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Theory and Experimental Verification on Valveless Piezoelectric Pump with Multistage Y-shape Treelike Bifurcate Tubes

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Abstract: Among most traditional piezo water cooling systems, piezoelectric valve pumps are adopted as their driving sources. The valves in these pumps induce problems of shock and vibration and also make their structure complicated, which is uneasy to minimize and reduce their reliability and applicability of the whole system. In order to avoid these problems caused by valve structure, a novel valveless piezoelectric pump is developed, which integrates both functions of transforming and cooling. The pump's Y-shape tree-like construction not only increases the efficiency of cooling but also the system reliability and applicability. Firstly, a multistage Y-shape treelike bifurcate tube is proposed, then a valveless piezoelectric pump with multistage Y-shape treelike bifurcate tubes is designed and its working principle is analyzed. Then, the theoretical analysis of flow resistance characteristics and the flow rate of the valveless piezoelectric pump are performed. Meanwhile, commercial software CFX is employed to perform the numerical simulation for the pump. Finally, this valveless piezoelectric pump is fabricated, the relationship between the flow rates and driving frequency, as well as the relationship between the back pressure and the driving frequency are experimentally investigated. The experimental results show that the maximum flow rate is 35.6 mL/min under 100 V peak-to-peak voltage (10.3 Hz) power supply, and the maximum back pressure is 55 mm H_2O under 100 V (9 Hz) power supply, which validates the feasibility of the valveless piezoelectric pump with multistage Y-shape treelike bifurcate tubes. The proposed research provides certain references for the design of valveless piezoelectric pump and improves the reliability of piezo water cooling systems.

Key words: piezoelectric, pump, valveless, Y-shape tube, treelike bifurcate

1 Introduction

In recent years, with the rapid development of MEMS technology, a variety of microfluidic devices come into being[1–3]. By integrating the driving device with the transporting function, the valveless piezoelectric pump has the features of no relative motion at joint of driving part and no internal contamination caused by abrasive wear and lubrication[4–5]. Many novel piezoelectric valveless pumps with high efficiency have been extensively investigated, which can be widely used in biological, medical and electronic device cooling and other fields. Therefore, the valveless piezoelectric pump is continually being exploited in functional integration, particularly in fields of piezoelectric liquid cooling system functions and applications[6].

HAM, et al[7], proposed a small piezoelectric pump to loop water for cooling purpose in 2006. Its maximum flow rate is 1.85 L/min. However, this piezoelectric pump is a valve piezoelectric pump, so the reliability of the internal valve determines the life of the pump.

PIRES, et al[8], proposed a piezoelectric pump used for loop medical light water in a cooling system in 2007. According to the bionic principle, this pump uses piezoelectric bimorph as its driving source. Its maximum flow rate is 41.3 mL/min. However, in this cooling system the external heat sink is installed to increase its cooling efficiency, which also increases the size of the system and is not conducive to miniaturization.

MA, et al[9], proposed a piezoelectric micro-pump for the liquid cooling system of notebook computers in 2009. Its maximum flow rate is 4.1 mL/s. However, the piezoelectric micro-pump contains an internal valve, while

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the cooling system also added a heat sink. Hence, the reliability and miniaturization are severely limited.

At present, most piezoelectric pumps employed in water cooling systems contain internal valves which decrease the reliability and service life of the valve piezoelectric pump. In order to increase the discharge amount of heat, some water cooling systems have attached the heat pipes, which increase the whole system volume and are not conducive to miniaturization.

The Y-shape tube as a kind of no-moving-part (NMP) valve has been widely studied due to its simple structure and unique bifurcation, since it was applied to valveless piezoelectric pumps[10–11]. Due to the little resistance as well as ideal size, the natural treelike bifurcation system is adopted to design energy conduction systems and heat transfer systems to reduce energy loss, such as vascular system in the vein network, water and plant material context. According to this idea and based on the Y-shape tube, a multistage Y-shape treelike bifurcate tube is designed, which will help to increase heat dissipation area and thus improve the cooling efficiency.

