Chapter

Design, Characterisation and Prospect of Piezoelectric Microfluidic Technology

Song Chen, Zhonghua Zhang, Junwu Kan, Jianping Li and Jianming Wen

Abstract

Fluidic driving device plays an important role in the delivery and distribution of minute amount of the liquid in the micro-fluidic system. Due to the unique advantages of simple structure, short response time, and low power consumption, piezoelectric actuation was employed to implement the microfluidic transportation. A piezoelectrically driven microfluidic device, piezoelectric pump, was developed and widely applied in many fields in last three decades. As a kind of displacement pump, piezoelectric pumps is able to realize accurate transportation of the liquid because of per stroke of output fluid is equal to the volumetric change of pumping chamber. And the output flow rate and pressure is easily to be controlled through adjusting the driving voltage or frequency. In this chapter, the design, structure, working principle and the characterisation of piezoelectric pumps with single chamber and multiple chambers are introduced.

Keywords: piezoelectric actuator, microfluidic technology, micropump, single chamber, multiple chamber, flow rate, pressure

1. Introduction

Microfluidic modules have broad application prospects in chemical analysis, biomaterial analysis, fuel cell, and medical [1, 2]. In the microfluidic system, the fluid pump is the core to realize small and accurate liquid delivery and distribution [3, 4]. Therefore, a variety kinds of micropumps have been developed [5–8]. Because of its simple structure, high energy density and simple control, piezoelectric pump has potential application prospects in drug delivery, chemical analysis, micro refrigeration system and micro spacecraft propulsion [9–11].

According to the driving components, piezoelectric pump can be divided into piezoelectric stack pump and piezoelectric diaphragm pump. The piezoelectric diaphragm pump owns superiorities of small volume and low power consumption. This chapter will take the piezoelectric diaphragm pump as the example to introduce the piezoelectric microfluidic technology.

2. Piezoelectric pump with single chamber

The piezoelectric pump with single chamber is the basic form of piezoelectric pump. The one-way fluid drive of piezoelectric pump is realized by matching with check valves. The common piezoelectric pumps with single chamber are that with single wafer, bimorph and double actuator.

2.1 Piezoelectric pump with single chamber

Figure 1 shows the structure and working principle of the piezoelectric pump with single chamber and single wafer (PPSCSW). Single wafer piezoelectric vibrator, pump body and two check valves (inlet and outlet) constitute a closed pump chamber. The volume of the pump chamber changes with the reciprocating motion of piezoelectric diaphragm driven by AC voltage signal. The inlet valve and outlet valve are opened and closed periodically to form suction and discharge. At the suction stage, the volume of the pump chamber increases, the inlet valve opens, the outlet valve closes, and the fluid enters the pump chamber. When discharging, the volume of the pump chamber is reduced, the outlet valve is opened, the inlet valve is closed, and the fluid is discharged from the pump chamber. This circulation enables one-way flow of fluid.

Figures 2 and **3** show the three-dimensional structure and prototype of PPSCSW. The shell and pump body are made of the polymethylmethacrylate (PMMA), which has superiorities of easy processing and transparent material. The dimension of upper, middle and bottom shells is 40 mm × 40 mm × 5.5 mm. The diameter of outlet pipe and inlet pipe is Φ7 mm. The inlet and outlet check valves made of rubber umbrella are installed in the same place, with the size of Φ10 mm × 0.5 mm. By adjusting the overall size to 40 mm × 40 mm × 16.5 mm, PPSCSW can precisely control the fluid output flow rate and pressure.

Figure 4 is the relationships between output flowrate of PPSCSW and the driving voltage and frequency. When the driving voltage is fixed at 150 V_{pp} and 75 V_{pp}, the maximum flow rates of 5.42 ml/min and 26.55 ml/min are obtained at 20 Hz and 30 Hz, respectively. When the driving frequency is fixed at 15 Hz and 30 Hz, the flow rate increases with the increase of the driving voltage. When the driving voltage increases to 210 V_{pp}, the output flow rate of PPSCSW reaches 26.55 ml/min.

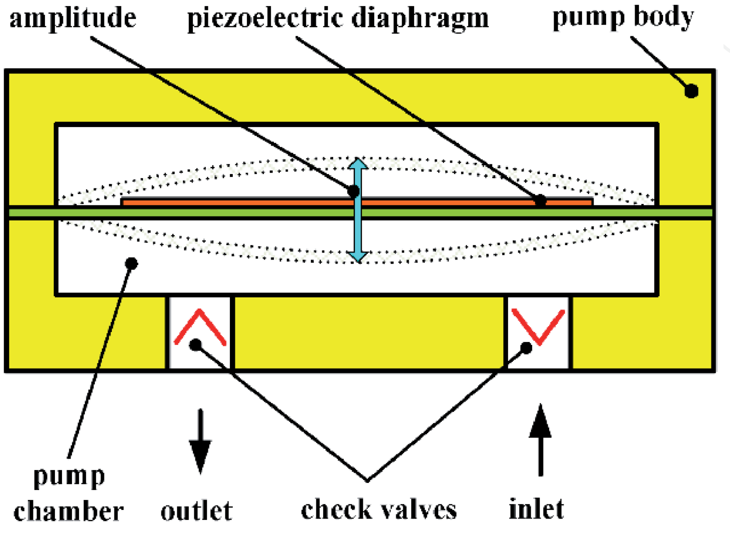

Figure 1.
The structure and working principle of PPSCSW [12].

Figure 2.
The three-dimensional structure of PPSCSW [12].

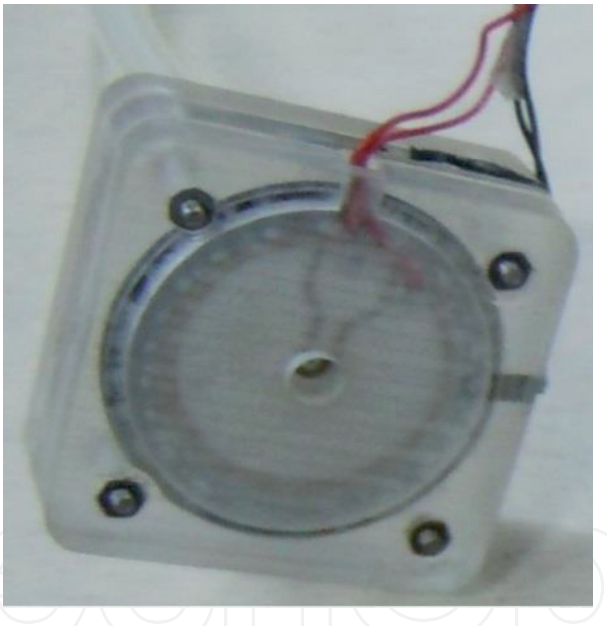

Figure 3.
The prototype of PPSCSW [12].

