Design and Experiment of Streamlined Piezoelectric Pump with Low Vortex and Large Flow Rate

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Abstract: Valveless piezoelectric pump is widely used in the medical, however, there is a general and difficult problem to be solved: Low vortex and large flow rate are not compatible, resulting in the blood prone to thrombosis during blood delivery. In this paper, a new valveless piezoelectric (PZT) pump with streamlined flow tubes (streamlined pump) is proposed. The design method and the working principle of the pump are analyzed. The velocity streamlines are simulated, and the results demonstrate that there are no obvious vortexes in the flow tube of the streamlined pump. Five prototype pumps (two cone pumps and three streamlined pumps) are designed and fabricated to perform flow rate and flow resistance experiments. The experimental results illustrate that the maximum flow rate of the streamlined pump is 142 mL/min, which is 179% higher than that of the cone piezoelectric pump, demonstrating that the streamlined pump has a large flow rate performance. This research provides an inspiration for future research on simple structure, low vortex and large flow rate volume-type pumps, and also provides a useful solution for thrombosis preventing.

Keywords: valveless piezoelectric pump; streamlined; low vortex; high flow rate; thrombosis

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0 Introduction

The formation of thrombosis usually leads to a lot of serious diseases, such as pulmonary infarction, respiratory cycle failure, limb numbness, and kidney failure. It is widely known that due to the vascular damage, high viscosity of blood and slow blood flow rate in vivo, the thrombosis will be formed. However, thrombosis can only be generated in the flowing and disturbing blood flow in vitro. The disturbing blood flow usually has the following characteristics, such as high shear stress zone, eddy current zone, retention zone repeated attachment zone and etc[1-2]. Therefore, if the pumping device possesses the performance of low vortex and large flow rate during delivering the blood in vitro, it can reduce the formation of thrombosis effectively.

As the rapid development of medical science, valveless piezoelectric (PZT) pumps have been widely used as delivering devices. To a valveless PZT pump, the PZT vibrator's inverse PZT effect is used as a power source. In addition, compared with the traditional PZT valve pump, the movable valves are replaced by immovable parts, which simplifies the structure of valveless pumps[3-4]. Thus, the valveless PZT pumps have the advantages of no electromagnetic interference, small size, low energy consumption, and accurate output[5-13].

In 1993, Stemme et al. developed the first valveless PZT pump with nozzle/diffuser tubes[14]. Since then the development of various types of valveless PZT pumps has sprung up, opening a new era of valveless PZT pumps[15-18]. Dau et al. pro-

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posed a cross-connected flow channel valveless PZT pump for high output flow rate[19]. He integrated two inlets and one outlet into this pump, and the diameter of the inlet was larger than the outlet's. Due to this characteristics, the flow resistance was generated to achieve pumping capacity. Cai et al. proposed a multi-cone spiral-cavity parallel valveless PZT pump[20]. Cai's pump was composed by multiple PZT vibrators in parallel pattern and multiple inlets, which could enhance the output performance. Bao et al. proposed a new type of PZT pump with built-in flexible structures. In this pump, the copper sheet was installed in the tube, which endowed this device with the advantages of valveless pump and valved pump at the same time[21]. Zhang et al. proposed a "Y"-shaped flow tube valveless PZT pump to reduce the vortex of the pump. When the fluid flowed along this tube, due to the in-variability of the cross-sectional area, the flow velocity can be reduced effectively. Thus, the purpose of reducing the vortex was achieved[22]. He et al. proposed a valveless PZT pump with a dome-composite structure[23]. By designing the dome, trapezoid and circular flow-guiding structure in the pump cavity, the fluid flow in specified direction was realized. He et al. designed a valveless PZT pump based on the Coanda effect[24]. This pump had three bifurcated channels and installed a diversion structure composed by the semi-cylindrical and triangular prism in the center of intersection instead of the traditional flow tube. However, there is a common problem in the studies above. Since the vortex is negatively related to the Reynolds number while the Reynolds number is positively related to the flow rate, it is difficult to coexist the low vortexes and large flow rate at the same time.

