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A Quintuple-Bimorph Tenfold-Chamber Piezoelectric Pump Used in Water-Cooling System of Electronic Chip

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ABSTRACT To meet the dual requirement of high flow rate and high output pressure in water-cooling system of electronic chip, a quintuple-bimorph tenfold-chamber piezoelectric pump (QTPP) is presented, which owns the comprehensive advantages of parallel and serial connection. QTPP is composed of two groups of five-chamber-in-series, and the two groups of five-chamber-in-series can be in parallel or serial. QTPP is designed and fabricated, the output performance of which is invested by experiments. The experimental results show that QTPP can obtain high flow rate and high output pressure under low driving voltage. When driven by quintuple piezoelectric vibrators under 60Vpp, QTPP in parallel can obtain the maximum flow rate of 251.1ml/min and the maximum output pressure of 60.2kPa. While in serial, QTPP can obtain 186.2ml/min and 109.9kPa respectively. The water-cooling system with QTPP is established and experimented. The experimental results indicate that the water-cooling system with QTPP can achieve a good cooling performance under low driving voltage. Under the driving voltage of 60Vpp, QTPP can reduce the temperature of stimulate chip from 107.8°C to 51°C.

INDEX TERMS Piezoelectric pump, multiple-chamber, serial, parallel, water-cooling.

I. INTRODUCTION

In recent decades, with the development of fabrication and processing technology, especially the rapid expansion of MEMS and IT, the integration level of various chips has improved by a large margin [1], [2]. Inevitably, the high integrated electronic chips have a common question of heat accumulation, which makes Moore's law face a considerable challenge. Promoting the heat dissipation efficiency has become the priority in the field of high integrated electronic devices [3], [4]. On account of high heat dissipation efficiency of the electronic chip, water-cooling system has been widely applied [5].

The key component of water-cooling system is micropump [6]. With the advantages of compact size, no electromagnetic interference and low power consumption, piezoelectric pumps own a wide application prospect to be used in water-cooling system of electronic chip [7]–[10]. Tang *et al.* [11] presented an integrated heat sink with a piezoelectric micropump (IHS-PMP). The experimental results indicated that with the optimal driving parameters of the IHS-PMP and at a heating power of 80 W, the wall temperature rise was 47.3°C. Davis *et al.* [12] demonstrated a water-cooling system driven by a piezoelectric pump based on double piezoelectric bimorphs. By imitating the behavior of fishes with double piezoelectric bimorphs and taking the flowing fluid circumstance generated by piezoelectric actuators as the vibrators, the transmission of flowing fluid can be realized. Ma *et al.* [13], [14] putted forward a

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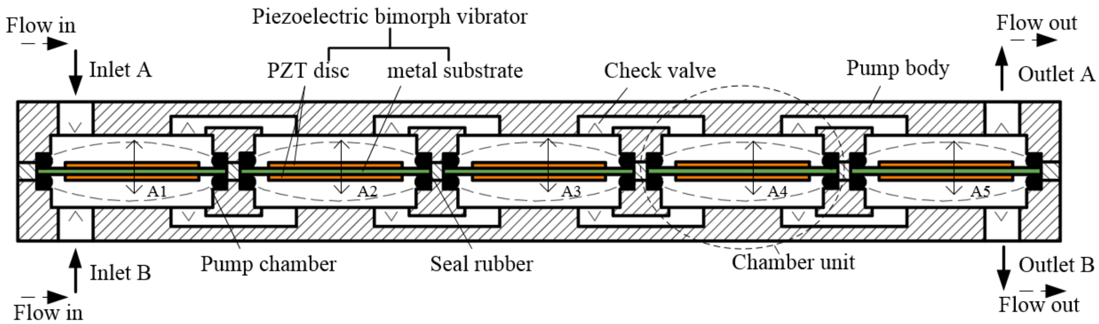


FIGURE 1. Structural schematic diagram of QTPP in parallel connection.