This paper will firstly propose the structure of multistage Y-shape treelike bifurcate tube for the next design valveless piezoelectric pump with multistage Y-shape treelike bifurcate tubes and analyze their working principles. Then, the theoretical analysis of flow resistance characteristics and the flow rate of valveless piezoelectric pump with multistage Y-shape treelike bifurcate tubes are performed. Furthermore the flow numerical analysis is performed. Finally, the experiment of pumping is conducted to prove the pump's feasibility and reliability of the theory.

2 Structure of Multistage Y-shape Treelike Bifurcate Tube

The fractal model of biological vascular network named WBE model, in which a fractal-like bifurcate configuration can fill up the entire space, was proposed by WEST, et al[12] in 1997, as shown in Fig. 1. WEST, et al[12], believed that plant grew with fractal scaling, self similarity, the ability to fill up the entire space as well as the characteristics of small flow resistance in processes of transporting nutrition and moisture. Based on this model, the authors design multistage Y-shape treelike bifurcate tube.

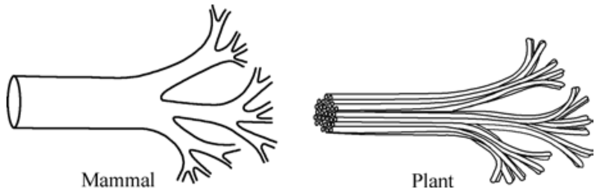


Fig. 1. Configuration of the exoskeleton arm system

For this treelike structure, Y-shape tube is gradually ranked into a planar structure (as called 2.5D structure) network, so it can be called the multistage Y-shape treelike bifurcate tube, as shown in Fig. 2.

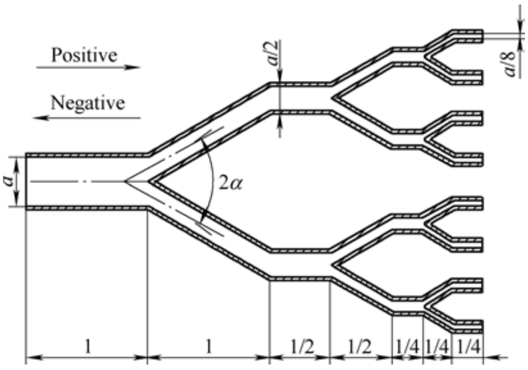


Fig. 2. Multistage Y-shape treelike bifurcate tube

The width of the main Y-shape tube is a, with the width of bifurcate tube as half width of the main tube. For each stage Y-shape tube in the whole treelike structure, the both main tubes and their related bifurcate tubes are equal in length, which is equal to half of their previous tubes' length respectively. For each Y-shape tube, the bifurcation angle is 2α, and the depth of the bifurcate tube is h. Thus, compared with a single Y-shape tube, there is a more broad flow area in the multistage Y-shape treelike bifurcate tube. So if used as a radiator, this treelike structure can broaden the radiating area and improve the radiating efficiency.

3 Structure and Principle of the Pump

The valveless piezoelectric pumps with multistage Y-shape treelike bifurcate tubes (VPTBT) is mainly composed of a piezoelectric vibrator, a pump chamber and a pair of multistage Y-shape treelike bifurcate tubes headed in the same direction (Fig. 3). When the fluid flows in a multistage Y-shape treelike bifurcate tube, for the whole treelike tube, $2i$ (i=1, 2, 3$\cdots$) bifurcate tubes are treated as outlet (defined as the positive flow), and the main tube is treated as outlet (defined as the negative flow). When the flow happens in the multistage Y-shape treelike bifurcate tube, the energy consumption of positive flow is unequal to that of negative flow. Therefore, their flow resistances are unequal too.