In order to solve the problem, this research proposes a streamlined pump. Firstly, the design method and the working principle of the streamlined pump are analyzed. Then to verify the low vortex performance we obtain the size of the vortex in the flow channel by simulating the velocity streamline using Fluent software. At last, to verify the large flow rate performance, we fabricated 5 propotypes (2 cone pumps and 3 streamlined pumps) by Stereolithography Apparatus (SLA), and implemented flow rate experiment and flow resistance experiment.

1 Design Method of Streamlined Flow Tube

There are four main design methods for streamline gyros, among which hyperbolic streamline gyros are not involved[25]. Hyperbolic structure is widely used in buildings, such as cooling tower, Canton Tower and so on. The structure can reduce the flow resistance and ensure the strength while reduce the weight of the overall structure. Based on this, a streamline flow tube with hyperbola and arc as generatrix is designed.

The design idea of the flow tube is shown in Fig. 1, where h_1 is the height of the arc section, h_2 is the height of hyperbolic section, and $r_{\min}$ is the minimum radius of the runner of the flow tube. First, the hyperbolic segment is constructed from the hyperbolic equation with the focus on the X-axis

$$\frac{x^2}{a^2}-\frac{y^2}{b^2}=1 \tag{1}$$

where

$$a=r_{\min} \tag{2}$$

There is only one variable b in Eq.(1). Then two straight lines $y=0$ and $y=9$ are used to intercept the hyperbola and select the right side(step 1 in Fig.1).

The arc segment is constructed according to Eq.(3).

$$(x-c)^2+(y-d)^2=r \tag{3}$$

In order to make the arc segment tangent to the hyperbolic segment, and set the maximum radius of the channel formed by the arc segment to 2 mm, parameters $c=2$, $d=0$, and $r=1$ are set and substituted into Eq.3. Then an image is depicted, and the 1/4 arc segment at the lower left corner is selected. Finally, the obtained streamline curve (Step 2 in Fig.1) is rotated 360° around the y-axis to form an internal flow channel of the streamlined flow tube (Step 3 in Fig.1). The perspective view of the designed flow tube is shown in Step 4 in Fig.1.

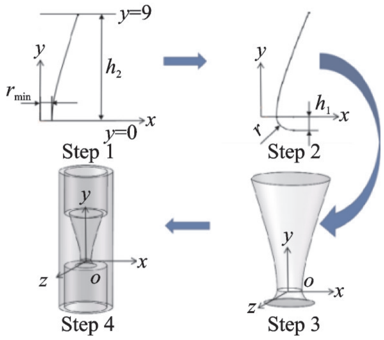
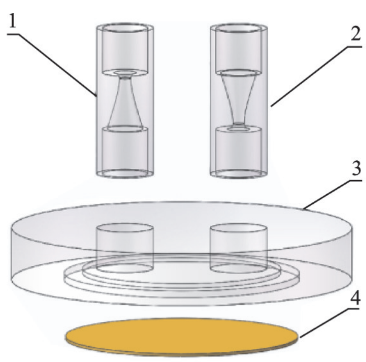


Fig.1 Flow tube design process

2 Working Principle and Theoretical Analysis

2.1 Working principle

The streamlined pump is composed of a PZT vibrator, a pump body, and two reciprocated streamlined flow tubes, as shown in Fig.2. The sectional view of the flow tube is shown in Fig.3, and several parameters are marked. In this study, the fluid flowing into the hyperbola from the arc section is defined as the forward flow, and the fluid flowing into the arc section from the hyperbola section is defined as the reversed flow, as shown in Fig.3.