2.2 Piezoelectric pump with single chamber and a bimorph actuator

As the name implies, the bimorph actuator is composed of two PZT disks with mechanical serial and parallel structure. **Figure 5** shows the structure of a piezoelectric pump with single chamber and a bimorph actuator (PPSCBA). The working principle of PPSCB is similar to that of PPSCSW in **Figure 1**. However, compared with single wafer piezoelectric pump, double piezoelectric actuators usually have symmetrical structures. In theory, PPSCBA can monitor the output performance by using a PZT disk as a monitor, which will make it more widely application.

In order to study the PPSCBA, the three-dimensional structure and prototype of PPSCBA have been designed, as shown in **Figures 6** and **7**. A bimorph is used as the actuator and sensor. The check valve is an umbrella valve made of rubber.

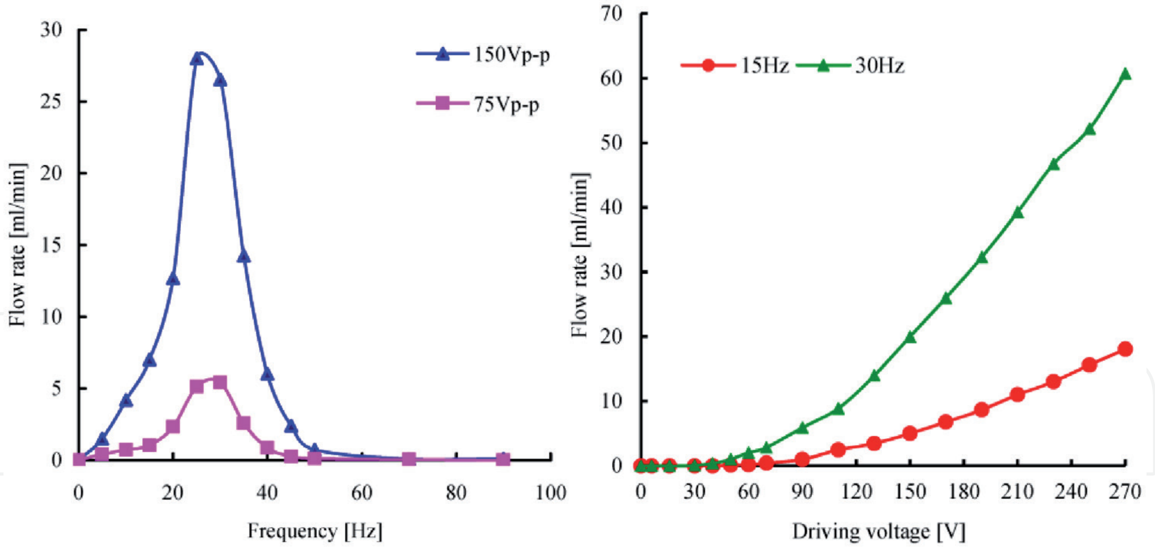

Figure 4.
The relationship between flowrate and driving frequency and voltage [12].

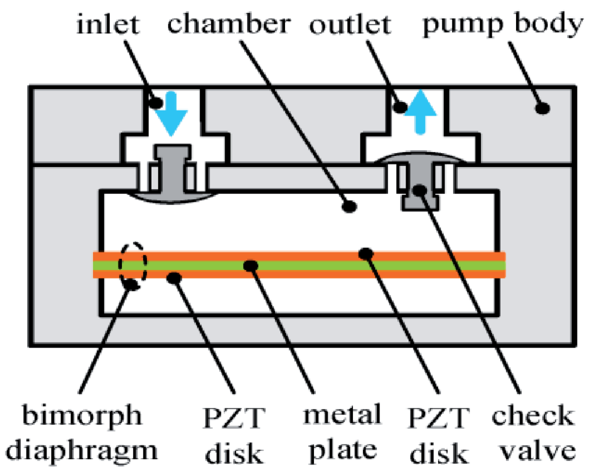

Figure 5.
The structure of PPSCBA [13].

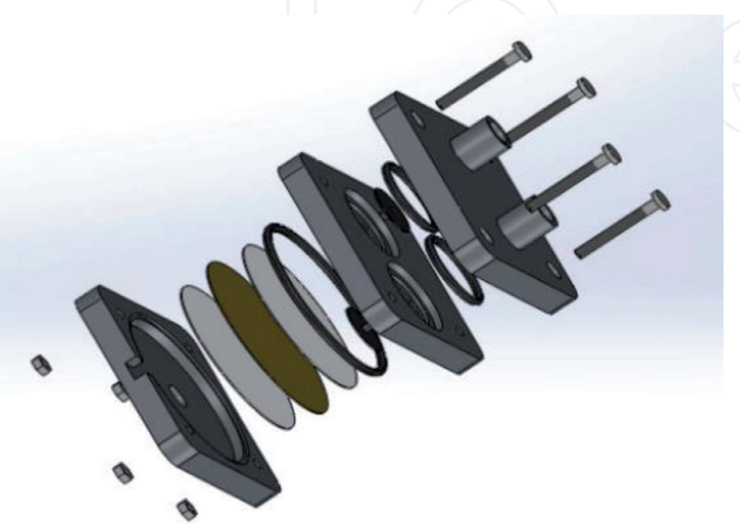

Figure 6.
The three-dimensional structure of PPSCBA [13].

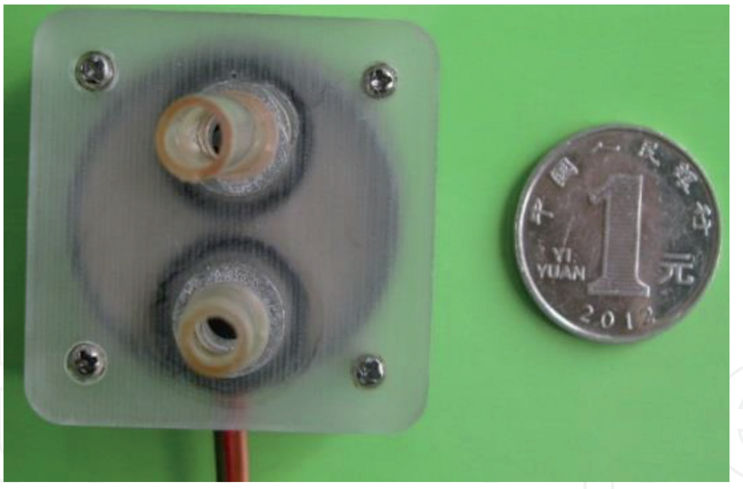

Figure 7.
The prototype of PPSCBA [13].