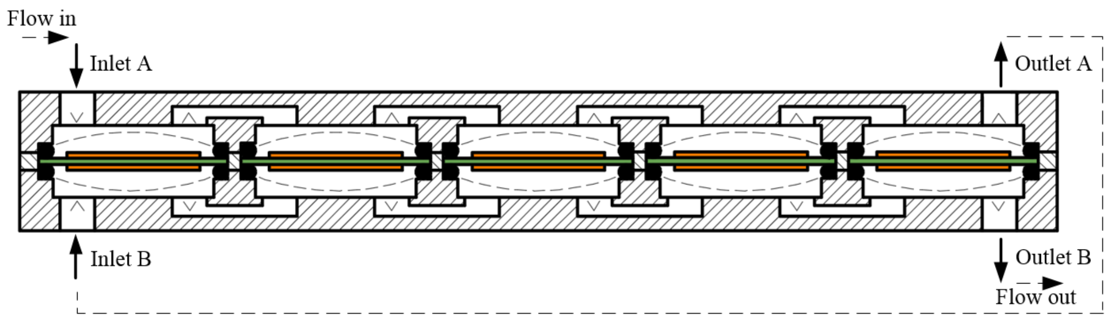


FIGURE 2. Structural schematic diagram of QTPP in serial connection.

one-side actuated diaphragm micropump to build a water-cooling system in laptops. The micropump achieved the maximum output flow rate of 4.1ml/s and the maximum backpressure of 9.9kPa.

In order to improve the output performance, serial and parallel connection piezoelectric pumps has been proposed [15]–[17]. Kan *et al.* [15] presented a serial-connection piezoelectric pump which can achieve high output performance under low driving voltage. The maximum flow rate and pressure of the 4-chamber-in-serial are 7.6ml/min and 48.6kPa at a low voltage of 40V. Kojima *et al.* [18] fabricated a microfluid valve piezoelectric pump with multi-channel use, multistage use to attain the output property of constant and low pulsation. When the serial-connection triple-chamber piezoelectric pump is working at 10Hz synchronously, the backpressure is 18kPa, which is approximately twice of that of single-chamber piezoelectric pump with the same structure. Shoji *et al.* [19] adopted the structure of dual-chamber four-valve (parallel) and dual-chamber three-valve (serial) when doing researches on piezoelectric pump used in chemical analyzing systems. The micropump realized low pulsation output by means of double-chamber alternating working. Zhang *et al.* [20] presented a hybrid multi-chamber piezoelectric pump. The structure of the pump is characterized by simultaneous occurrence of serial/parallel forms through a combination of synchronous and asynchronous modes of piezoelectric actuators. The previous studies indicated that serial-connection piezoelectric pumps increase the output pressure and parallel-connection piezoelectric pumps increase the output flow rate. However, in the highly integrated electronic device, the water cooling system needs the piezoelectric pump to provide a large output pressure to ensure the coolant flow and to provide a large output flow rate ensure the heat transfer capacity. As far as we know, the previous piezoelectric pump studies are difficult to meet the dual needs of high output pressure and high flow rate in chip water-cooling system.

A quintuple-bimorph tenfold-chamber piezo electric pump (QTPP) used in water-cooling system of electronic chip is presented in this article. The QTPP consists of five chamber units in serial. Each chamber unit is composed of a piezoelectric bimorph vibrator and dual chamber, which owns high energy conversion efficiency. Five chamber units in serial form two groups of five-chambers-in-series, and the two groups of five-chambers-in-series are in parallel. Therefore, QTPP has the comprehensive advantages of serial and parallel connection, which can provide high flow rate and high output pressure under low driving voltage. At the same time, by changing connection mode of inlet and outlet, two groups of five-chambers-in-series can be changed into ten-chambers-in-series, so that QTPP will obtain higher output pressure, which will extend the application scope of piezoelectric pump in water-cooling system. In this article, a simulate chip water-cooling system with QTPP is assembled and the cooling performance is investigated by experiments, which provide a reference in practical application.

II. DESIGN AND WORKING PRINCIPLE

As shown in Figure 1 and Figure 2, QTPP is composed of ten chambers, five piezoelectric bimorph vibrators (A1, A2, A3, A4, A5), two inlets (Inlet A, Inlet B), two outlets (Outlet A, Outlet B), check valves, seal rubbers and pump body, among which a piezoelectric bimorph vibrator and dual chamber constitute a chamber unit. Five chamber units are connected in serial by check valves and tubes. Between inlet A and outlet A is the first group of five-chambers-in-series, and between inlet B and outlet B is the second group of five-chambers-in- series. As shown in Figure 1, the fluid flows into inlet A/inlet B and flows out from outlet A/outlet B, two groups of five-chambers-in-series are in parallel. As shown in Figure 2, when outlet A is connected to inlet B, the fluid flow into inlet A and flows out form outlet B, two groups of five-chambers-in-series in parallel are changed to ten-chambers-in-series.