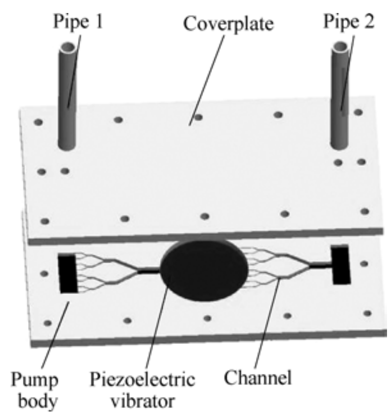


Fig. 3. valveless piezoelectric pump with multistage Y-shape treelike bifurcate tubes

The piezoelectric vibrator loaded by an alternating voltage will vibrate upwards and downwards, which can cause a periodical change of the pump chamber volume, driving the fluid movement under the role of multistage Y-shape treelike bifurcate tubes. When the piezoelectric vibrator moves downward, the volume of the pump chamber will become larger and the fluid flows into the pump chamber through pipes 1 and 2. When the piezoelectric vibrator moves upward, the volume of the pump chamber becomes smaller and the fluid flows out of pump through pipes 1 and 2. As a result of the difference flow resistances between the positive and negative flows, the fluid flow rate is unequal between chamber inflow and outflow from both pipes in a vibration period.

In this way, the reciprocating motion of piezoelectric vibrator loaded by alternating sine-wave voltage signal will drive the fluid in chamber flowing, which is constant from the inlet to the outlet overall. The one-way flow of pump depends on the characteristics of difference flow resistances of the multistage Y-shape treelike bifurcate tube. Furthermore, as a tube system, this multistage Y-shape treelike bifurcate tube is effective in increasing the flow area because of its broader flow room, which can be used as a substitute for the traditional cooling pipe, reducing the room space for the cooling system.

4 Theoretical Analysis for the Flow Resistance and Flow Rate

The local resistance and frictional resistance are overcome when the fluid flow though the multistage Y-shape treelike bifurcate tube, resulting in the pressure loss. From the Bernoulli equation,

$$\frac{p_1}{\rho g}+\frac{v_1^2}{2g}+z_1=\frac{p_2}{\rho g}+\frac{v_2^2}{2g}+z_2+h_{\mathrm{L}}, \tag{1}$$

$$h_{\mathrm{L}}=\zeta\frac{v^2}{2g}+f\frac{L}{D_{\mathrm{h}}}\frac{v^2}{2g}, \tag{2}$$

where p is pressure, v is velocity of fluid, z is height of the liquid level position, ρ is the density of the liquid, h_{L} is head loss and subscript 1 and 2 mean two end faces of the tube. h_{L} is determined by the local resistance loss and frictional resistance loss. ζ is coefficient of local resistance, f is coefficient of frictional resistance, L is length of the tube. Due to the rectangular cross section of the tube, hydraulic diameter is used for standard diameter, $D_{\mathrm{h}}=4A/P_{\mathrm{e}}$. A is cross-sectional area of the tube, P_{e} is perimeter.

As a quiescent component of valveless piezoelectric pump, multistage Y-shape treelike bifurcate tube plays the role of valve by its characteristics of difference resistances between positive and negative flows. Frictional resistance can be neglected for the balanced results between positive and negative flows. The major issue is to study the coefficient of local resistance of multistage Y-shape treelike bifurcate tube. Moreover, considering the fact that the multistage Y-shape treelike bifurcate tube is constructed by Y-shape tubes, we discuss the coefficient of local resistances where the flow merges or divides in a Y-shape tube.

4.1 Merging and dividing local resistance coefficient of Y-shape tube

When flowing through the Y-shape tube, fluid can be merged or divided in the flowing direction (Fig. 4). Due to the energy loss in the tube's bifurcation in both positive and negative flows, the local resistance arises. Therefore, the energy loss can be obtained by calculating the local resistance coefficient at bifurcation.

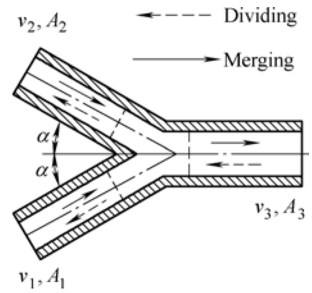


Fig. 4. Y-shape tube

4.1.1 Merging local resistance coefficients

As the vibration amplitude of the piezoelectric vibrator of valveless piezoelectric pump is very small, the flow driven by the vibrator can be considered as laminar flow. Supposing the density is a constant and the flow rates in two bifurcation pipes of Y-shape tube are equal, the mass flow-rate through two bifurcation pipes can be expressed as follows:

$$\frac{\mathrm{d}}{\mathrm{d}t}m=\rho vA, \tag{3}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}m_1=\frac{\mathrm{d}}{\mathrm{d}t}m_2, \tag{4}$$

where m is fluid mass; subscripts 1 and 2 correspond to two bifurcated pipes of Y-shape tube.