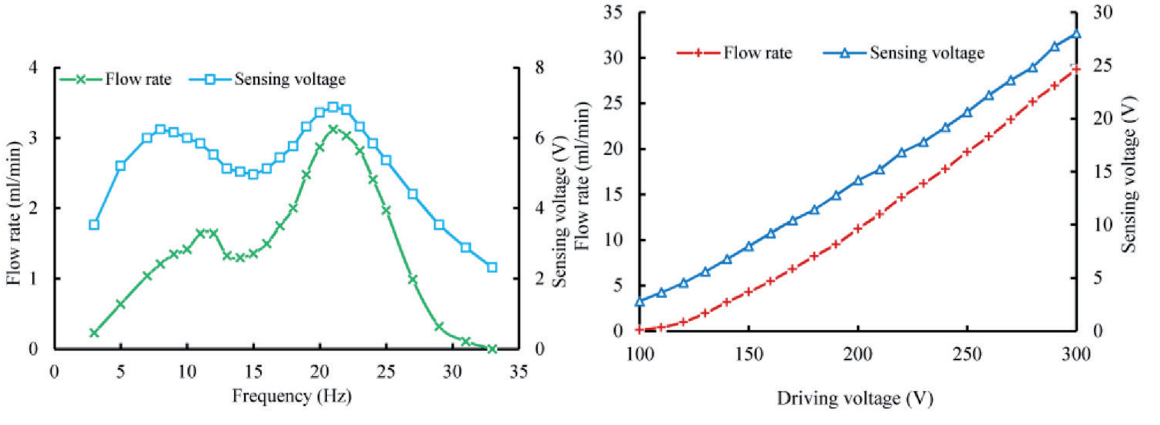

Figure 8.
The relationship between flowrate and driving frequency and voltage [13].

The material of pump body is PMMA. The overall dimension of PPSCBA is 40 mm × 40 mm × 17 mm. When one PZT disc is used as the driver and the other as the monitor, the monitor of output flow rate is achieved.

As shown in **Figure 8**, when one piezoelectric wafer of the bimorph piezoelectric vibrator is used as the driver and the other as the sensor, the relationship between the output flow rate and the sensing voltage of PPSCBA and the driving frequency and voltage is analyzed. When the driving voltage is fixed at 150 V_{pp}, the peak values of sensing voltage and output flow, 6.88 V_{pp} and 3.12 ml/min, are obtained at 21 Hz. Therefore, the optimal frequency of PPSCBA is able to realize self-sensing. When the driving frequency is fixed at 21 Hz, the flow rate and sensing voltage increase with the increase of driving voltage, and the increasing trend is similar. When the driving voltage increases to 300 V_{pp}, the output flow rate and sensing voltage reach the maximum, which are 28.71 ml/min and 28.0 V_{pp} respectively. Therefore, PPSCBA can realize the self-sensing of output flow rate.

2.3 Piezoelectric pump with single chamber and double piezoelectric actuator

In order to improve the drive ability of pump chamber, the piezoelectric pump with single chamber and double piezoelectric actuator (PPSCDPA) is proposed. **Figure 9** shows the structure of PPSCDPA. PPSCDPA consists of an inlet, two

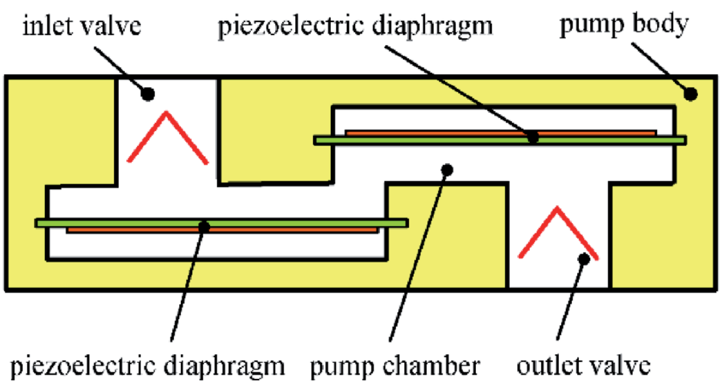

Figure 9.
The structure of PPSCDPA [14].

Figure 10.
The 3-D structure of PPSCDPA [14].

Figure 11.
The prototype of PPSCDPA [14].

piezoelectric diaphragm, two check valves, a pump chamber, a pump body and an outlet. The vibration of the two piezoelectric diaphragms is the same, that is, their driving voltage signals are the same. In the process of suction, two piezoelectric diaphragms bend out of the chamber at the same time; while discharging, the two piezoelectric diaphragms bend to the chamber at the same time. Combined with the unidirectional characteristic of the check valve, the PPSCDPA can realize the one-way transportation of fluid from the inlet to the outlet under the AC voltage signal drive.

The three-dimensional structure and prototype of PPSCDPA with the overall dimension of 65 mm × 40 mm × 12 mm are shown in **Figures 10** and **11**, respectively. The check valves are umbrella valve made of rubber. The material of pump body is PMMA. The performance test platform of PPSCDPA is established, and the output performance of piezoelectric pump is tested. The experimental results show that the maximum flow rate of 45.98 ml/min is achieved when the driving parameters are 15 Hz and 200 V_{pp}.

3. Piezoelectric pump with multiple chambers

The output performance of the piezoelectric pump can be improved by increasing the number of chambers. When the pump chambers are connected in series, the pressure of the piezoelectric pump increases; when the pump chambers are parallel, the flow rate of the piezoelectric pump increases.

3.1 Piezoelectric pump with single actuator and double chamber

As shown in **Figure 12**, the piezoelectric pump with single actuator and double chamber (PPSADC) includes a piezoelectric bimorph vibrator, two chambers (chamber A and B), four check valves and a pump body. Chamber A has inlet 1 and outlet 1, and chamber B has inlet 2 and outlet 2. The chamber A and chamber B of the piezoelectric pump can be connected in series or in parallel, which can improve the applicable range of the pressure and flow. **Figure 12(a)** shows the series connection of chambers A and B. In the process of working, the fluid enters the chamber B from the inlet 2, and the outlet 2 is connected with the inlet 1, and the liquid enters the chamber A through the inlet 1, so that chamber B and chamber A are in series, which can make the piezoelectric pump obtain high pressure. **Figure 12(b)** shows the parallel connection of chamber A and B. In the process of working, the fluid enters the chamber A and B from the inlet 1 and 2, and flows out from the outlet 1 and 2, so that the chamber A and B form a parallel connection, which can obtain a large flow rate.