QTPP is driven by AC voltage signal, and the phase difference of driving voltage between two adjacent piezoelectric vibrators is 180°. When 5 piezoelectric bimorph vibrators are driven, A1/A2/A3/A4/A5 vibrate at the same time after power on. Firstly, the driving voltage of A1/A3/A5 is opposite to the polarization direction of the PZT disc, while the driving voltage of A2/A4 is the same. As a result, A1/A3/A5 are bent upward and A2/A4 are bent downward. Secondly, applying a voltage opposite to the working voltage of first step, A1/A3/A5 are bent downward and A2/A4 are bent upward. Under the action of pressure, with the opening and closing of check valve, the liquid flows from inlet to outlet. When an alternating voltage is continuously applied to the piezoelectric vibrators, the first and second working states are changed repeatedly. In this article, in order to test the output performance of DSPP with driving different number of piezoelectric vibrators, three piezoelectric vibrators are used to be driven, that is, three of the five vibrators are chosen to be driven randomly. When the three piezoelectric vibrators are driven, the working principle is the same as that of the five piezoelectric vibrators are driven, and the phase difference between two adjacent piezoelectric vibrators is still 180°.

It is assumed that each chamber can obtain the same output flow rate and pressure when working alone. The output flow rate of single chamber is Q_0, and the output pressure of single chamber is P_0. When QTPP in parallel connection, the output flow rate and output pressure are respectively [15], [20]

$$Q_p = 2\eta_f Q_0\sqrt{5} \tag{1}$$
$$P_p = 5P_0 \tag{2}$$

where $\eta_f = f_s/f_0, f_s$ is the optimum frequency of the one group of five-chambers-in-series, f_0 is the optimum frequency of single chamber. When QTPP in serial connection, the output flow rate and output pressure of the pump are [15], [20]

$$Q_s = \eta_f Q_0\sqrt{10} \tag{3}$$
$$P_s = 10P_0 \tag{4}$$

According to Eqs. (1), (2), (3) and (4), when in parallel, QTPP can obtain higher flow rate, which is fitted for small heat dissipation area and low pipeline pressure drop; when in serial, QTPP can obtain higher output pressure, which is suitable for the situation of big heat dissipation area and high pipeline pressure drop.

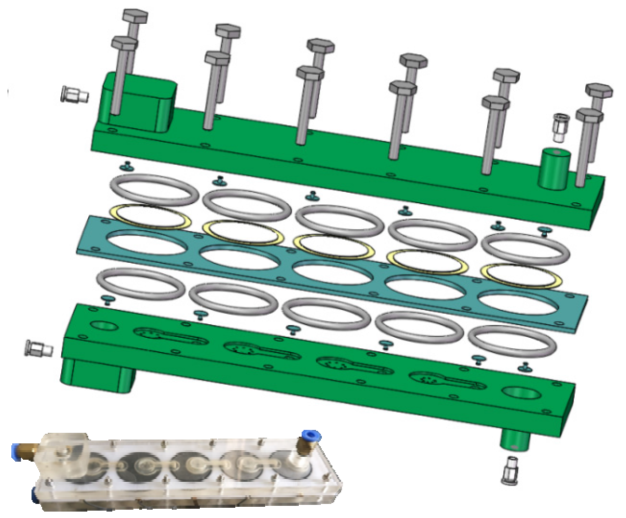


FIGURE 3. The prototype picture of QTPP.

In order to simplify the analysis, it is assumed that the heat conduction of heat extractor is large plate heat transfer. According to the first boundary condition, the heat flux per unit area is [21]

$$q_s = \lambda\frac{t_{w1} - t_{w2}}{\delta} \tag{5}$$

where λ is the heat conductivity coefficient of plate, δ is the thickness of heat transfer plate, t_{w1} and t_{w2} are the temperature between the two sides of the heat transfer plate, respectively.