Due to the cross-sectional area of two bifurcated pipes of Y-shape tube, $A_1=A_2$ and $A_3=A_1+A$. According to the Continuity Theory, we obtain $v_1=v_2=v_3$. Subscript 3 corresponds to main pipe of Y-shape tube.

According to the Bernoulli equation, we can obtain the local resistance coefficients from tube 1 to tube 3:

$$\zeta_{1,3}=\frac{(p_1+v_1^2\rho/2)-(p_3+v_3^2\rho/2)}{v_3^2\rho/2}=\frac{p_1-p_3}{v_3^2\rho/2}. \tag{5}$$

According to Ref. [13],

$$\zeta_{1,3}=\frac{\Delta p_{1,3}}{\rho v_3^2/2}=a\frac{Q_1}{Q_3}+b\left[\left(\frac{Q_1}{Q_3}\right)^4+\left(1-\frac{Q_1}{Q_3}\right)^4\right]-c\left(\frac{Q_1}{Q_3}\right)^2-d, \tag{6}$$

where the parameter a, b, c and d depends on the bifurcation angle of Y-shape tube. According to Ref. [14], the local resistance coefficient of merging of Y-shape tube can be expressed as

$$\zeta_{\mathrm{YM}}=\frac{Q_1}{Q_3}\zeta_{1,3}+\frac{Q_2}{Q_3}\zeta_{2,3}. \tag{7}$$

4.1.2 Dividing local resistance coefficients

FRIED, et al[13], provided all the local resistance coefficients on the dividing flow about the concerned Y-shape tube. This paper discusses the Y-shape tube with $A_1=A_2$ and $A_3=A_1+A_2$, so the local resistance coefficient from the tube 3 to tube 1 is

$$\zeta_{3,1}=S(1+\lambda^2-2\lambda\cos\alpha), \tag{8}$$

where the parameter S depends on cross-sectional area and flow rate, $\lambda=v_1/v_3$.

The local resistance coefficient of dividing flow of Y-shape tube can be expressed as

$$\zeta_{\mathrm{YD}}=\frac{Q_1}{Q_3}\zeta_{3,1}+\frac{Q_2}{Q_3}\zeta_{3,2}. \tag{9}$$

4.2 Local resistance coefficient of multistage Y-shape treelike bifurcate tube

As mentioned above, multistage Y-shape treelike bifurcate tube is gained based on the Y-shape tubes, so the local resistance coefficient of the whole tube can be roughly considered as the sum of coefficient of local resistances of all the stages of Y-shape tubes[15].

When the fluid flow along positive direction (to be divided), local pressure loss can be expressed as follows:

$$\Delta p_{\mathrm{D}}=\Delta p_{11}+\Delta p_{21}+\Delta p_{22}+\Delta p_{31}+\cdots+\Delta p_{ij}=\frac{\rho v_{11}^2}{2}\xi_{11}+\frac{\rho v_{21}^2}{2}\xi_{21}+\cdots+\frac{\rho v_{ij}^2}{2}\xi_{ij}, \tag{10}$$

where Δp_{D} is local pressure loss when fluid flow along positive direction; Δp_{ij} is local pressure loss with fluid flowing to the every stage Y-shape tube along positive direction; i is the stage number of Y-shape tube in the whole tube; j is the number of Y-shape tube in this stage, as for in this paper, i=1, 2, 3 and j=1, 2, 3, 4; ξ_{ij} is the local resistance coefficient with fluid flowing to the ith stage and jth of Y-shape tube along positive direction; v_{ij} is the average flow speed; ρ is the fluid density.