Figure 13 is the three-dimensional structure of PPSADC with the overall dimension of 41 mm × 41 mm × 25 mm. **Figure 14** is the prototype of PPSADC. Chamber A and chamber B are symmetrical. The upper and lower O-rings are used to seal the chambers, which realizes the flexible support of the piezoelectric vibrator. The flexible support can amplify the displacement of the piezoelectric vibrator. The structure of check valve is umbrella valve. The material of pump body is PMMA. The series and parallel switching of chamber A and chamber B is realized through the connection transformation of rubber tube.

Figure 15 shows the relationship between the output flow rate and the driving voltage when the driving frequency is 100 Hz. It can be seen from the **Figure 15** that the output flow increases with the increase of the driving voltage. When the driving

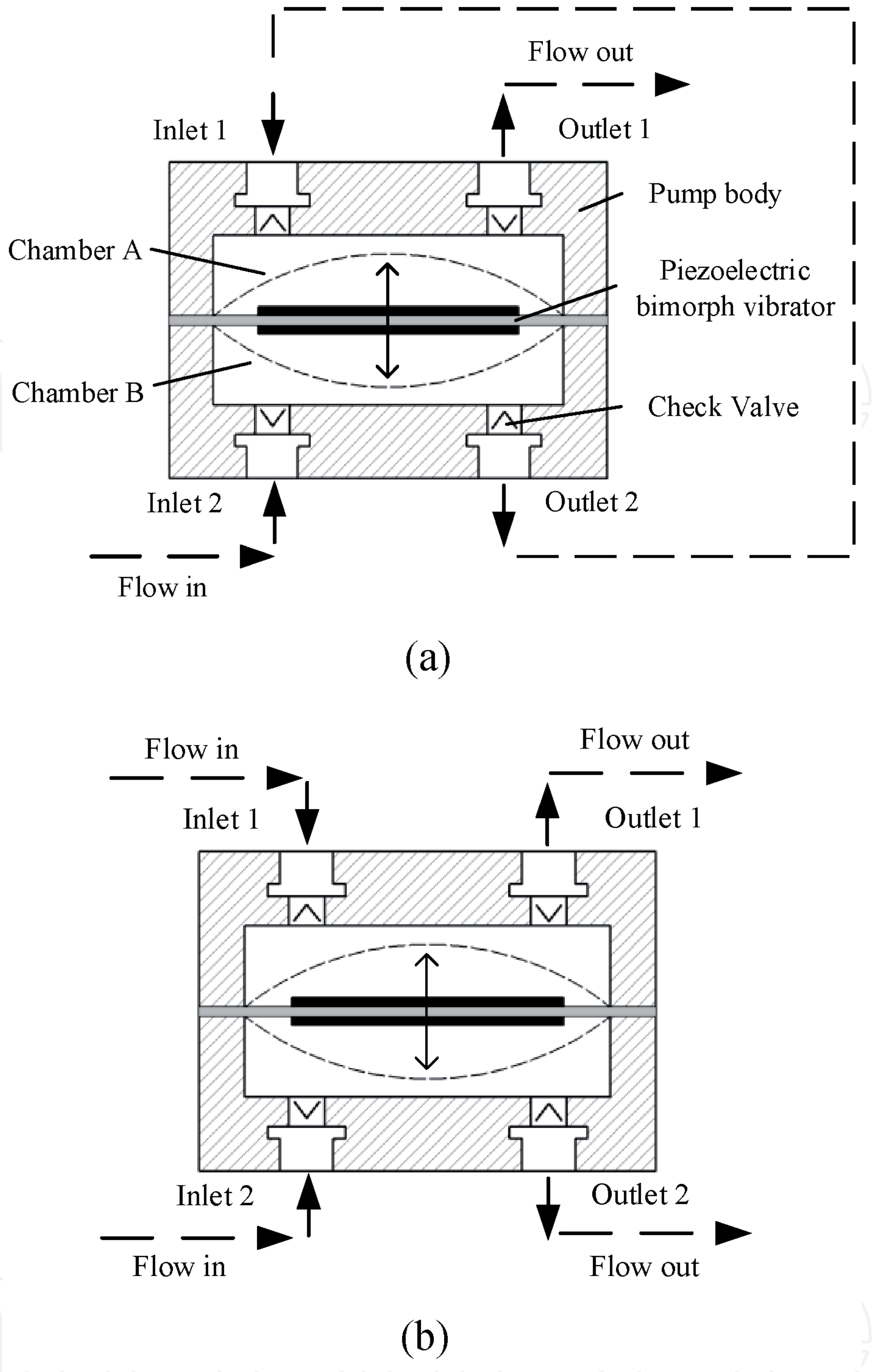

Figure 12.
The structure and working principle of PPSADC. (a) Serial connection. (b) Parallel connection [15].

voltage is increased to 250 V_{pp}, the output flow rate of the two chambers in series and in parallel is 17 ml/min and 32 ml/min respectively. The PPSADC can achieve high energy conversion efficiency.

3.2 Piezoelectric pump with five actuators and five chambers

Figure 16 is the structure of piezoelectric pump with five actuators and five chambers (PPFAFC). Five piezoelectric actuators and five chambers constitute five pumps in series, which improves the output pressure. A_i (i = 1, 2, 3, 4, 5) represents five piezoelectric actuators; C_j (j = 1, 2, 3, 4, 5) represents five chambers; V_k (k = 1, 2, 3, 4, 5, 6) represents 6 check valves (**Figure 16**).