Assuming the heat dissipation of radiator is cylinder wall's heat conduction, according to the theory of first boundary condition, the heat flux per pipe length is [21]

$$q_t = \frac{t'_{w1} - t'_{w2}}{R_{\lambda t}} = 2\pi\lambda'\frac{t'_{w1} - t'_{w2}}{\ln(d_2/d_1)} \tag{6}$$

where $R_{\lambda t}$ is the thermal resistance per unit length, t'_{w1} and t'_{w2} are the temperature between the two sides of the cylinder wall, respectively. d_1 and d_2 are the inner and outer diameter of the cylinder wall, respectively. λ' is the heat conductivity coefficient of cylinder wall.

Combining Eqs. (5) and (6), in water-cooling system, when the temperature of the chip reaches a steady value, that is

$$q_s A = q_t L \tag{7}$$

where A is the area of heat transfer plate. L is the length of cylinder. Even if the flow rate continues to increase, the temperature of the chip cannot drop down. At this point, there exists a critical coolant flow rate, under which the energy conversion efficiency of the system is highest.

According to Eqs. (1), (2), (3), (4) and (7), if a certain number of vibrators are driven, the critical flow rate of QTPP is obtained. The increase of vibrators cannot achieve better heat dissipation performance. For example, the heat dissipation

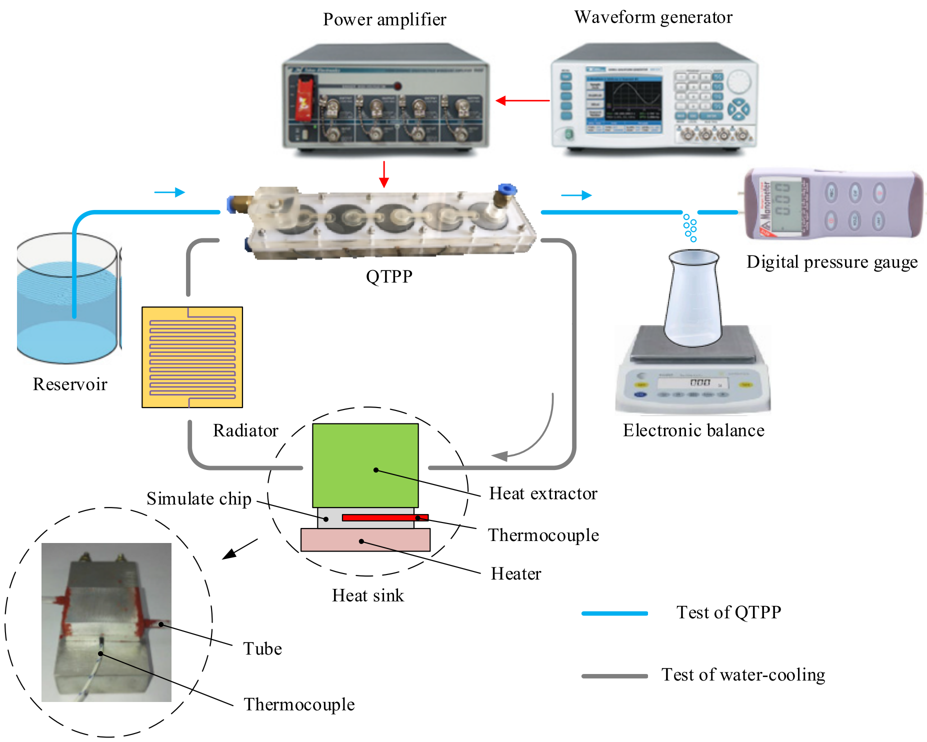


FIGURE 4. The schematic of experiments of QTPP and chip water-cooling system.

TABLE 1. Main parameters of QTPP.

Type	Value and Material
Size of QTPP	270mm×55mm×28mm
Material of pump body	PMMA
Check valve type	Umbrella valve
Material of check valve	Silica gel
Material of metal substrate	Brass
Coolant liquid	Water
Diameter of metal substrate	35mm
Thickness of metal substrate	0.4mm
Diameter of PZT disc	28mm
Thickness of PZT disc	0.2mm
Driving voltage	60Vpp
Driving frequency	60~400Hz, 15Hz intervals
Driving waveform	Sine wave

performance driving by quintuple vibrators may be the same as that of triple vibrators.

III. EXPERIMENT SETUP

The pump body of QTPP is made up of PMMA for convenient observation. To fabricate the pump, bolts and seal rubbers are used to link and seal. QTPP is isolated by putting black insulating tape on. More detailed parameters are illustrated in Tab. 1. Figure 3 is the prototype picture of QTPP.