The bifurcation angles of Y-shape tubes in every stage are 2α, thus the local resistance coefficient of each bifurcation is the same. Eq. (10) can be expressed as

$$\Delta p_{\mathrm{D}}=\frac{\rho v_{11}^2}{2}(\xi_{11}+\xi_{21}+\cdots+\xi_{ij})=\sum_{i=1}(2^{i-1})\rho v_{11}^2\xi_{\mathrm{YD}}. \tag{11}$$

Similarly, when the fluid flows along negative direction, the pressure loss of the whole tube can be expressed as

$$\Delta p_{\mathrm{M}}=\frac{\rho v_{11'}^2}{2}\xi_{11'}+\xi_{21'}+\cdots+\xi_{ij'})=\sum_{i=1}(2^{i-1})\rho v_{11'}^2\xi_{\mathrm{YM}}, \tag{12}$$

where Δp_M is local pressure loss when fluid flow along negative direction. $\xi_{ij'}$ is the local resistance coefficient with fluid flowing to the ith stage and jth of Y-shape tube along negative direction. $v_{ij'}$ is the average flow speed likewise.

For positive and negative directions, the local resistance coefficient of the whole tube can be expressed respectively as follows:

$$\begin{cases}\xi_{\mathrm{D}}=\sum_{i=1}(2^{i-1})\xi_{\mathrm{YD}},\\ \xi_{\mathrm{M}}=\sum_{i=1}(2^{i-1})\xi_{\mathrm{YM}},\end{cases} \tag{13}$$

where ξ_{D} is the local resistance coefficient in positive direction; ξ_{M} is the local resistance coefficient in negative direction.

4.3 Flow rate analysis

According to Ref. [16], the flow rate of the piezoelectric pump can be approximately expressed as

$$q=V_{\mathrm{m}}\omega\frac{\pi(\xi_{\mathrm{M}}-\xi_{\mathrm{D}})}{16(\xi_{\mathrm{M}}+\xi_{\mathrm{D}})}, \tag{14}$$

where q is the flow rate; ω is angular frequency.

V_{m} is the amplitude of the maximum volumetric displacement which can be expressed as

$$V_{\mathrm{m}}=2\pi\int_0^R w\left(r,\frac{T}{2}\right)r\mathrm{d}r, \tag{15}$$

where $T/2$ is the time for the vibrator to move from the balance position to the maximum displacement; $w(r,T/2)$ is the displacement function of piezoelectric vibrator at time $T/2$; R is the radius of the piezoelectric vibrator.

From Eq. (14), it is known that when $\xi_M-\xi_D\neq 0$, the flow rate of the pump $q\neq 0$, which means it can produce a net flow.

5 Simulation Analysis

The commercial software CFX was employed to perform the finite element analysis on valveless piezoelectric pump with multistage Y-shape treelike bifurcate tubes (VPTBT).

The finite element model was drawn, as shown in Fig. 5. In Fig. 5, FSI was defined to be fluid-solid coupling surface in flow field simulation, with Inlets 1 and 2 to be the import and export surface of flow field respectively. In this model, all stage Y-shape bifurcation angles are 60°. D is diameter of the pump chamber, with specific parameters as shown in Table 1.

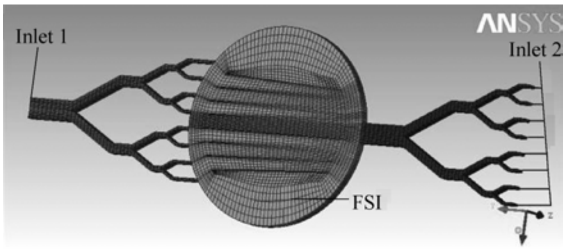


Fig. 5. Finite element model of VPTBT

Table 1. Geometrical parameters of the pump mm

Width a	Depth h	Length l	Diameter D
4	2	10	40

In the process of simulation, displacement load changing with frequency was loaded on FSI surface. Inlets 1 and 2 surfaces, working under an atmospheric pressure, were defined for opening boundary and the other surfaces were defined as no-slip boundary. Due to the micro amplitude of vibration of piezoelectric vibrator, the flow was assumed to be laminar in this research.