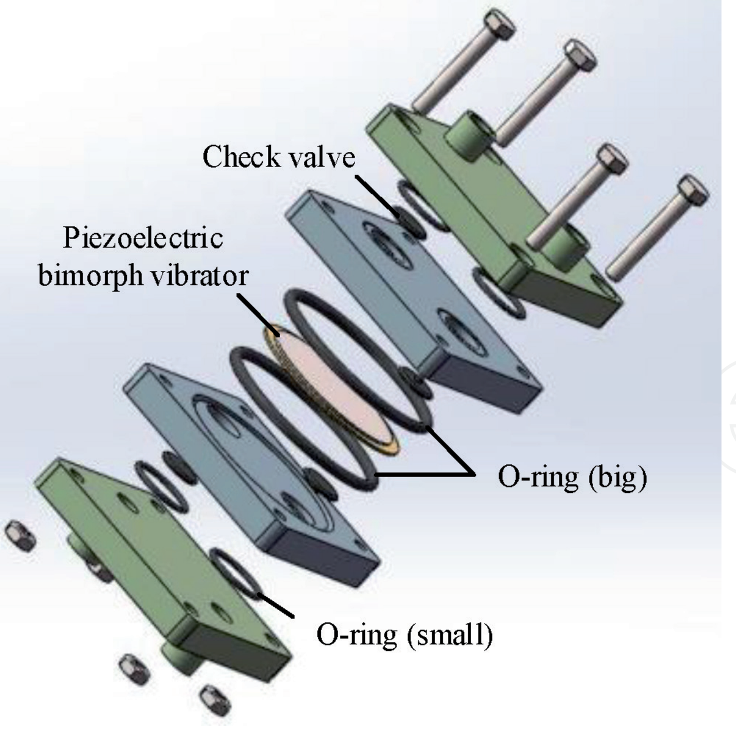

Figure 13.
The 3-D structure of PPSADC [15].

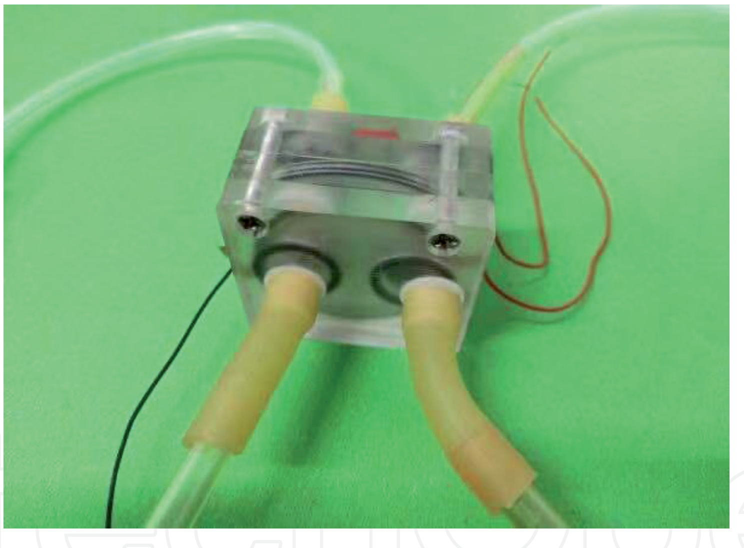

Figure 14.
The prototype of PPSADC [15].

Figure 17 shows the working principle of PPFAFC. PPFAFC is driven by an AC voltage signal, and the driving voltage of the adjacent piezoelectric vibrator has a phase angle of 180°. As shown in **Figure 14(a)**, during the suction process, A1/A3/A5 bends outwards of the cavity and A2/A4 bends into the cavity. Then the volume of the chamber C1/C3/C5 increases, and the volume of the chamber C2/C4 decrease, valve V1/V3/V5 opens, valve V2/V4 closes; as shown in **Figure 14(b)**, during the discharge process, A2/A4 bends outwards of the chamber and A1/A3/A5 bends towards the chamber, then the volume of the C2/C4 increases, the volume of C1/C3/C5 decreases, the valve V2/V4 opens, and the valve V1/V3/V5 closes. When it is driven by an AC voltage signal, the suction and discharge processes are alternately performed to achieve continuous fluid output (**Figure 17**).

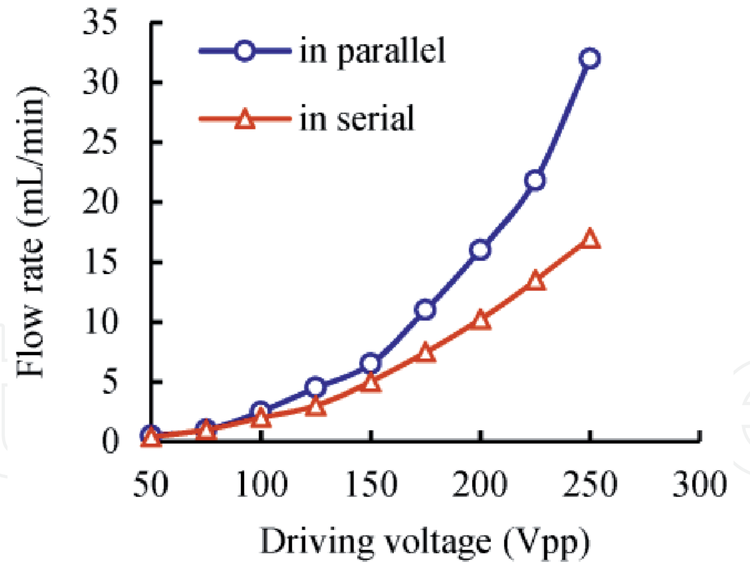

Figure 15.
The relationship between flow rate and driving voltage [15].

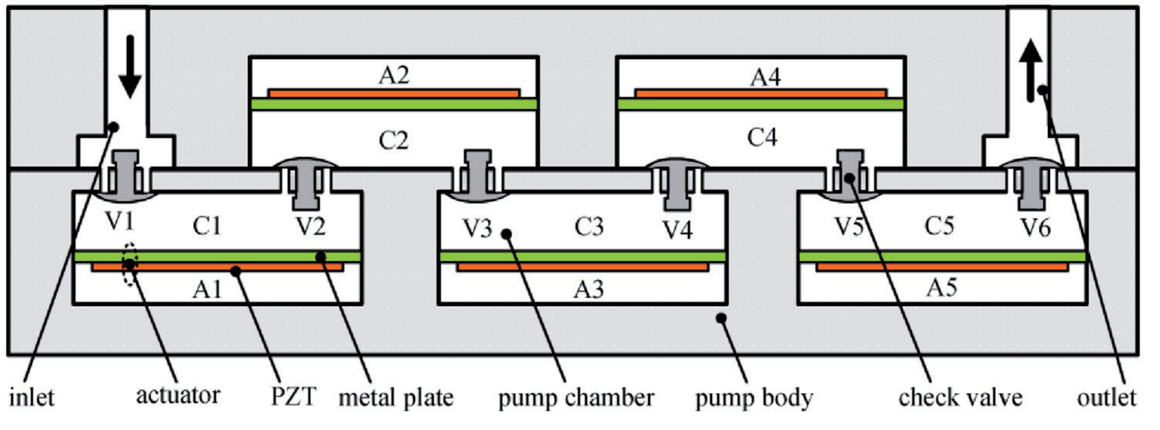

Figure 16.
The structure of PPFAFC [16].