1—Streamlined flow tube A; 2—Streamlined flow tube B; 3—Pump body; 4—PZT vibrator

Fig.2 Exploded view of the streamlined pump

2.2 Theoretical analysis

The circular PZT vibrator is fixed by bonding its periphery to the pump body, and is applied with alternating voltage to generate periodically uplift and sink vibration. The vibration form is approximately a paraboloid where a polar coordinate system is established. The coordinate origin is set at the center

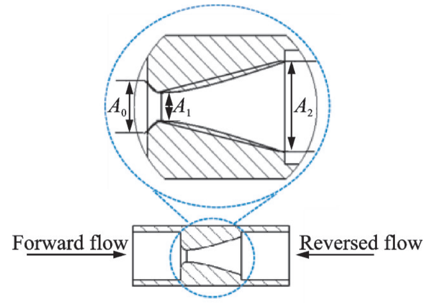


Fig.3 Sectional view of the streamlined flow tube

of the PZT vibrator, then the polar coordinate equation of this paraboloid is given

$$W(r)=w_0\left(1-\frac{r^2}{R^2}\right) \tag{4}$$

where w_0 is the maximum amplitude, and R the radius of the PZT vibrator. Then the maximum volume change of the pump cavity during the vibration of the PZT vibrator is

$$\Delta V=2\pi\int_0^R w_0\left(1-\frac{r^2}{R^2}\right)=\pi w_0\frac{R^2}{2} \tag{5}$$

The flow resistance experienced by a fluid in a flow tube mainly including local resistance and friction resistance, which is given as[26]

$$\xi_+=\xi_{T+}+\xi_{D+} \tag{6}$$

$$\xi_-=\xi_{T-}+\xi_{D-} \tag{7}$$

where ξ_+ is the forward flow resistance coefficient, and ξ_- the reverse flow resistance coefficient.

Then the flow formula of the streamlined pump is given

$$Q=\Delta Vf\frac{(\xi_+-\xi_-)}{(2+\xi_++\xi_-)} \tag{8}$$

where Q is the flow rate, and f the driving frequency of the PZT vibrator.

3 Simulation

According to the streamlined flow tube design method, streamlined pumps are classified into three groups according to b=3 (pump A), b=4 (pump B), and b=5 (pump C). The main size parameters of the three groups streamlined pumps are shown in Table 1. The automatic meshing method is used to mesh the fluid domain. The total number of mesh elements is 1 120 466. The transient analysis method and the Realizable-k-epsilon model are selected.

Table 1 Main size parameters of each pump mm

Item	A	B	C
A_0	4	4	4
A_1	2	2	2
A_2	6.32	4.92	4.12
Cavity height	0.8	0.8	0.8

The fact that the reverse pressure gradient region exists in both the reverse flow and the forward flow may cause the separation of the boundary layer in the flow channel and will lead to a circular jet at the smallest diameter. Fortunately, the Realizable-k-epsilon turbulence model can better simulate a circular jet, and has a good performance in simulating strong streamline bending, adverse pressure gradient, flow separation and secondary separation.

The velocity streamline diagrams of these pumps in the suction stroke and the exhaust stroke are shown in Fig.4 and Fig.5, respectively. It can be concluded from Figs.4,5 that the flow velocity is first increased to the maximum at the minimum channel diameter, and then decreased. The simulated streamlines are smooth, and there is no entanglement of streamlines, which demonstrates that streamlined pumps has low vortex performance.

