

# Research Article

# Investigation on the Influence of Design Parameters of Streamline Flow Tubes on Pump Performance

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Studies have shown that the valveless piezoelectric pump with streamline flow tubes (VPPSFTs) can increase the flow rate while reducing the vortex, which has a broad application prospect and conforms to the huge potential demand in the fields of medical treatment, sanitation, and health care. The flow runner of the VPPSFT was designed as two segments with a smooth transition between the hyperbola segment and the arc segment. However, the effect of the radius of the arc segment on pump performance is not clear. Therefore, three groups of VPPSFT with arc segments of different curvature radii were designed in this study, and the influence of curvature radius of arc segment on the pump performance was explored. On the basis of the theoretical analysis of fluid continuity and conservation of energy, the structure of VPPSFT was designed, the experimental test was carried out, and the finite element simulation software was used for numerical analysis. The results show that the output performance increases with the increase in the radius of the arc segment, and the maximum flow rate was 116.78 mL/min. The amplitude and the flow rate are almost the same trend as the frequency. This study improves the performance of the valveless piezoelectric pump and provides reference for the structure design of VPPSFT.

# 1. Introduction

In general, the valveless piezoelectric pumps are composed of piezoelectric vibrator and immovable parts [1, 2]. With the advantages of no electromagnetic interference, impacted size, low energy consumption, and accurate output [3–8], the pumps have been widely used in microfluidic pumping systems [7, 9–11], biomedical precision pumping [12–14], cooling systems for electronic component [15–17], chemical mixing and analysis [18], spray drying [19–21], fuel cells [22], and electronic sensors [23, 24].

However, to the piezoelectric valveless pumps, the performance of low vortex and large flow cannot exist simultaneously. It means that if one performance increases, the other will decrease [25, 26]. For example, Zhao et al. proposed a valveless piezoelectric micropump with crescent-shaped immovable parts [27]. The experiment showed that the flow rate of the valveless piezoelectric pump with four

parallel crescent immovable parts reached the maximum, which was 286 mL/min. However, the simulation showed that there were many vortexes in the pump chamber during transmitting fluid. Zhang et al. proposed a valveless piezoelectric pump with a Y-type flow tube [28]. By finite element (FEM) simulation, there were only a bit of vortexes in the bifurcation only when the fluid flowed in forward flow. However, its maximum flow was only 3 mL/min. Tang et al. proposed a valveless piezoelectric pump with raindrop streamlined flow tube [29]. Although there were only a bit of vortexes in the largest diameter of the runner, the flow rate was only 17.01 ml/min. The simulation results showed that the pump had a small amount of vortex at the largest diameter of the runner, but the flow rate was only 17.01 mL/ min. The single performance restricted the applications of the piezoelectric valveless pump. To solve this problem, Huang and Yang proposed a valveless piezoelectric pump with streamline flow tubes (VPPSFTs) [30], which were

composed of hyperbola section and arc section. When the fluid flowed through the flow tube, the flow rate always increased firstly and then decreased. By experiments and FEM analysis, there was no obvious vortex during fluid flowing in forward and reverse flow, and the maximum flow rate reached 142 ml/min. However, as an immovable part, the size of arc section will influence the performance of the pump. Unfortunately, in the last paper, the investigation of the influence of the arc section's size on the pumps' performance was lacking.

In this paper, three groups of VPPSFT with different radii of arc section were designed, and the influence of curvature radius of the arc segment on the pump performance was explored. On the basis of the theoretical analysis, three groups of VPPSFT were designed. In order to analyze the vortex inside the pump, the internal flow field of the VPPSFT was calculated through the FEM method. The experiments were implemented to obtain the relation between the radius of the arc segment and the output performance.