Figure 15 shows the three-dimensional structure and prototype of PPFAFC. A prototype of PPFAFC was designed, manufactured and assembled. The performance of PPFAFC is tested. The pump body is made of PMMA and sealed by O-ring. It was driven by five piezoelectric actuators. PPFAFC can achieve high output performance at low voltage, where it can meet the needs of different applications (**Figure 18**).

As shown in **Figure 19**, when the driving voltage is 180 V_{pp}, the relationship between the output flow rate and backpressure of PPFAFC and the driving frequency is analyzed. It can be seen from **Figure 19** that the output flow rate increases with the increase of the driving frequency. When the driving frequency increases to 400 Hz, the flow rate increases to 279.2 ml/min. When the driving frequency is 90 Hz, the maximum output pressure of 10.8 kPa is obtained. PPFAFC owns high output performance.

3.3 Piezoelectric pump with five actuators and ten chambers

Figures 20 and **21** show the three-dimensional structure and working principle of piezoelectric pump with five actuators and ten chambers (PPFATC). PPFATC is composed of five groups of single vibrator double chamber piezoelectric pumps in

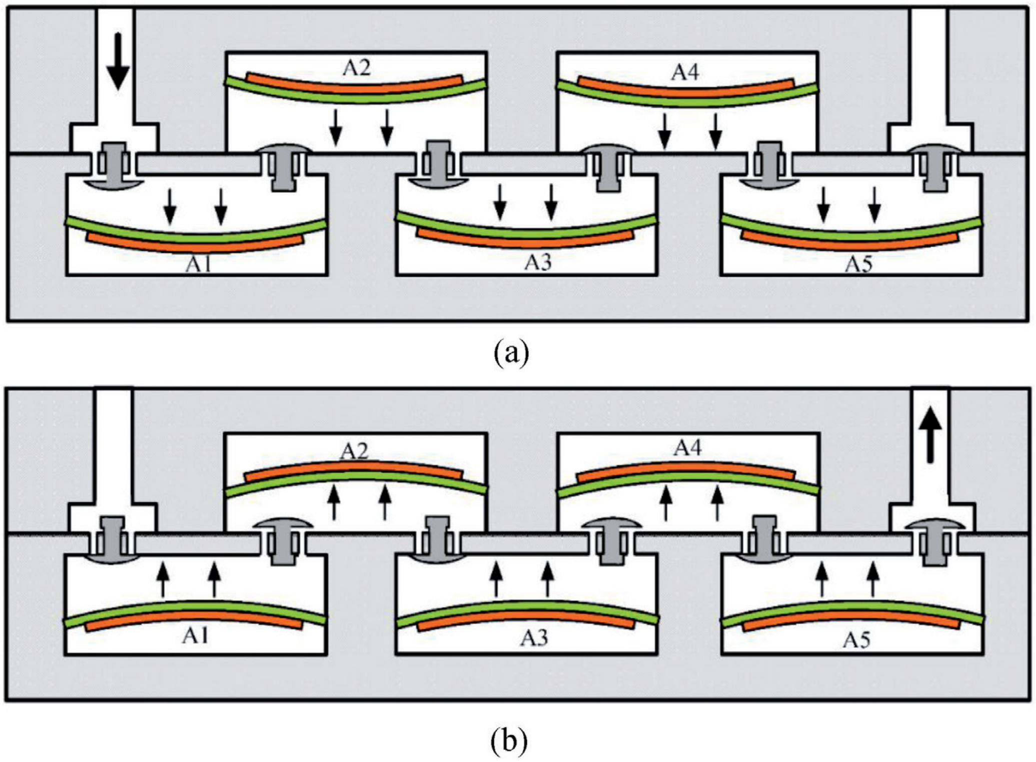

Figure 17.
Working principle of PPFAFC. (a) Suction. (b) Discharge [16].

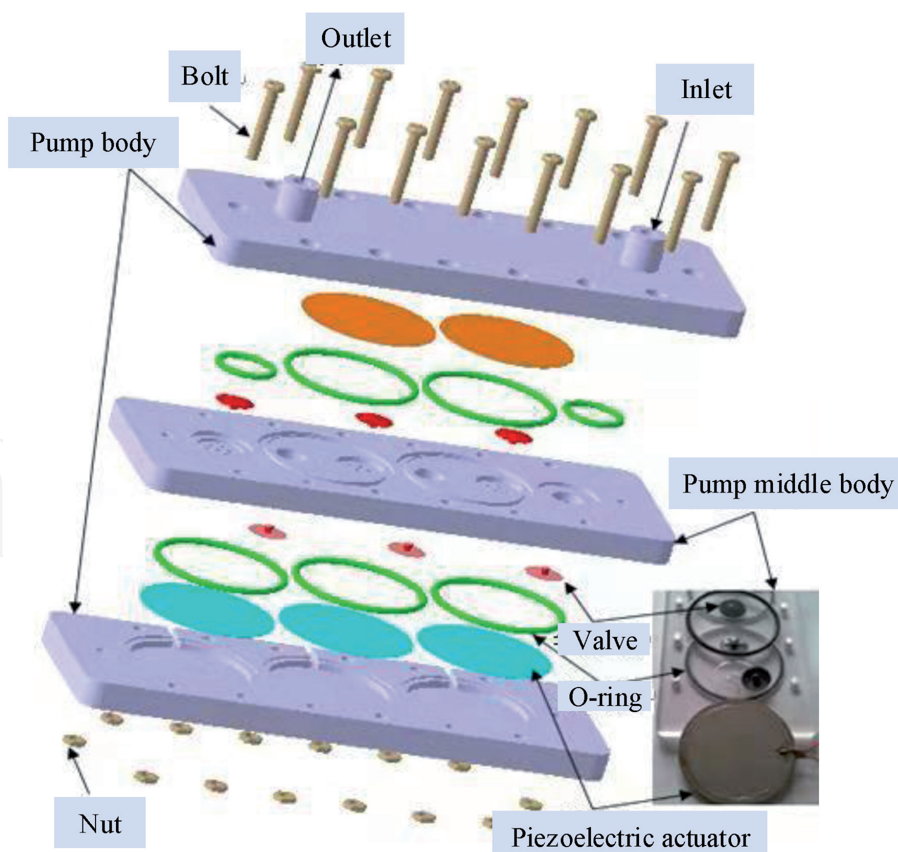

Figure 18.
The three-dimensional structure and prototype of PPFAFC [16].