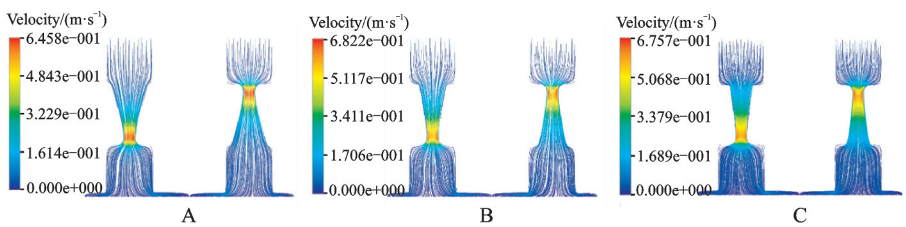


Fig.4 Velocity streamline in the suction stroke

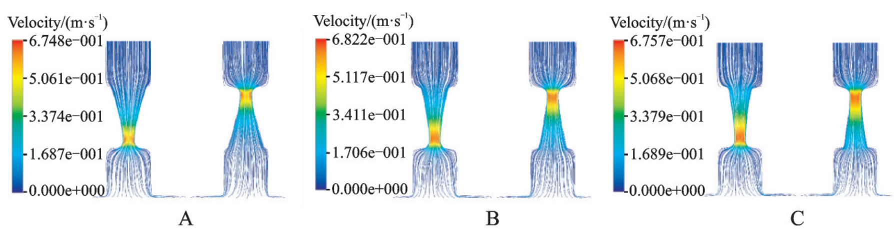


Fig.5 Velocity streamline in the exhaust stroke

4 Fabrication and Experiment

4.1 Fabrication

Three groups of streamlined pump bodies were fabricated by SLA. The PZT vibrator was fixed to the pump body by epoxy resin and the assembly of the pump was completed after eight-hour resin curing. In addition, two types of cone PZT pumps were designed and fabricated as other comparing groups according to the Ref. [14]. The schematic diagram of the structure is shown in Fig.6, and the physical map of all pumps are shown in Fig.7.

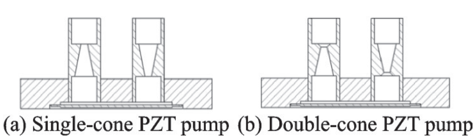


Fig.6 Structure diagram of the two types of cone-shaped PZT pump

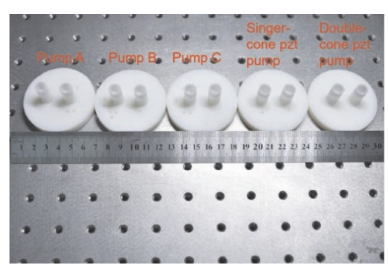


Fig.7 Physical map of the pumps

4.2 Experimental setups

Under the same design conditions, flow rate experiments and flow resistance experiment were performed on the five sample pumps. The instruments included function signal generators (AFG1062, Tektronix, Beaverton, WA, USA), oscilloscopes (DSO-X2004A, Keysight, Santa

Rose, CA, USA), and power amplifiers (HVP-300D, NJFN, Nanjing, China). The fluid medium was deionized water and white blood (the viscosity is 3cP Protein solution) at room temperature. The purpose of using white blood as the medium is to mimic the human blood (the viscosity was 3.01-5.07 cP), to better simulate when a PZT pump was pumping blood.

4.2.1 Flow rate experiment

The experimental schematic diagram of flow rate measurement is shown in Fig.8. The pump was fixed on the platform and connected with two beakers by two silicone rubber tubes. Water was fulfilled the cavity of the pump and all tubes, and the fluid level in each beaker kept the same when the pump was not working. The applied driving voltage of the PZT vibrator was 100 V varied from 5—160 Hz, and was generated, amplified and monitored by signal generator, power amplifier and oscilloscope, respectively.

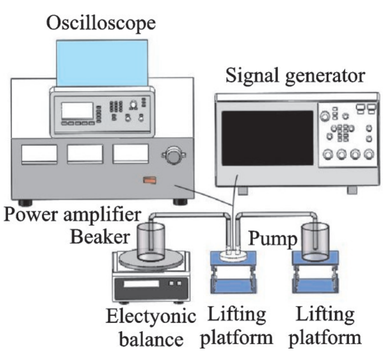


Fig.8 Experimental schematic of flow rate measurement

4.2.2 Flow resistance experiment

The schematic diagram of flow resistance experiment is shown in Fig.9. The pump was placed on the platform, and connected with a needle tubing and a beaker by two silicone rubber tubes. The needle tubing was fixed at a certain height from the platform to generate pressure of 1 kPa. There were two pouring directions in the experiment: the one was forward pouring referring to the placement that the needle tubing connected with the flow tube A; the other one was reversed pouring referring to the placement that the needle tubing connected with the flow tube B. The fluid medium was poured into the needle tubing and the duration of the liquid level was dropping from 150 mL to 10 mL.

