

Journal of Micromechanics and Microengineering

J. Micromech. Microeng. **32** (2022) 055004 (9pp)

https://doi.org/10.1088/1361-6439/ac60a7

Development of a piezoelectric pump with unfixed valve

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Received 20 October 2021, revised 16 February 2022
Accepted for publication 24 March 2022
Published 4 April 2022

Abstract

Piezoelectric pump, driven by piezoelectric actuator, is one of the most promising micropumps in compact system. However, the application of piezoelectric pump is limited by the check valve, which is not efficient enough and needs careful fixation. This work presents a novel design with unfixed check valve, which greatly simplifies the assembly of valve-based piezoelectric pump and improves the output performance. The valve is unfixed with a small gap to obtain variable stiffness at different working stages, making it open more quickly. The piezoelectric pumps with three different valve gaps were designed, fabricated, and tested. The pump with the unfixed valve shows a 25.6% flow rate improvement compared with the fixed check valve without reducing the output pressure. To reveal the mechanism of the flow rate improvement, we investigated the flow resistance and the volumetric efficiency of the piezoelectric pump. The results show that the unfixed valve increases the volumetric efficiency of the piezoelectric pump, which improves the flow rate. The prototype pump achieved the maximum output performance of 162 ml min^{-1} and 33 kPa. The power consumption was less than 100 mW, reaching a pump efficiency of 21.7%.

Keywords: micropump, piezoelectric pump, passive check valve

(Some figures may appear in colour only in the online journal)

1. Introduction

Micropump is the heart of microfluidic system, which has been widely used as the key component for driving fluid in drug delivery [1, 2], fuel cells [3, 4], and electronic cooling systems [5–7]. Several kinds of micropumps have been developed with different working mechanisms, such as micromechanical pump [8], electroosmotic pump [9], electrohydrodynamic pump [10], and piezoelectric pump [11]. Among them, piezoelectric pump has a higher working efficiency and larger power density [11–13]. Therefore, it attracted the attention of both researchers and companies in recent times.

The piezoelectric pumps can be divided into valve-based pumps and valveless pumps according to the flow control method [11]. The valveless pump generates different flow resistance to control the flow direction by fixed structures, such as Tesla valve [14], diffusion nozzle [15], and fluid guiding body [16]. The valveless pump has a simple structure, but the performance of valveless pump is not good as the valve-based pump because of its low flow control ability. The valve-based pump utilizes movable check valves to obtain desired flow. The performance of valve-based pump is highly correlated with the design of the check valve [17]. A well-designed check valve is supposed to have low flow resistance, low reversed leakage flow, and quick response to the pressure change to maximize the desired flow.

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Various kinds of check valves have been proposed to improve the performance of piezoelectric pump, such as cantilever valves [18–20], two fixed ends valves [21–23], wheel valves [24–26], and umbrella valves [27–29]. With different structure and fixation, check valves show different deformation patterns under pressure and lead to different performance in piezoelectric pump. Cantilever valve has sheet-like structure with one end fixed and another free. With its simple structure, cantilever valve is preferable in miniature and integrated piezoelectric pumps [30, 31]. But it has poor cut-off performance and a small opening area, resulting in high leakage flow and high flow resistance at large flow rate. Two fixed ends valve has the same shape as cantilever valves. Differently, with two ends fixed structure, it is able to provide better cut-off performance. Wang *et al* designed a piezoelectric pump with two fixed ends polydimethylsiloxane (PDMS) valves, obtaining the maximum performance of 105 ml min^{-1} and 23 kPa [22]. To get better performance, Ye *et al* modified the valve deformation pattern by adding a blocking edge over two fixed ends PDMS valve, and improved the flow rate by over 40% and improved output pressure by 5–6 kPa [32]. Wheel check valves are another favorable kind of valves used in piezoelectric pumps. It is fixed at the valve ring and has a relatively high performance. Hwang *et al* developed a piezoelectric stack pump for UAV brake system with wheel check valves, providing an output of 205 ml min^{-1} and 5.2 MPa with a voltage of 900 V [26]. Peng *et al* proposed a high-flow piezoelectric pump driven by four chambers with umbrella-shaped valves, which achieved 1845 ml min^{-1} and 32.47 kPa with the voltage of 210 VAC at 120 Hz [27]. The umbrella valve is embedded in the central fixing hole of the valve seat, and it has good performance in most cases, but requires larger installation space. Despite the benefits provided by the valves mentioned above, they are generally glued on, clamped by or embedded in the valve seats, which is not easy to use and not compact. On the other hand, the flow resistance of the check valve system is very large when the valve opening is small. Unfortunately, the valve opening of fixed valves comes from valve deformation, which increases slowly under low pressure, hindering the further improvement of performance. The massive production of piezoelectric pump calls for better performance with a simple valve structure, fabrication and installation.