Fig. 6 shows velocity contour on the intermediate plane of the pump within a vibrating cycle T at these four characteristic positions passed by the piezoelectric vibrator in succession: the equilibrium position, maximum position, equilibrium position, and negative maximum position.

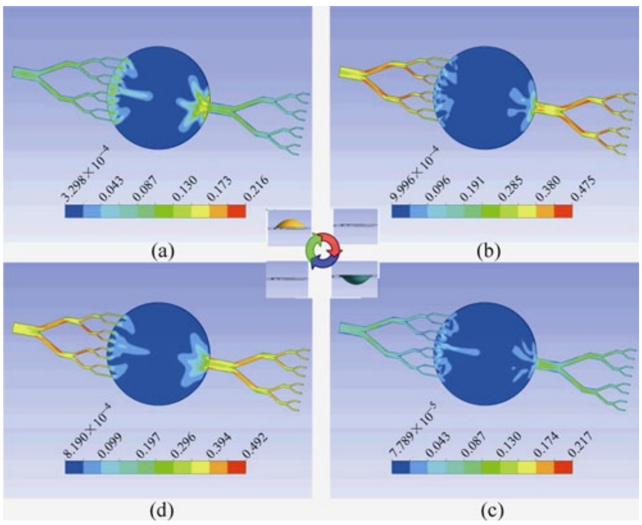


Fig. 6. Velocity contour pattern of VPTBT (m/s)

From Figs. 6(a) to 6(c), piezoelectric pump is in the discharging period with piezoelectric vibrator moving from the maximum position to the negative maximum position. In this period, fluid is discharged outside the pump chamber with piezoelectric vibrator downward motion. Form Figs. 6(c) to 6(a), piezoelectric pump is in suction period with piezoelectric vibrator moving from the negative maximum position to the maximum position. In this period, the fluid is sucked into the pump chamber with piezoelectric vibrator upward motion.

According to Fig. 6, the flow velocities are different between the discharging period and suction period from the ends of the tubes. It can be seen that the flow velocity in positive direction is bigger than that in negative direction through the multistage Y-shape treelike bifurcate tube. And the flow rate into inlet1 is more than that into inlet 2, and the flow rate out inlet1 is smaller than that out inlet2 within a vibrating cycle T as well. It shows that the pump has a one-way transmission function.

6 Experimental Study

The geometrical parameters are the same with that used in simulation. Fig. 7 shows the photograph of the VPTBT for experiments. Fig. 8 represents a picture of flow measurement for the VPTBT. In this research, we use high-accuracy electronic balance to measure the mass of liquid flowed out in a phase of time, calculating the volume flow rate of the pump. Fig. 9 indicates back pressure measurement for the VPTBT, a method of measuring the maximum exporting height on the zero flow condition. CCD Laser displacement sensor is employed to measure the displacement of the center of the piezoelectric vibrator in this research.

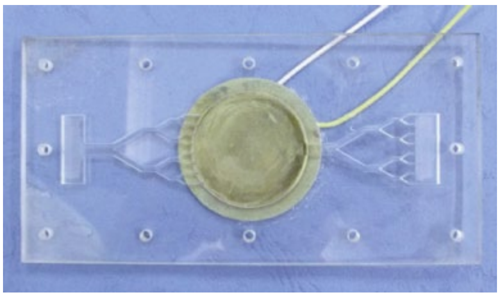
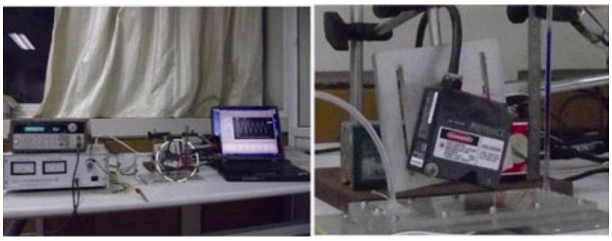


Fig. 7. Photograph of the VPTBT

Fig. 8. Set-up of flow rate experiment



(a) Global graph (b) Local graph

Fig. 9. Set-up of back pressure experiment

The piezoelectric pump is driven by an alternating sine-wave input. The input signal within 100 V peak to peak is controlled by a function generator. The liquid in the piezoelectric pump is deionized water. Through measuring the volume flow rate of piezoelectric pump in unit time by changing driving frequency of the piezoelectric vibrator, we can obtain the experimental results of volume flow rate with changing frequency in 100 V peak-to-peak voltage. And the central displacement values of the piezoelectric vibrator were measured by CCD Laser displacement sensor, which can be taken into Eq. (14) and Eq. (15). The theoretical results about the flow rate vs. driving frequency are shown in Fig. 10.