series, forming two group of five-chambers mechanisms. When PPFATC is connected in parallel, two groups of five-chambers mechanisms are formed in parallel, which can make the outlet obtain continuous fluid output without fluctuation;

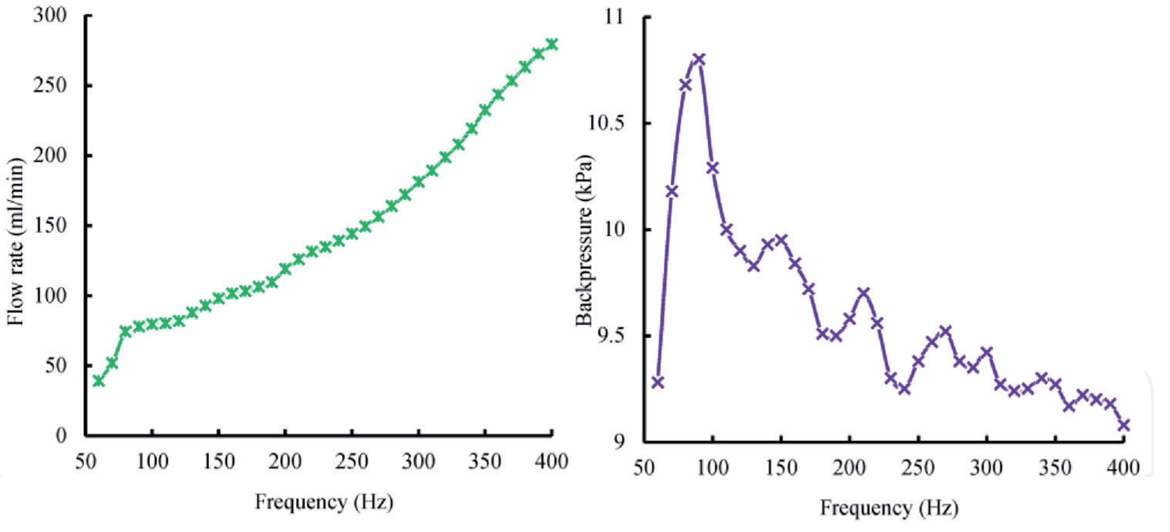

Figure 19.
The relationship between flow rate and backpressure and excitation frequency [16].

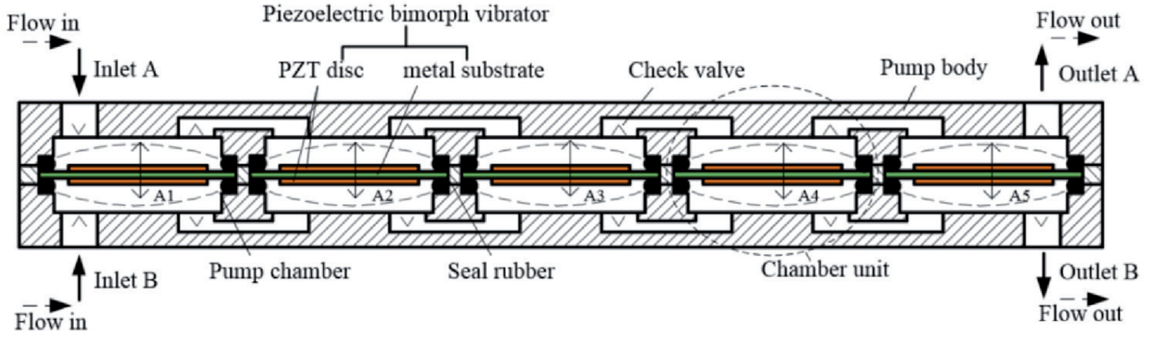

Figure 20.
The structure and working principle of PPFATC in parallel connection [17].

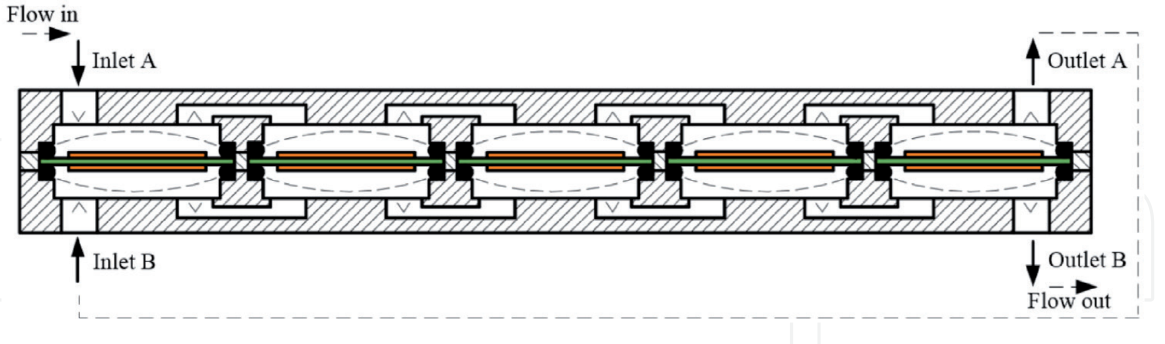

Figure 21.
The structure and working principle of PPFATC in serial connection [17].

when PPFATC is connected in series, two groups of five-chambers mechanisms are formed in series, namely ten chambers in series, which can make the output pressure increase. In the working process, the phase of the driving voltage signal of the adjacent piezoelectric vibrator is 180 degrees, that is, the vibration direction of the adjacent piezoelectric vibrator is opposite in the working process. Combined with the function of check valve, the continuous one-way fluid output of PPFATC is formed under the driving of AC voltage signal.