This study is dedicated to simplifying the assembly of the valve and improving the output performance of piezoelectric pump by designing unfixed valve with a small gap. The unfixed valve shows variable stiffness at different working stages. The valve is free when the valve opening is smaller than the valve gap, which enables the valve to open more quickly. A series of piezoelectric pumps were designed, fabricated, and tested with unfixed valves at different valve gaps. The unfixed valves only need to be placed in the valve seats without any additional step. We measured the output performance of the pumps simultaneously at different driving frequencies to investigate the effects of the unfixed valve. Moreover, the flow resistance and the volumetric efficiency are calculated to evaluate the efficacy of the valve design. All the results demonstrate that the new design improves the performance of the piezoelectric pump significantly.

2. Design and working principle

The basic structure of the prototype pump is illustrated in figure 1(a). The piezoelectric actuator consists of a piezoelectric ceramic (PZT) and a brass plate. The check valves adopted here are wheel check valves, as shown in figure 1(a), with thicknesses of 100 μm, 50 μm, and 25 μm, respectively. The wheel valve is composed of valve ring, valve arm, and valve plate, which were made out of polydimethylsiloxane (PDMS) or polyimide (PI) film by laser cutting with designed pattern, and then placed in the valve chamber formed by the combination of pump base and pump chamber. The size of the valve chamber is larger than the valve in diameter and height, so the valve is free in the valve chamber. The case of the pump was made out of aluminum alloy (Al 6063) by computer numerical control milling. Three O-rings were set to seal the pump chamber and valve seat. Figure 1(b) shows the assembled pump with an external dimension of 40 mm $\times$ 40 mm $\times$ 9 mm. Detailed parameters of the prototype pump are listed in table 1.

With the vibration of the piezoelectric actuator under AC voltage, the volume of pump chamber changes periodically. The change of volume further induces the change in pressure, which drives the check valves to move and the working fluid flow. As the piezoelectric actuator moves upward (shown in figure 1(c)(I)), the decreased chamber pressure makes the inlet check valve opens and the outlet check valve closes, driving fluid flow into the chamber. As the piezoelectric actuator moves downward (shown in figure 1(c)(II)), the increased chamber pressure makes the inlet check valve closes and the outlet check valve opens, driving fluid flow out of the chamber. Then, the working fluid is pumped continuously in the repeated process.

The theoretical volumetric flow rate Q_V of the piezoelectric pump can be calculated as [28]

$$Q_V = \Delta V \times f \approx \pi \times f \times w \times r^2 \tag{1}$$

where ΔV is the pump chamber volume change in one cycle, f is the driving frequency, w is the amplitude of piezoelectric actuator, r is the radius of piezoelectric actuator. And the actual flow rate Q is calculated as [30]

$$Q = Q_V \times \eta_v \tag{2}$$

where η_v is the volumetric efficiency.

It can be seen that the flow rate of the piezoelectric pump depends on the amplitude-frequency characteristics and the volumetric efficiency. Besides the piezoelectric actuator, the valve plays another important role in the piezoelectric pump because it determines the flow resistance and the volumetric efficiency of the piezoelectric pump. The flow resistance of the valve represents the local hydraulic loss when fluid flow through the valve, which can be calculated as the outflow of orifice:

$$\Delta P_{\text{v}} = \frac{\rho {C_d}^2 Q^2}{2{A_{\text{v}}}^2} = \frac{\rho {C_d}^2 Q^2}{2(\pi D_{\text{v}} h)^2} \tag{3}$$

where C_d is the coefficient, D_{v} is the diameter of the valve hole, h is the opening height of the valve. The flow resistance