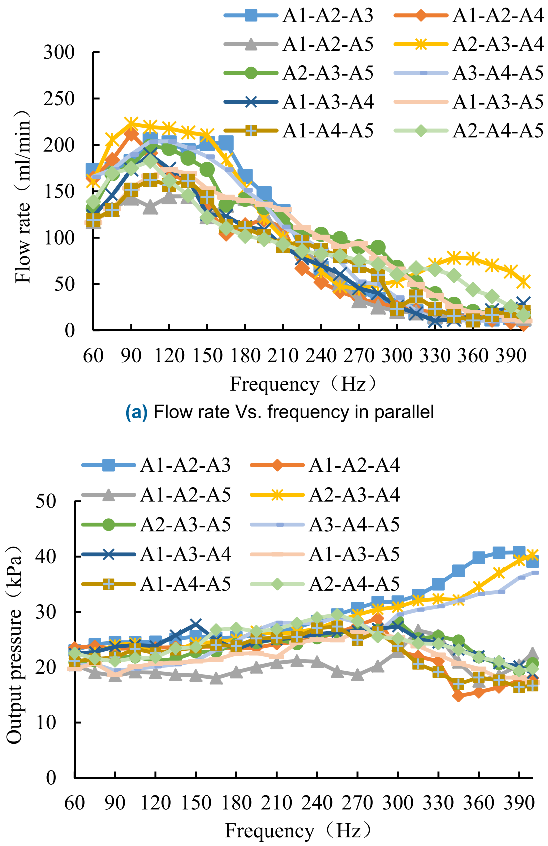
Figure 4 is the schematic of experiments setup of QTPP and chip water-cooling system. In regard to the flow rate and output pressure experiment of QTPP, the waveform generator (Rigol: DG4162) and power amplifier (Tabor: 9400) are used to provide sine wave for driving QTPP. The fluid medium is distilled water and the output flow rate of QTPP is measured by electronic balance. Meanwhile, the output pressure is measured by digital pressure gauge (AZ Instrument: 8215). At the driving voltage of 60Vpp, the frequency varies between 60∼400Hz, the output performance of QTPP is tested in serial/parallel connection. In addition to the output performance of QTPP driven by 5 piezoelectric vibrators, the output performance of QTPP driven by 3 piezoelectric vibrators is also tested.

In order to better satisfy the water cooling application, a water-cooling system with a heat sink and a radiator (Aigo: T120) is assembled. The heat sink mainly consists of a heat extractor, a simulate chip and a heater. K-type thermocouple is inserted in the simulate chip to measure its temperature. The heater, simulate chip and heat extractor are bonded by thermal conductive adhesive. In the water-cooling experiments, the driving voltage of 60Vpp and the optimum frequency of flow rate are applied to the QTPP.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

A. EXPERIMENTS OF QTPP IN PARALLEL CONNECTION

When QTPP is driven by triple vibrators in parallel connection, the output property of QTPP is shown like Figure 5. Figure 5(a) indicates that, with frequency rising, the output flow rate goes up firstly but later down. At 90Hz, driven by A2-A3-A4, the maximum output flow rate of QTPP is 222.6ml/min. While Figure 5(b) shows the output pressure of A1-A2-A3, A2-A3-A4 and A3-A4-A5 have



(a) Flow rate Vs. frequency in parallel

(b) Pressure Vs. frequency in parallel

FIGURE 5. Output flow rate and pressure of QTPP driven by triple vibrators under 60Vpp.