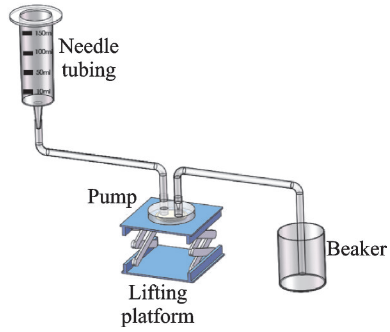


Fig.9 Experimental schematic diagram of flow resistance measurement

5 Results and Discussion

5.1 Flow experiment results

The experimental flow rate results of deionized water are shown in Fig.10. The maximum flow rate of pump A, pump B, and pump C, are 109.141 mL/min at 140 Hz, 110 mL/min at 130 Hz, and 142 mL/min at 80 Hz, respectively. The maximum flow rate of the single-cone PZT pump and the double-cone PZT pump are 42.87 mL/min at 160 Hz and 79.53 mL/min at 150 Hz, respectively.

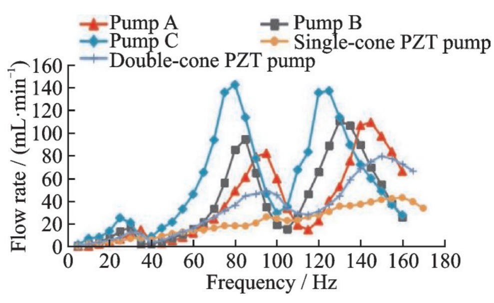


Fig.10 Flow rate comparison of white blood and deionized water in each pump

The experimental flow rate results of white blood are shown in Fig.11. The maximum flow rate of pump A, pump B, and pump C, are 82.39 mL/min at 135 Hz, 97.925 mL/min at 130 Hz, and 111.37 mL/min at 125 Hz, respectively. The maximum flow rate of the single-cone PZT pump and the double-cone PZT pump are 42.08 mL/min at 160 Hz and 75.14 mL/min at 145 Hz, respectively.

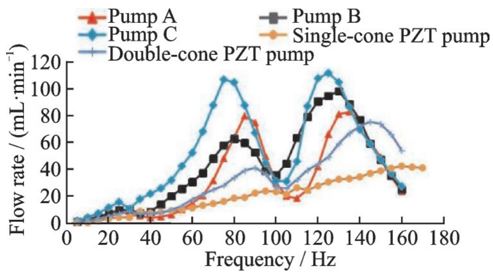


Fig.11 Experimental flow rate results of deionized water

5. 2 Experimental results of flow resistance difference

The duration results of the flow resistance experiment are shown in Fig. 12. The duration differences of deionized water of the forward and reverse pouring are 7.955 s (pump C), 5.27 s (pump B), 3.6 s (pump A), 2.565 s (double), and 1.895 s (single). The duration differences of white blood of the forward and reverse pouring are 5.89 s (pump C), 4.37 s (pump B), 3.575 s (pump A), 2.775 s (double), and 1.575 s (single).