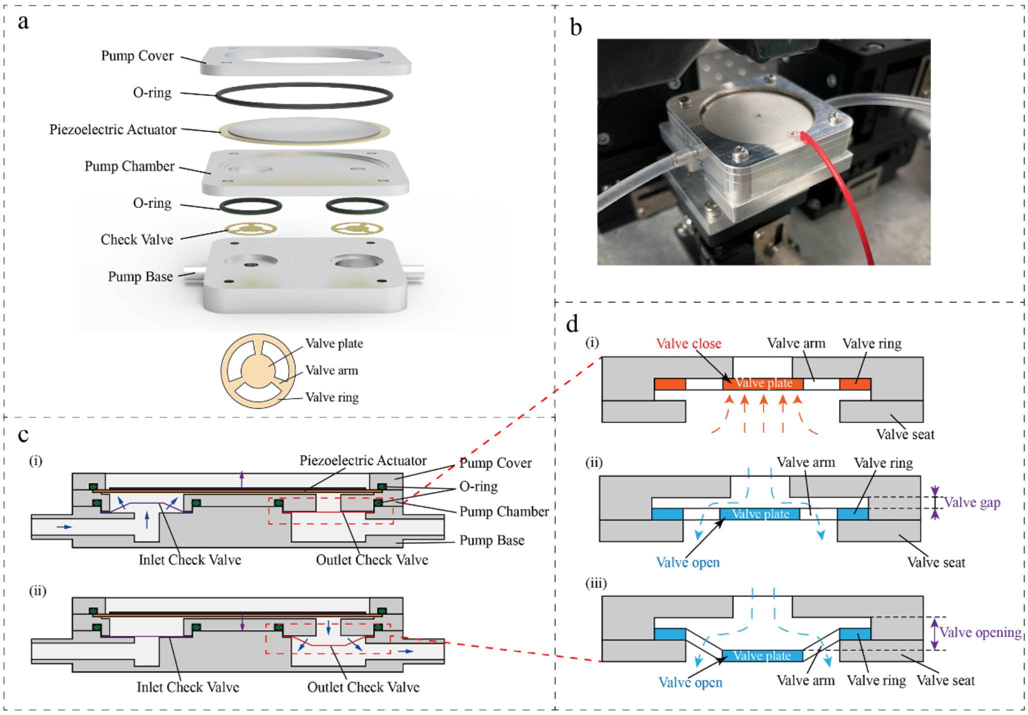

Figure 1. (a) Exploded view of the structure, (b) picture of the assembled pump, (c) schematic view of the pumping process, (d) schematic view of the unfixed valve.

Table 1. Parameters of the prototype pump.

Parameters	Values
Piezoelectric ceramics diameter	31 mm
Piezoelectric ceramics thickness	0.23 mm
Brass plate diameter	35 mm
Brass plate thickness	0.3 mm
Pump chamber diameter	33 mm
Pump chamber depth	0.25 mm
Valve chamber diameter	11 mm
Valve diameter	10.8 mm

is highly sensitive to the opening height of the valve, and the reduction of flow resistance helps improve the amplitude and volumetric efficiency of piezoelectric pump. Another important characteristic of the valve is the natural frequency which indicates the frequency the valve is able to work with. The natural frequency of the valve can be calculated as:

$$f_{nv} = \frac{1}{2\pi}\sqrt{\frac{k_v}{m_v}} \tag{4}$$

where k_v is the equivalent stiffness of the valve, m_v is the equivalent mass of the valve. The natural frequency of the valve should be much larger than the working frequency of the piezoelectric pump, if not, the volumetric efficiency is likely to decrease. Large valve opening provides low flow resistance, and high natural frequency increases the volumetric efficiency of the piezoelectric pump. But it is hard to meet the two requirements at the same time for the fixed valve because a large valve opening requires low valve stiffness, which reduces the natural frequency of the valve.

In this study, we proposed a new valve design using unfixed wheel valves with gaps, which increases the valve opening and the volumetric efficiency of the piezoelectric pump. The valve gap is designed as 0 mm, 0.15 mm, and 0.25 mm, respectively. When the fluid flows in the opposite designed direction of the check valve, the valve plate blocks the channel, preventing the undesired flow (shown in figure 1(d)(I)). When the fluid flows in the designed direction, the valve opens under the fluid pressure to get the channel unblocked. The opening process of the valve consists of two stages. At the first open stage (shown in figure 1(d)(II)), the valve moves downward as a whole without resistance from valve deformation. At the second open stage (shown in figure 1(d)(III)), the valve arm deforms under fluid pressure, and the valve opening increases simultaneously.

Compared with the fixed valve, the unfixed valve opens more quickly because there is no elastic force from valve deformation at the first open stage. Besides, the gaps provide a larger valve opening under the same pressure at the second open stage. Therefore, the unfixed valve is expected to provide better performance for quick response and low flow resistance. But, it was possible to take a longer time when the check valve returns to the block state, which may lead to additional backflow. The valves should be light-weighted to get big acceleration and the gap should not be too large, which would shorten the time. It should be mentioned that the unfixed valve is designed for low working frequency, it cannot work at high frequency because of the delay the valve gap provides. Apart from the performance improvement the design provides, it also shows the advantage of being easy to install. As shown in figure 2, the assembly of the unfixed valve is compared with the commonly used valves. The unfixed valve does not need to be glued to, clamped by, or embedded in the valve seat, it is

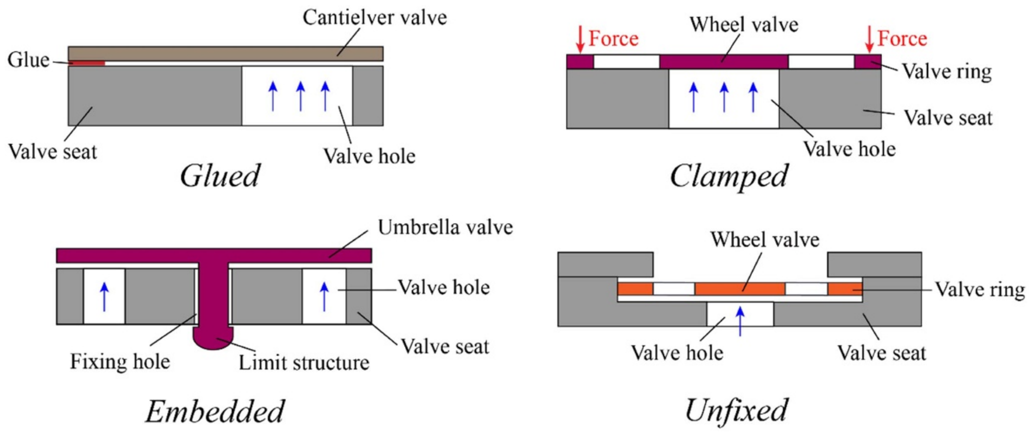

Figure 2. The assembly of different valves.