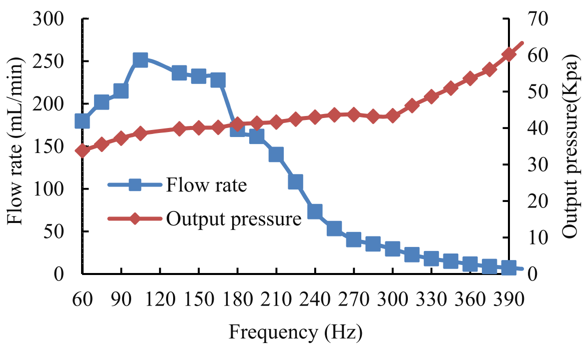
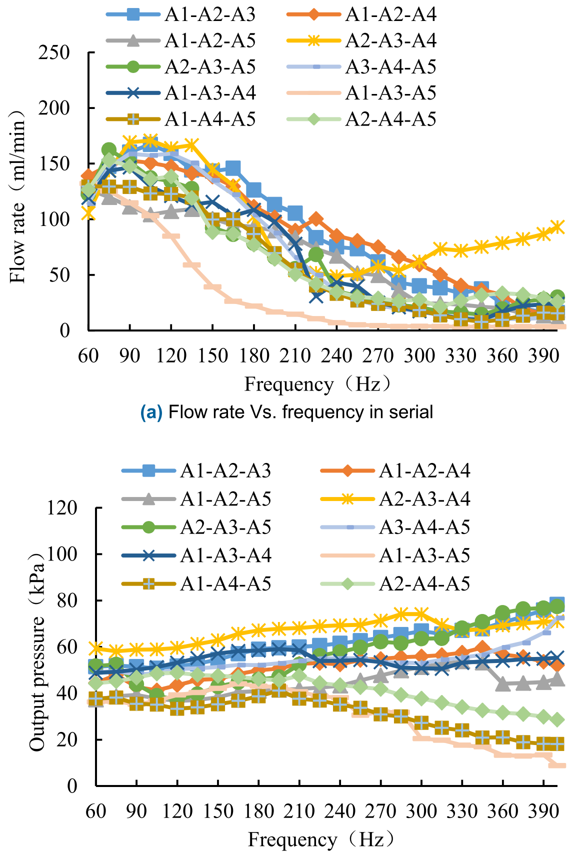


FIGURE 6. Output flow rate and output pressure of QTPP driven by quintuple vibrators under 60Vpp in parallel.

better performance. At 400Hz, driven by A2-A3-A4, the maximum output pressure of QTPP is 40.3kPa.

When QTPP is driven by quintuple vibrators in parallel connection, Figure 6 demonstrates the output property of QTPP in terms of the flow rate and output pressure. With frequency growing, the output flow rate goes up progressively firstly but later down. At 105Hz, the output flow rate of QTPP obtains the maximum of 251.1ml/min. While the output pressure increases integrally with frequency increasing. At 390Hz, the output pressure of QTPP attains the maximum of 60.2kPa.



(a) Flow rate Vs. frequency in serial

(b) Output pressure Vs. frequency in serial

FIGURE 7. Output flow rate and pressure of QTPP driven by triple vibrators under 60Vpp.

B. EXPERIMENTS OF QTPP IN SERIAL CONNECTION

When QTPP is driven by triple vibrators in serial connection, Figure 7(a) displays output flow rate versus frequency, and Figure 7(b) indicates output pressure versus frequency. Figure 7(a) shows that, the output flow rate of QTPP reaches a peak in each curve with frequency increasing. When QTPP is driven by A2-A3-A4, the output performance is best. At 105Hz, driven by A2-A3-A4, the maximum output flow rate of QTPP is 170.8ml/min. While in Figure 7(b), the output pressure of QTPP appears a stable varying tendency with frequency increasing. At 300Hz, driven by A2-A3-A4, the maximum output pressure of QTPP is 74.1kPa.

When QTPP is driven by quintuple vibrators in serial connection, the output performance of QTPP is shown in Figure 8. Figure 8 demonstrates that, with frequency rising, the output flow rate grows progressively firstly but later drops. At 105Hz, the output flow rate of QTPP obtains the maximum of 186.2ml/min. While the output pressure grows integrally with frequency rising. At 390Hz, the output pressure of QTPP attains the maximum of 109.9kPa.

C. EXPERIMENTS OF QTPP IN WATER-COOLING SYSTEM

In order to manifest the importance of QTPP in water-cooling system, the temperature of the simulate chip at different heating powers without water-cooling is firstly tested.

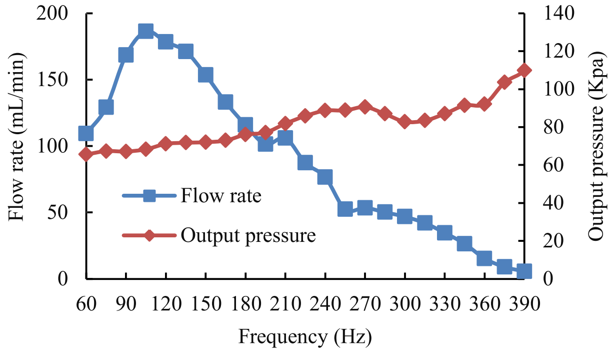


FIGURE 8. Output flow rate and output pressure of QTPP driven by quintuple vibrators under 60Vpp in serial.