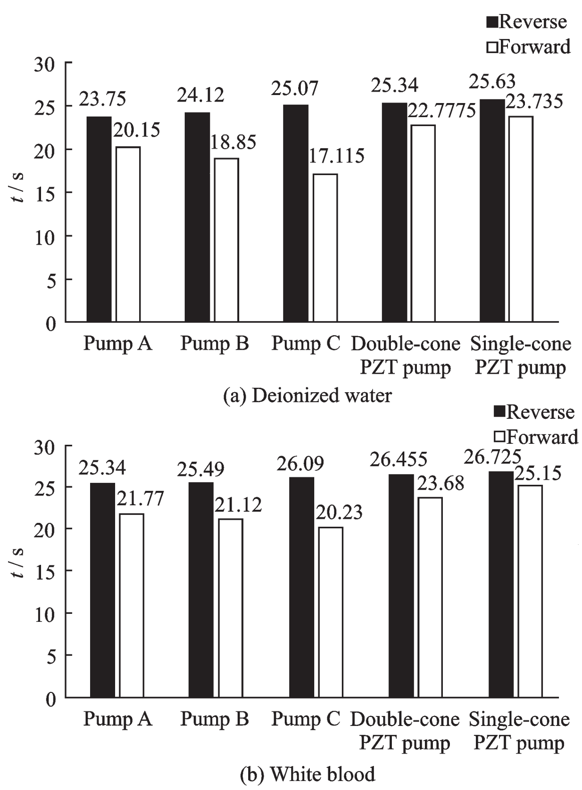


Fig.12 Experimental flow rate results of white blood

5. 3 Discussion

There are three important phenomena should be listed, which are shown in Fig. 10 and Fig. 11. First, the flow rate of streamline pump is larger than that of cone piezoelectric pump, with a maximum difference of 99.31 mL/min. This is because along the flow direction, the cross-sectional areas of all sample pumps' flow channels were always changing. In this situation, the flow resistance of the flow tube was mainly the pressure drag. Compared with cone piezoelectric pumps, the internal passage of the flow tube of the streamline pump was streamlined, which caused the boundary layer separation point to move backward and reduced the pressure drag. Second, with the increase of b value, the maximum flow of the streamline pumps also increased. The reason is there was an adverse pressure gradient in the hyperbola when the fluid flowed forward. The change rate of the flow channel in the hyperbolic section decreased with the increase of b value, resulting in the decrease of the pressure drag. However, when the fluid flowed in the reverse direction, it was in the adverse pressure gradient in the arc section. The curvature of the arc and the pressure drag did not change as the change of b value. The combination of these two factors resulted in that as the value of b increased, the resistance difference of the fluid in the forward and backward flow increased, and the maximum flow rate of the pumps increased. The above two phenomena also explain the phenomenon shown in Fig. 12. When the a certain volume of fluids flowed into the sample pump in the positive and negative directions, separately, the time difference used by the streamline pump was larger than that of the cone pump, and the pump C was the largest. Third, as b increased, the resonance frequency points of the three pumps A, B, and C moved forward. It may because the curvature of the hyperbola increased with the increase of value b.

It can be found from Fig. 13 that influence of different fluid viscosities on the output flow rate of the pumps were small in the non-resonant frequency range. However, the flow rate of the deionized water was significantly higher than that of the white blood at the resonant frequency, because the fluid with higher viscosity had more obvious resistance effect at the resonance frequency. On the contrary, the effect of different fluid viscosity on the output flow rate was unobvious for the cone PZT pumps.