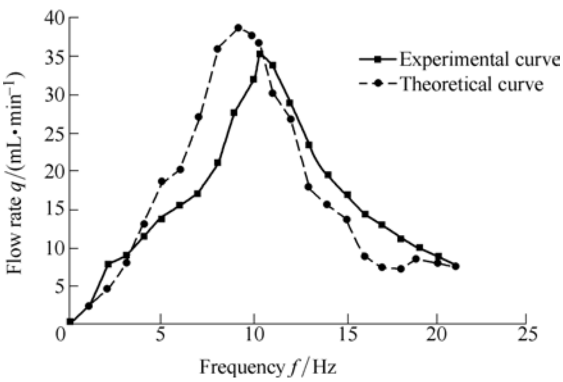


Fig. 10. Curves between the flow rate and the driving frequency

The experimental results show that the maximum flow rate is 35.6 mL/min under 100 V peak-to-peak voltage (10.3 Hz) power supply. Fig. 10 shows that the theoretical value is bigger than the experimental value when the driving frequency is less than 10.3 Hz. When the driving frequency is greater than 10.3 Hz, the theoretical value is smaller than the experimental value. The maximum relative error between the experimental and theoretical values is 40.1% when the driving frequency is 9 Hz. As the theory calculation does not take the frictional resistance of channel into account, the theoretical value is bigger than the experimental value when the driving frequency is low. The flow field *Re* number changes as the driving frequency increase and local resistance coefficient of channel also changes, thereby causing theoretical and experimental values inconsistent.

According to back pressure experiment, the maximum back pressure of the piezoelectric pump is 55 mm H_2O when the driving frequency is 9 Hz (Fig. 11).

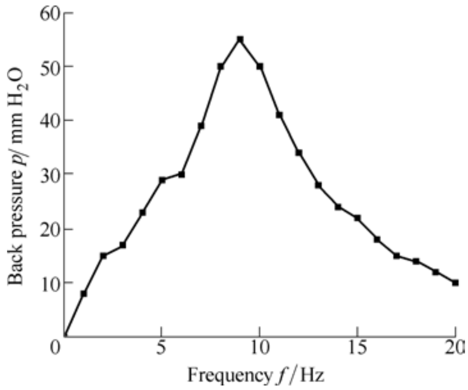


Fig. 11. Curve between the back pressure and the driving frequency

The experiments show the effectiveness of valveless piezoelectric pump with multistage Y-shape treelike bifurcate tubes, which prove that it has different flow resistances in positive and negative directions.

7 Conclusions

(1) A VPTBT is presented, and the pump is designed. This pump achieves the integration of piezoelectric liquid cooling and delivery, which makes the overall system miniaturization possible. The pump owns both driving and transferring functions, which is quite suitable for integrating in cooling system.

(2) The working principle of the VPTBT is analyzed and the flow resistance and flow rate of the pump are analyzed. The commercial software CFX is employed to simulate the performance of VPTBT, which validates that the pump has the function of one-way transmission.

(3) A prototype of this type of pump is designed and fabricated. The relationships between the driving frequency and the flow rates, as well as the relationship between the driving frequency and the back pressure are experimentally investigated. The experimental results show that the maximum flow rate of the valveless pump is 35.6 mL/min under 100 V peak-to-peak voltage (10.3 Hz) power supply, and the maximum back pressure of the valveless pump is 55 mm H_2O under 100 V peak-to-peak voltage (9 Hz) power supply, which validates the feasibility of the VPTBT.

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