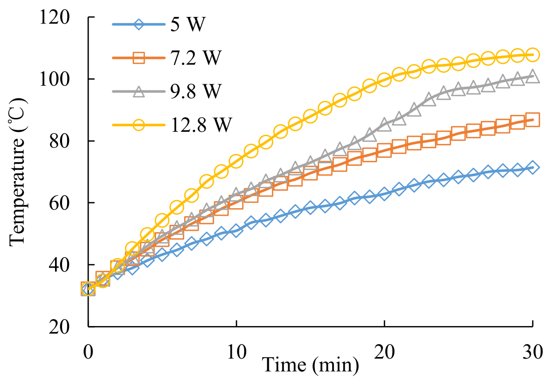


FIGURE 9. Temperature of the simulate chip at different heating powers without water-cooling.

As observed in Figure 9, the temperature of the simulate chip keeps rising in the entire 30 minutes heating period and the higher the heating power is, the faster the temperature rises. Eventually, the simulate chip's temperature reaches 71.4°C, 86.8°C, 100.9°C, and 107.8°C with heating powers of 5 W, 7.2 W, 9.8 W, and 12.8 W, respectively.

Figure 10 shows the temperature of the simulate chip with water-cooling system at heating power of 12.8 W. When QTPP is in serial and parallel, triple or quintuple vibrators are selected to be driven. When QTPP is driven by triple vibrators, A2-A3-A4 has been selected, which owns better output performance compared with other combinations of triple vibrators. The driving voltage is 60Vpp, and the driving frequency is the optimum frequency of flow rate. As shown in Figure 10(a), when QTPP is connected in serial and driven by quintuple vibrators, the cooling performance is better than it driven by triple vibrators (A2-A3-A4). However, the thermal equilibrium temperature of chip with QTPP driven by triple vibrators (A2-A3-A4) is 57.6°C, which is similar to that driven by quintuple vibrators. As shown in Figure 10(b), the cooling performance is almost similar among the two curves (triple and quintuple vibrators) when QTPP is in parallel. When driven by triple vibrators, The thermal equilibrium temperature of 51.0°C is obtained at 25min; when driven by quintuple vibrators, the thermal equilibrium temperature of 51.0°C is obtained at 29min. The temperature of chip will stay at same, even if the flow rate increases to more than the critical coolant flow rate. At the critical coolant flow rate, the energy conversion efficiency will be highest.

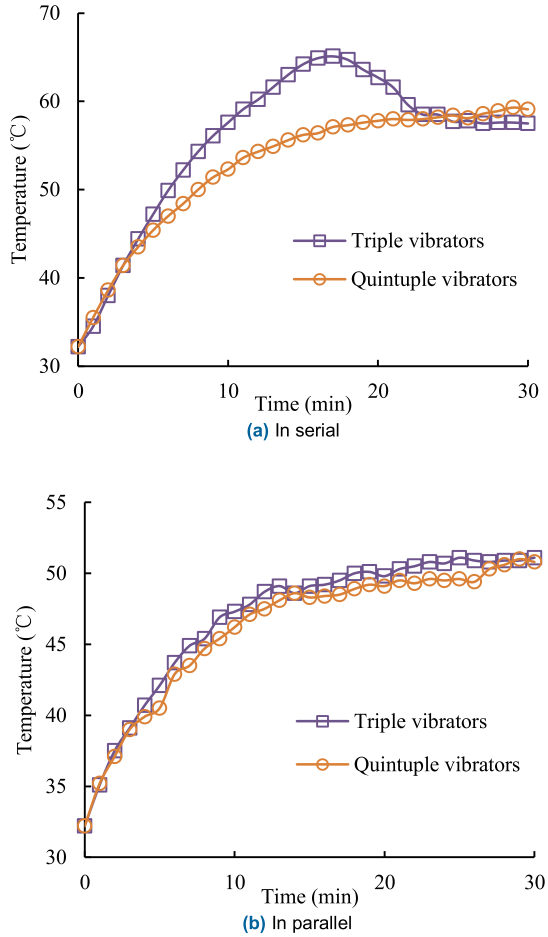


FIGURE 10. Temperature of the simulate chip with water- cooling system at heating power of 12.8 W.