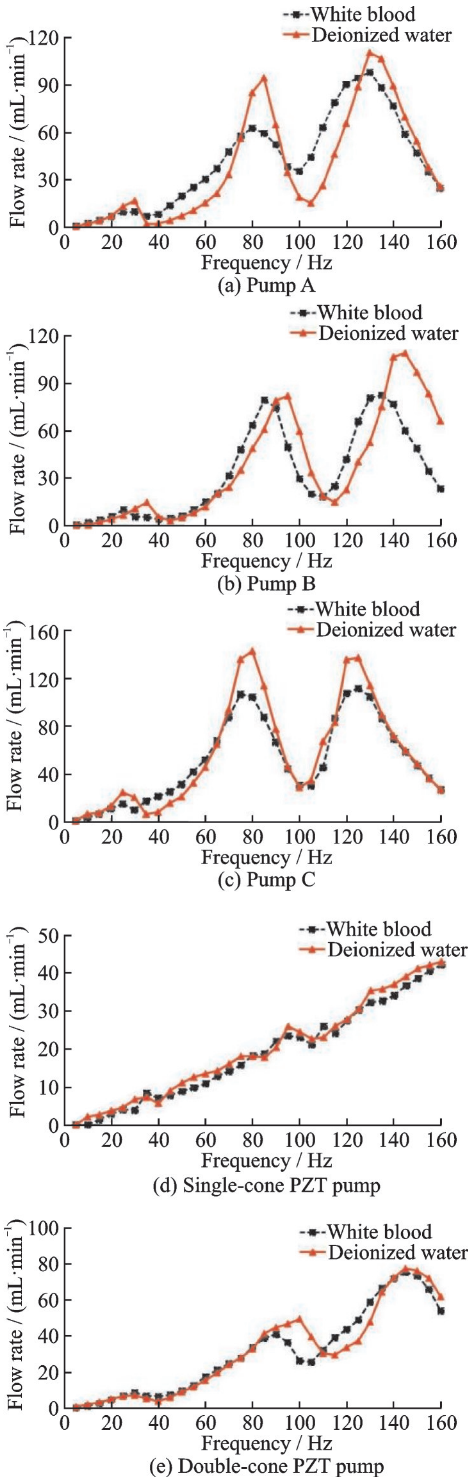


Fig.13 Experimental data of flow resistance

This perhaps because the flow resistance of the pumps were large, which resulting in the increases of fluid viscosity did not have a qualitative change on the flow resisitance of pumps.

The experimental results confirmed that the streamline pumps had excellent flow rate performance, and the flow rate was as high as 111.37 mL/min when white blood with a viscosity similar to human blood was pumped. Therefore, when the experimental fluid is human blood, the streamline pump will also have a higher flow rate. Combining with the simulation results, it can be confirmed that the streamline pumps have low vortex and large flow rate, which is of great significance to reduce the generation of thrombus during delivering blood.

6 Conclusions

This paper proposes a streamlined flow tube valveless PZT pump. The design method and the working principle of the streamlined pump are analyzed. The combination of simulation and experiment proves that the pump is compatible with low vortex and large flow, and has high practicability. This paper provides a solution to the problem of blood clots. In the future, the influence of different streamline structures on the performance of PZT pumps will be further studied to find the optimal streamline construction method of valveless PZT pump and explain its mechanism.

(1) The Realizable-k-epsilon model is used to simulate the streamline of the turbulence flow in the streamlined pump by FEM analyses. By analyzing the calculated results, there is no entanglement of streamlines, which indicates that there is no vortex during the fluid flow.

(2) Five propotypes (two cone pumps and three streamlined pumps) are established to test the flow rate and flow resistance by delivering deionized water and white blood, respectively. In the experiments, the maximum flow rate was 142 mL/min delivering deionized water by streamlined pump, which was 179% higher than that using single-cone PZT pump. When the delivered fluid was white blood, the maximum flow rate in the streamline pump was 111.37ml/min, which was 165% higher than that of the single cone PZT pump. Obviously, this type of pump has a large flow rate, and can increase the flow rate effectively.

(3) As the value of b increased, the resonance

frequency of pumps A, B and C decreased while the flow rate increased. Thus, by changing the value of b, the type of pump can work under the required frequency in different applications while retaining the best performance. For example, by changing the value of b, the type of pump can work under 50 Hz, which is the common voltage frequency in China.

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Author contributions Dr. **BIAN Kan** contributed to the theoretical analysis and the simulation analysis. Mr. **HUANG Zhi** designed a 3d model of the flow tube, explained the experimental results and wrote the manuscript. Mr. **BAO Qibo** contributed to the background of the study. Prof. **ZHANG Jianhui** proposed the idea and designed the experiment. Ms. **LAI Liyi** provided the experimental data. Mr. **CHEN Zhenlin** and Mr. **CHEN Xiaosheng** fabricated the sample pump. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: ZHANG Bei)

低漩涡大流量流线型流管无阀压电泵的设计与实验

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摘要:无阀式压电泵在医学上应用广泛,但存在着低涡流、大流量不兼容问题,在输送血液过程中产生血栓形成,是一个亟待解决的难题。本文提出了一种流线型流管无阀压电泵(流线型泵)。分析了该泵的设计方法和工作原理。仿真结果表明,流线型泵的流管内不存在明显的漩涡。设计和制造了5个压电泵泵,用于进行流量和流阻实验。实验结果表明,流线型泵的最大流量为142 mL/min,比锥形流管无阀压电泵的最大流量高179%,说明流线型泵具有更好的泵送性能。本研究为今后研究结构简单、低涡流、大流量压电泵提供了启示,也为预防血栓形成提供了有效的解决方案。

关键词:无阀压电泵;流线型;低漩涡;大流量;血栓