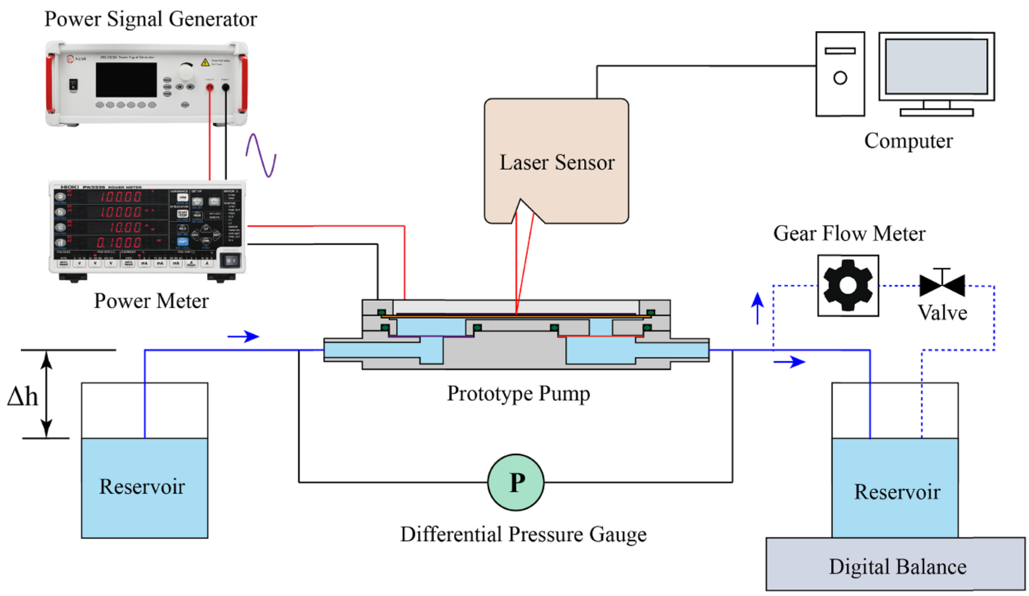

Figure 3. Experimental setup.

free in the valve seat. During the assembly of the pump, the valves only need to be placed in the valve seat without any additional step.

3. Experimental setup

The experimental setup of the prototype pump is depicted in figure 3. Signal generator and power amplifier are integrated in the power signal generator (Aigtek, ATG2031, China). The power signal generator generates a sinusoidal signal to actuate the piezoelectric pump and the power consumption is recorded by a power meter (HIOKI, PW3335, Japan). The applied driving signal is set as 300 Vpp (106 VAC) with a frequency varying from 5 Hz to 100 Hz. A laser displacement sensor (Keyence, LK-G5000, Japan) is used to measure the amplitude of piezoelectric actuator. And the flow rate of the pump is quantified by measuring the increased weight of the outlet reservoir by a digital balance (Fangrui, FA2104, China). The flow rate under different back pressure is measured by adjusting the valve with a gear flow meter (CX, DC8S, China) and differential pressure gauge (XST, HT1895, China), shown as the dashed line. Water, ethanol, and Fluorinert (3M FC3283) are tested to figure out the influence of working fluid. Besides, the self-suction pressure of the pump is measured by adjusting the height of the prototype pump (Δh).

4. Results and discussion

4.1. The influence of unfixed valve on the performance of piezoelectric pump

The characteristics of piezoelectric actuator determine the limits of the performance of piezoelectric pump. The piezoelectric actuator in the pump is the first to be tested after assembly. Due to electro-mechanical coupling effects of the piezoelectric actuator, its characteristics can be explored by mechanical and electrical measurements. Both the electrical impedance and mechanical amplitude of the piezoelectric actuator are