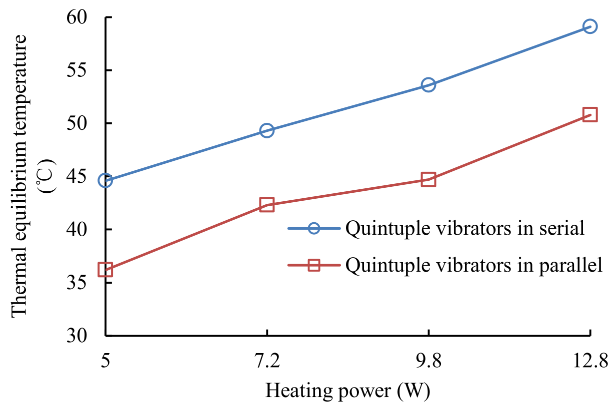


FIGURE 11. Thermal equilibrium temperature at different heating powers with QTPP driven by quintuple vibrators.

Figure 11 indicates the thermal equilibrium temperature of simulate chip with QTPP driven by quintuple vibrators at different heating powers. The thermal equilibrium temperature tends to increase with the heating power rises. As shown in Figure 18, when heating power is 9.8 W, the thermal equilibrium temperature of chip with QTPP in serial and parallel is 44.6°C and 36.2°C respectively; when heating power is 12.8 W, the thermal equilibrium temperature of chip with QTPP in serial and parallel increase to 59.1°C and 51.0°C respectively. Under different heat power, the thermal equilibrium temperature of chip with QTPP in parallel is lower than that in serial, that is, the cooling performance of QTPP in parallel is better.

V. CONCLUSION

A quintuple-bimorph tenfold-chamber piezoelectric pump (QTPP) used in water-cooling system of electronic chip is presented in this article. QTPP is composed of five chamber units in serial. Five chamber units form two groups of five-chamber-in-series, and two groups of five-chamber-in-series are in parallel. Therefore, QTPP owns the comprehensive advantages of serial and parallel connection, which can achieve high flow rate and high output pressure under low driving voltage. By connecting outlet A and inlet B, QTPP can be in serial, which get higher output pressure. The output performance of QTPP is invested by experiment, and the chip water-cooling system with QTPP is established and experimented. Experimental results show

(1) QTPP can obtain high flow rate and high output pressure under low driving voltage. When driven by triple piezoelectric vibrators (A2-A3-A4) under 60Vpp, QTPP in parallel can obtain the maximum flow rate of 222.6mL/min and the maximum output pressure of 40.3kPa. While in serial, QTPP can obtain 170.8mL/min and 71.8kPa respectively. When driven by quintuple vibrators under 60Vpp, QTPP in parallel can obtain the maximum flow rate of 251.1ml/min and the maximum output pressure of 60.2kPa. While in serial, QTPP can obtain 186.2ml/min and 109.9kPa respectively.

(2) The water-cooling system with QTPP owns a good chip cooling performance. When heating power of stimulate chip is 9.8 W, with the water-cooling system, the temperature of chip and can be reduced from 100.9°C to 44.6°C (in serial) and 36.2°C(in parallel) respectively; when heating power is 12.8 W, with the water-cooling system, the temperature of chip can be reduced from 107.8°C to 59.1°C (in serial) and 51.0°C (in parallel) respectively. Under different heat power, the cooling performance of QTPP in parallel is better.

(3) The energy conversion efficiency of the water-cooling system can be improved by selecting different number of vibrators to drive. When the heating power of chip is 12.8W and QTPP is driven by triple vibrators in serial, the thermal equilibrium temperature of 57.6°C is obtained at 25min, which is similar to that driven by quintuple vibrators. When QTPP is driven by triple vibrators in parallel, the thermal equilibrium temperature of 51.0°C is obtained after 25min, which is the same with that driven by quintuple vibrators. At the critical coolant flow rate, the energy conversion efficiency will be highest. The temperature of chip will stay at same, even if the flow rate increases to more than the critical coolant flow rate.

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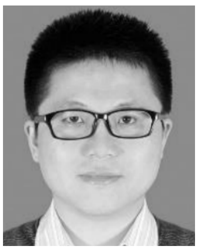

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