Figure 22 is the three-dimensional structure and prototype of the PPFATC. A prototype of the PPFATC is fabricated, and then carried out its output performance test and water cooling test with the PPFATC as the power source, as shown

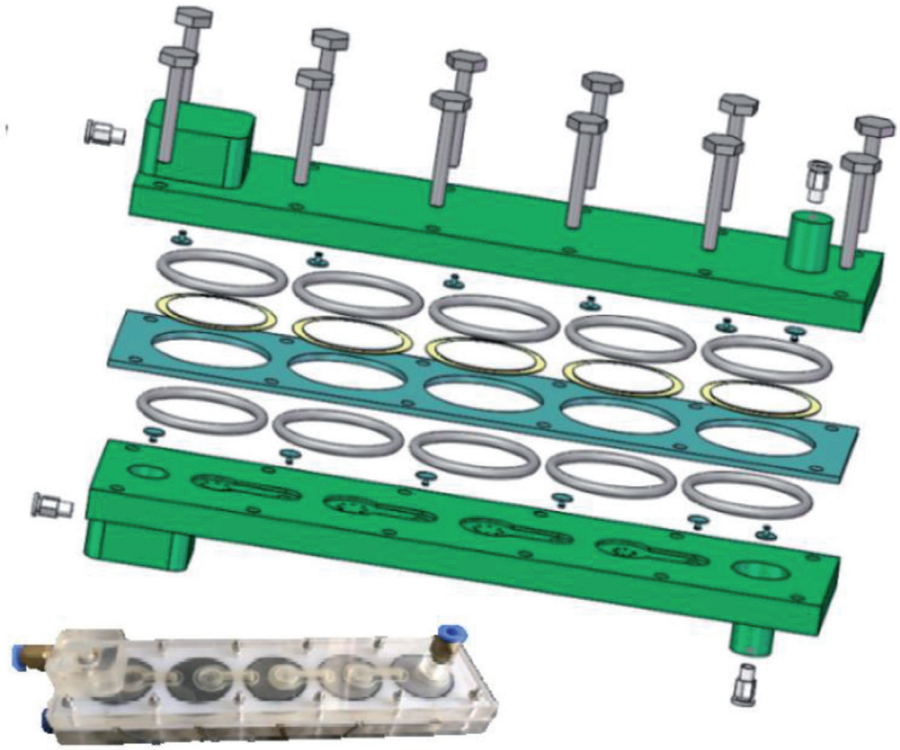

Figure 22.
The three-dimensional structure and prototype of PPFATC [17].

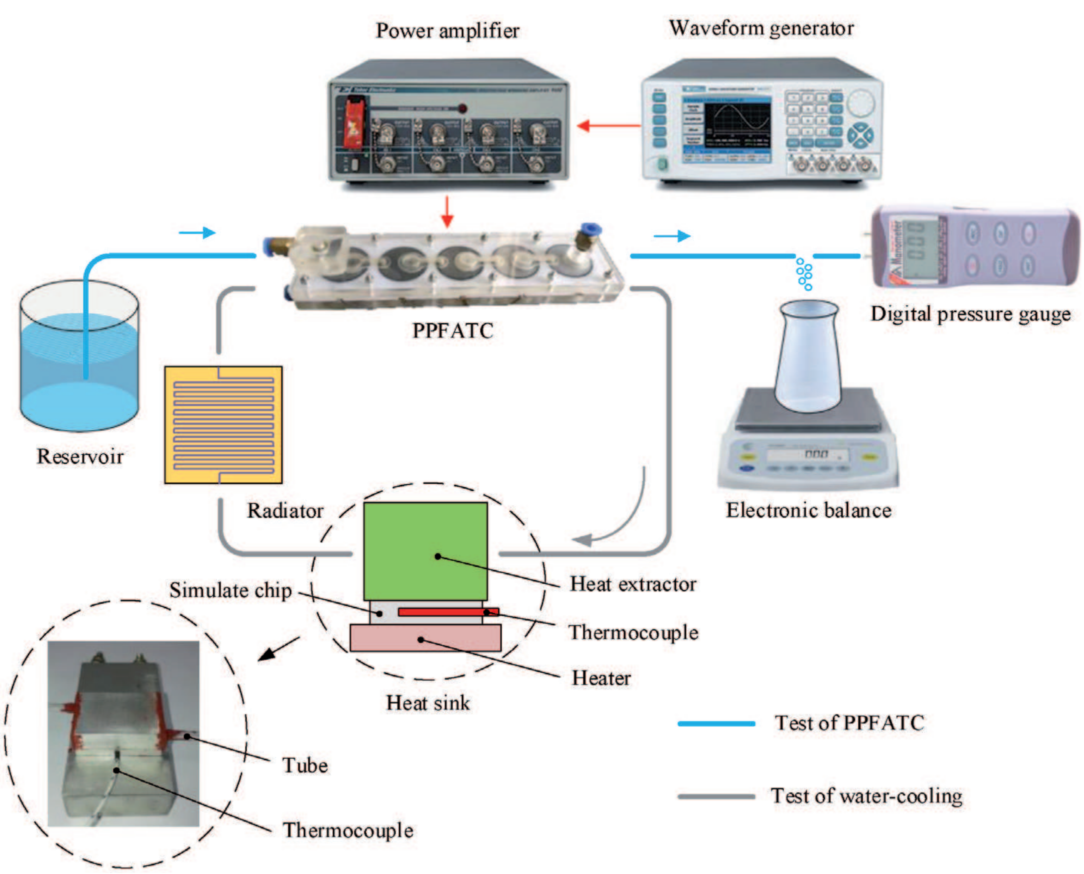

Figure 23.
The experimental platform of PPFATC and chip water-cooling system [17].

in **Figure 23**. The experiment shows that when the driving voltage is 60 V_{pp}, the maximum flow rate of the PPFATC in parallel is 251.1 ml/min and the maximum output pressure is 60.2 kPa. In series, the PPFATC can achieve 186.2 ml/min and

109.9 kPa, respectively. The water cooling system with PPFATC can obtain good cooling performance under low driving voltage. When the driving voltage is 60 V_{pp}, the PPFATC can reduce the chip temperature from 107.8–51°C.

4. Conclusion

Piezoelectric microfluidic technology is currently undergoing a period of prosperous development, partly motivated by the demands for pumping devices in the fields of drug delivery, biological fluid handling, micro total analysis systems, electrophoresis detection, liquid cooling of microelectronics and polymerase chain reaction (PCR). To meet various application requirements, quite a few novel principles and configurations have been presented over the last two decades, including liquid micropump, air micropump, single-chamber micropump, multi-chamber micropump, single-actuator micropump, multi-actuator micropump. This work mainly presented the structure and operating principle of single-chamber and multi-chamber piezoelectric micropumps and demonstrated an application in the field of chip water-cooling system. Some influencing factors on the performance of the piezoelectric micropumps were tested by the experimental frequency and voltage responses. Experimental results showed that there was an optimal driving frequency to maximize the flowrate of the piezoelectric micropump. Basically, the output flowrate was enhanced with the increasing driving voltage. It was helpful to increase the flowrate and backpressure of micropumps through combining the pumping chamber in parallel and serial, respectively. In this work, a maximum flowrate of about 280 ml/min could be achieved by combining five chamber in serial as well as the maximum output pressure approximately approached 11 kPa. Therefore, this work can be used as a reference and guideline for the design and application of piezoelectric microfluidic technology.

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