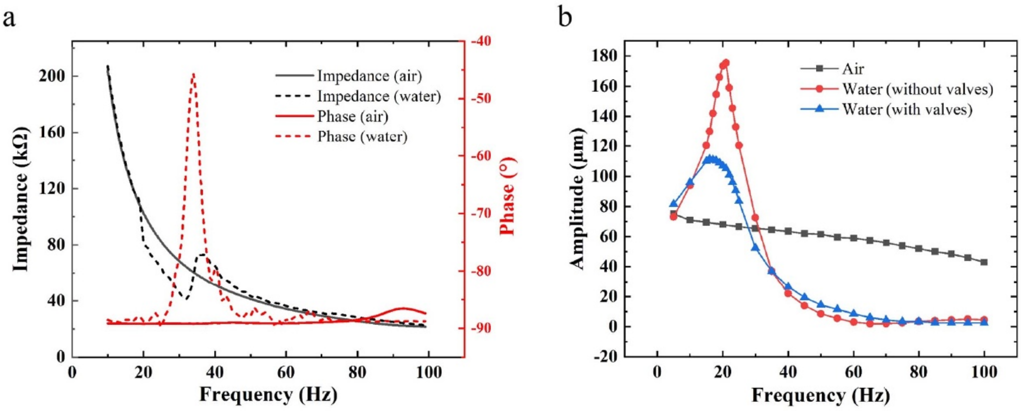

Figure 4. Characteristics of the piezoelectric actuator: (a) impedance and phase, (b) amplitude.

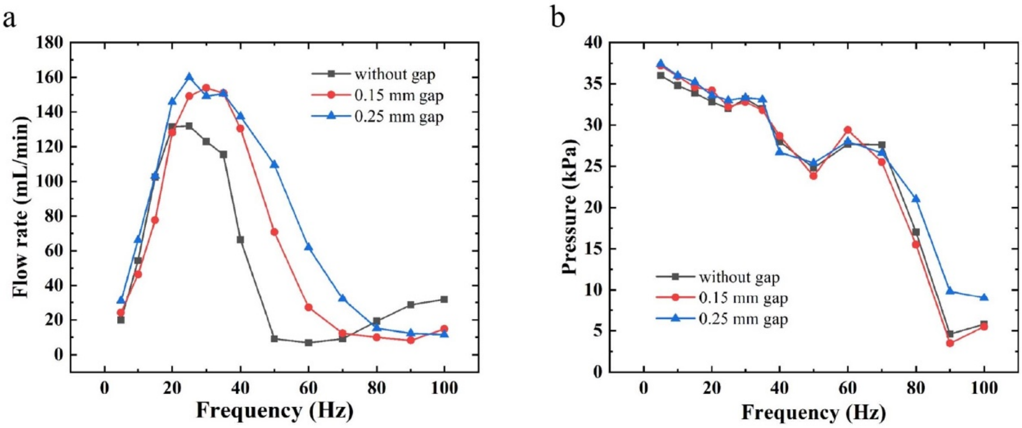

Figure 5. Performance of the pump with PDMS valves: (a) flow rate, (b) maximum output pressure.

investigated in this study. The piezoelectric actuator has an original resonant frequency of 1.8 kHz. But the resonant frequency decrease to about 25 Hz when pumping water, leading to the increase of the amplitude at low driving frequency. As shown in figure 4(a), the impedance and phase show a local minimum of 41.3 kΩ and a local maximum of −45.7° around 33 Hz, respectively. For the amplitude of the piezoelectric actuator, as shown in figure 4(b), the peak appears at 20 Hz when using water as the working fluid, and it is much higher than the amplitude with air. The maximum amplitude in three cases is 175 μm, 110 μm, and 75 μm, respectively. The amplitude decreases when the pump is equipped with valves, which increase the flow resistance. The difference between the two identified resonant frequencies comes from the different voltages applied in the tests. The results indicate that there is a strong resonant effect between the piezoelectric actuator and the working fluid.

To investigate the influence of the unfixed valve on the performance of piezoelectric pump, pumps with 50 μm PDMS valve at three different gaps were tested. The gaps are designed as 0 mm, 0.15 mm and 0.25 mm, respectively. As shown in figure 5(a), the flow rates of the pumps are similar at low driving frequency but different at a higher frequency. The pump with 0.25 mm gap reached a 20.3% improved flow rate (160 ml min^{-1}) at the optimal driving frequency. In addition, the maximum output pressure of the pumps was also tested. As shown in figure 5(b), the maximum output pressure declines with the increase of driving frequency as a whole and shows no significant difference between different gaps, which indicates that the valve gaps have no negative effects on the output pressure of the pumps.

Simulations and experimental tests were carried out to reveal the mechanism of the flow rate improvement provided by the unfixed valve. The gap in the unfixed valve changes the response of the valve, which determines the flow resistance at different times. To estimate the flow resistance at different valve openings, simulations were performed by computational fluid dynamics software (ANSYS Fluent 19.2). Figure 6(a) shows the fluid pressure of the valve system. It can be observed that the narrow gap between the valve and the valve seat produces a large pressure drop when the fluid flows through, which is harmful to the piezoelectric pump. The pressure drop at different valve opening and flow rates is shown in figure 6(b). As the valve opening decrease, the pressure drop increases sharply, reducing the flow rate of the pump. When the valve opening is 0.15 mm and the flow rate is 212 ml min^{-1}, the flow resistance reaches 4.4 kPa. The pressure drop decreases to 1.0 kPa when the valve opening

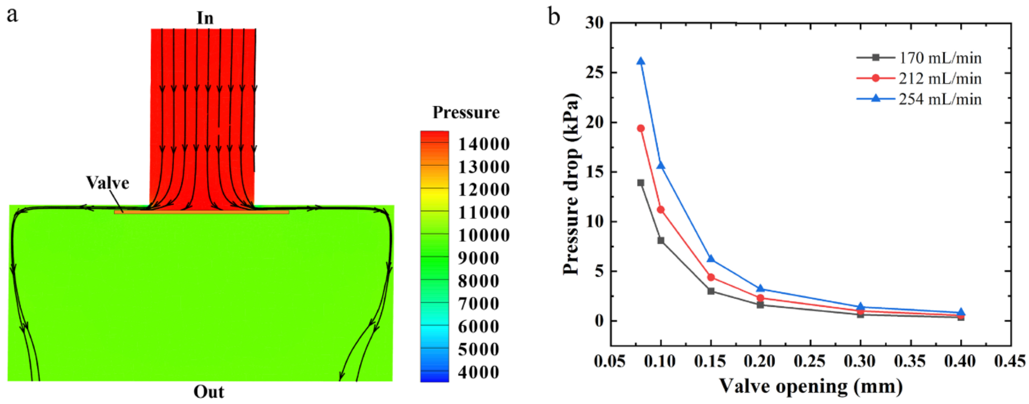

Figure 6. Flow resistance of the check valve system: (a) pressure contour, (b) pressure drop.

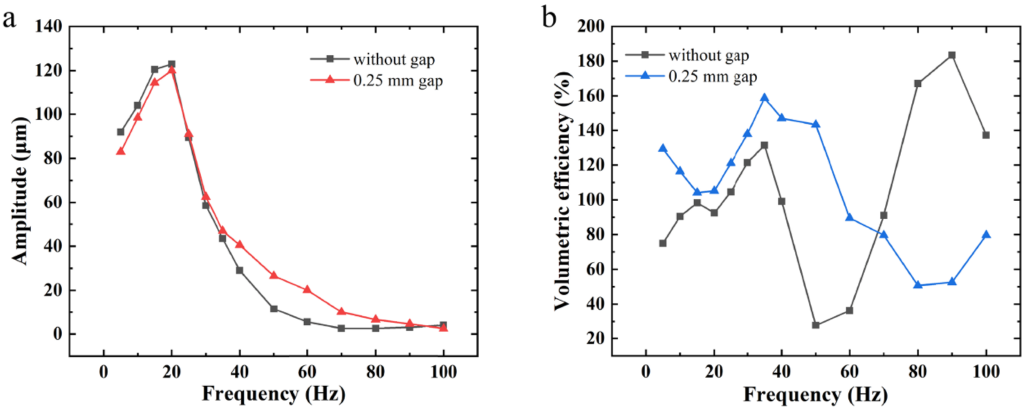

Figure 7. The characteristics of the pump: (a) the amplitude, (b) the volumetric efficiency.

is 0.30 mm. With the unfixed valve, the time with small valve opening is shortened. Hence, the pump with a higher flow rate is achieved.

The volumetric efficiency of the piezoelectric pump was calculated according to equations (1) and (2). The amplitude measured and volumetric efficiency of the pumps are shown in figure 7. The gaps increase the volumetric efficiency of the pump at 25 Hz. As shown in figures 7(a) and (b), the amplitude of the pump with valve gap is almost the same as the amplitude of the pump without valve gap from 20 Hz to 30 Hz, but larger at a higher frequency. The volumetric efficiency is improved from 104% to 121% at 25 Hz. Hence, the maximum flow rate improvement of the pump with PDMS valve is mainly produced by the increase of volumetric efficiency at 25 Hz. The volumetric efficiency is greater than 100% because there is additional inertial flow from the pulsatile pressure change and the working of the check valves [33, 34]. The higher volumetric efficiency is obtained due to the quick response of the unfixed valve.

To further verify the improvement by the unfixed valve, the pump was also tested with three PI valves with the thickness of 100 μm, 50 μm, and 25 μm, which have different valve stiffness. The mechanical properties of the valves are calculated with peripheral fixation boundary conditions by Ansys workbench. As listed in table 2, the valves have equivalent stiffness and natural frequency ranging from 9.2 to 580 N m^{-1}, and

Table 2. Properties of the valves.

Valve	Thickness (μm)	Equivalent stiffness (N m^{-1})	Mass (mg)	Natural frequency (Hz)
1	100	580	8.0	1355.2
2	50	73.4	4.0	682.7
3	25	9.2	2.0	341.3

341.3–1355.2 Hz, respectively. It should be mentioned that the effective working frequency of the valves is much smaller than the calculated values because of the added mass of the fluid and the valve gap [35].

As shown in figure 8, appropriate gaps improve the maximum flow rate of the piezoelectric pumps by over 15% for all valves at the optimal driving frequency. But the impacts produced by the gaps are diverse for three valves. For the pump with 100 μm thick PI check valves, as shown in figure 8(b), the highest flow rate of 153 ml min^{-1} was obtained at 25 Hz with 0.25 mm gaps, showing a 23.4% improvement compared with the pump without valve gap (124 ml min^{-1}). As the thickness of PI check valves decreased to 50 μm, as shown in figure 8(c), the maximum flow rate increased to 162 ml min^{-1} due to the lower stiffness of the valves. And the maximum flow rate of the pump with fixed valves increased to 129 ml min^{-1}. The maximum flow rate improvement is 25.6%. However,

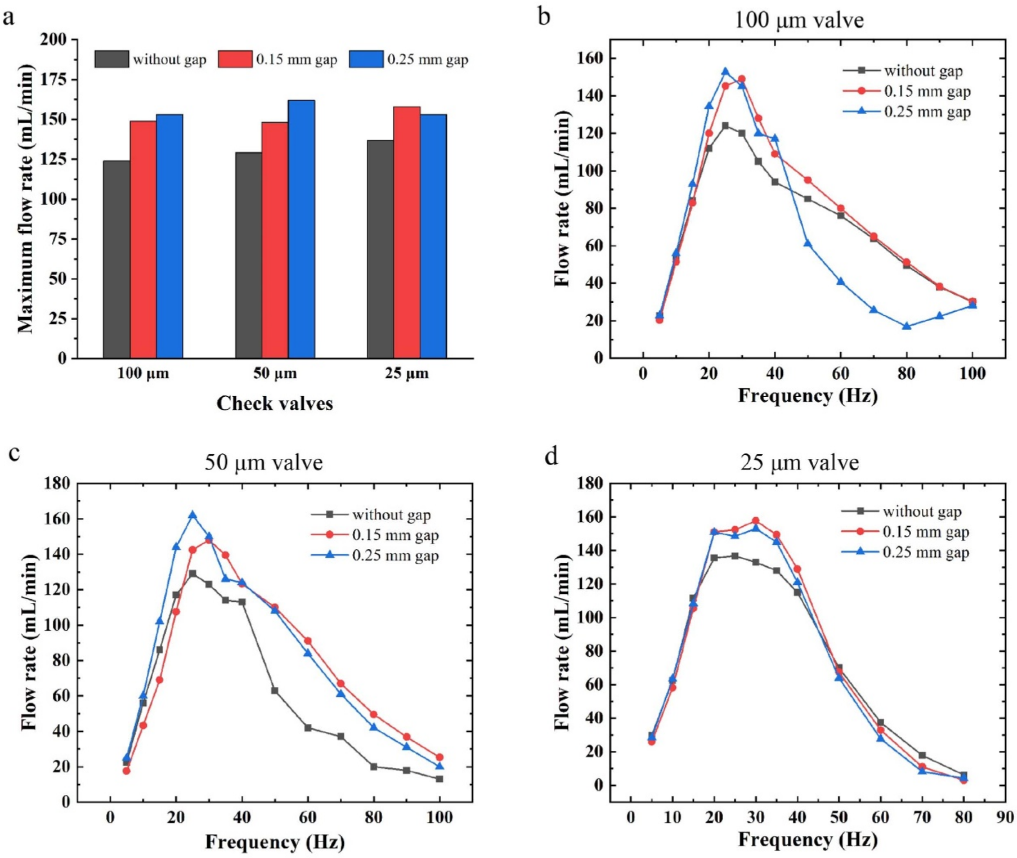

Figure 8. Flow rates with PI valves: (a) overview, (b) 100 μm PI check valve, (c) 50 μm PI check valve, (d) 25 μm PI check valve.

the pumps using 25 μm thick valves with 0.25 mm gaps show no significant improvement than 0.15 mm gap (shown in figure 8(d)). The soft 25 μm thick valve provides a big valve opening itself. When the gap is bigger than 0.15 mm, the flow resistance reduction by additional gap is not significant enough and the volumetric efficiency reduces because the effective working frequency of the valve decreases. To sum up, the valve gap improves the flow rate of the piezoelectric pump, but the gap parameter should be carefully chosen to obtain the best performance based on the valve stiffness and driving frequency.

4.2. The characteristic of the piezoelectric pump with unfixed valve

To identify the characteristics of the piezoelectric pump with unfixed valve, we further measured the flow rate, pressure and power consumption at the same time as the experimental setup. The working efficiency of the pump is also calculated to evaluate the performance. The pump efficiency η_{pump} is calculated as

$$\eta_{\text{pump}} = \frac{P_{\text{hydraulic}}}{P_{\text{consumed}}} = \frac{P \times Q}{P_{\text{e}}} \tag{5}$$

where P is output pressure, Q is the flow rate, P_{e} is the electric power consumption. Figure 9 shows the output pressure,

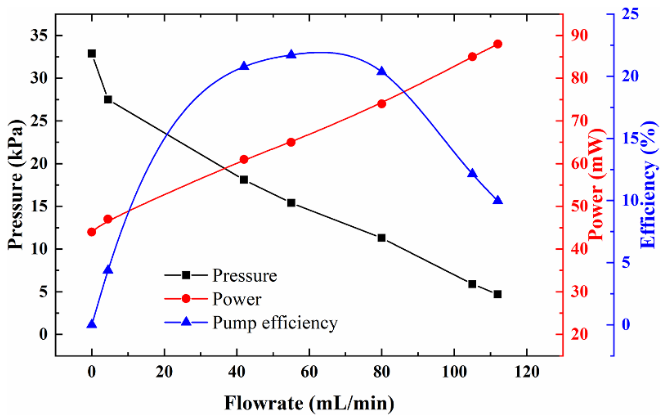

Figure 9. The P–Q characteristics, power and efficiency of the pump with 50 μm PDMS valves with 0.25 mm gap.

power consumption and pump efficiency at different flow rates of the prototype pump with PDMS valves holding a 0.25 mm gap at 30 Hz. The output pressure decreases almost linearly with the increase of the flow rate. And the power consumption increases continuously from 44 mW to 88 mW. The pump efficiency increases first and then decreases, reaching a peak efficiency of 21.7%. Besides, the self-suction pressure of the pump was measured to be −7.6 kPa.

Table 3. The physical properties of the working fluids.

Fluid	Density (kg m^{-3})	Viscosity (mPa s)
Water	997	0.89
Ethanol	785	1.06
Fluorinert (FC3283)	1820	1.40

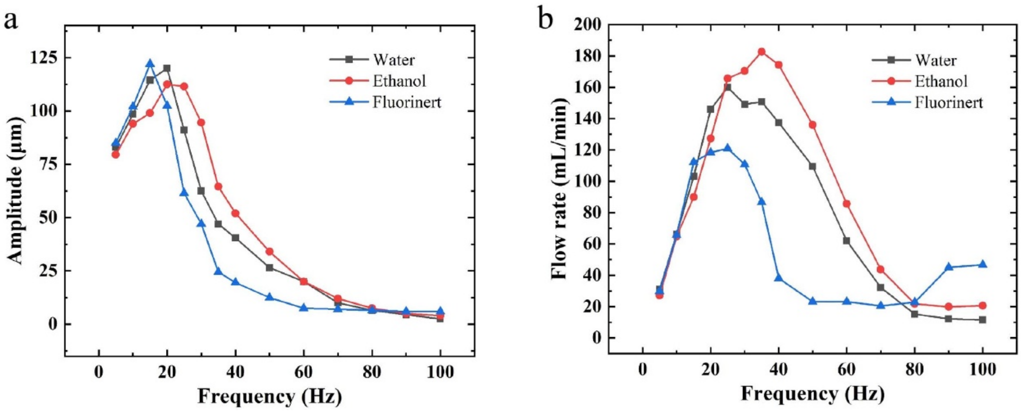

Figure 10. Pump with different working fluids: (a) the amplitude, (b) flow rates.

To explore the application of the piezoelectric pump in wider areas, we investigated the impact of three typical working fluids on the performance of the piezoelectric pump. The physical properties of three typical working fluids are listed in table 3. As shown in figure 10(a), when the density of working fluid increases, the optimal driving frequency decreases. Figure 10(b) compares the performance of the prototype pump with the fluids. A maximum flow rate of 182 ml min^{-1} was achieved with ethanol. And the maximum flow rate sharply decreased by 24.3% with Fluorinert which has a higher density and viscosity than water. Ethanol has a higher viscosity than water, but the pump with ethanol has a higher flow rate. The results show that the piezoelectric pump is sensitive to the density of working fluids because the inertial load increases linearly with the increase of the density [36]. The inertial load from working fluid not only affects the piezoelectric actuator, but also the response of the check valve. Therefore, the flowrate of the piezoelectric pump sharply decreases with the increase of the density of working fluid. The working fluid discussed here has low viscosity, so the impact of density is more obvious. When working with high-viscosity fluid, the flow resistance becomes larger and the flowrate is likely to decrease too [37].

5. Conclusion

This study has proposed a new valve design with an improved flow rate using unfixed check valve. A series of pumps with different valves and gaps were fabricated and tested. Flow rate, pressure, and power consumption of the prototype pump were investigated. Volumetric efficiency and pump efficiency were also calculated to evaluate the performance of the piezoelectric pumps. The major conclusions are listed as follows:

(a) The new design of check valves provides an easy-to-install structure which would largely simplify the assembly of valve-based piezoelectric pumps.
(b) The unfixed valves improve the maximum flow rate of the piezoelectric pumps by 25.6% without affecting the output pressure. The pump using 50 μm thick PI valves with 0.25 mm gap shows the best output performance (162 ml min^{-1}, 33 kPa).
(c) The improvement of flow rate mainly comes from the increase of volumetric efficiency.
(d) The flow rate of the piezoelectric pump sharply decreases with the increase of the density of working fluid.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgment

This work was supported by the National Natural Science Foundation of China (Grant No. 51625601).

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