#### 2. Working Principle and Theoretical Analysis

2.1. Working Principle. The VPPSFT's structure diagram is shown in Figure 1(a), which is composed of piezoelectric vibrator, pump body, and a pair of inverted streamlined flow pipes. The sectional view of the flow tube is shown in Figure 1(b). The rotating bar of the main runner of the flow tube is composed of two sections of curves, one of which is an arc and the other is a hyperbola. Moreover, the arc segment is tangent to the hyperbola segment at the point of intersection, and the center of the circle of the arc segment is on the normal line at the point of intersection. The fluid flowing from the arc to the hyperbola is defined as the forward flow, and the fluid flowing from the hyperbola to the arc is the reverse flow.

In the forward flow, the fluid is in the reverse pressure gradient at the hyperbola section. Meanwhile, the curvature radius of the hyperbola section is small and the flow rate changes slowly, which can reduce the pressure drag, thus reducing the flow resistance. In the reverse flow, the arc segment has a large curvature radius and the fluid is in an adverse pressure gradient in the arc segment. Therefore, the velocity change rate of fluid in the arc section is relatively large, which makes it easy to generate vortex in the flow passage and increases the flow resistance. Specifically, due to the flow resistance difference in forward-and-reverse flow, the flow tube acts as a check valve.

2.2. Theoretical Analysis. The flow resistance analysis of the pump is primarily aimed at the main runner, and the main runner can be divided into the diffuser and the nozzle according to the trend of the cross-sectional area, so

$$\xi = \xi_D + \xi_N,\tag{1}$$

where  $\xi$  is the flow resistance of the flow tube,  $\xi_D$  is the flow resistance of the diffuser, and  $\xi_N$  is the flow resistance of the nozzle. According to [30],

$$\begin{cases} \xi_D = \xi_{\rm TP} + \xi_{\rm pacm}, \\ \xi_{\rm TP} = f(\alpha, n_1), \\ \xi_{\rm pacm} = g(\alpha, n_1), \end{cases}$$
(2)

where  $\xi_{\text{TP}}$  is the frictional resistance,  $\xi_{\text{pacm}}$  is the local resistance of the diffuser,  $\alpha$  is the spread angle of the diffuser,  $n_1$  is the diffusance, and  $n_1 = S_1/S_2$ .

$$\begin{cases} \xi_N = \xi_{TP} + \xi_M, \\ \xi_{TP} = f(\alpha, n_1), \\ \xi_M = \varphi(n_0), \end{cases}$$
(3)

where  $\xi_M$  is the local resistance of the nozzle,  $n_0$  is the degree of shrinkage, and  $n_0 = S_2/S_1$ .

The fluid in the hyperbola segment is the diffuser in the forward flow, so

$$\alpha = \alpha_2, \tag{4}$$

where  $\alpha_2$  is the spread/contract angle of the hyperbola segment. However, the fluid in the arc segment is the diffuser in the reverse flow, so

$$\alpha = \alpha_1, \tag{5}$$

where  $\alpha_1$  is the spread/contract angle of the arc segment. So,

$$\xi_{-} - \xi_{+} \neq 0, \tag{6}$$

where  $\xi_+$  is the flow resistance of the forward flow and  $\xi_-$  is the flow resistance of the reverse flow. Therefore, there is a flow resistance difference in the forward flow and reversed flow, which is proved that the pump has pump effect.

According to [31], when the piezoelectric vibrator is at its maximum displacement, the maximum volume-change quantity can be simplified to the following:

$$V_{\rm max} = \pi w_0 \frac{R^2}{2},\tag{7}$$

where  $V_{\text{max}}$  is the maximum volume-change quantity of the pump chamber,  $w_0$  is the maximum amplitude, and R is the radius of the substrate of the piezoelectric vibrator.

The flow rate of the pump can be calculated by the following:

$$Q = V_{\max} f \frac{(\xi_{-} - \xi_{+})}{(2 + \xi_{+} + \xi_{-})},$$
(8)

where Q is the flow rate and f is the driving frequency of the piezoelectric vibrator. As can be seen, the greater the resistance difference of forward-and-reverse flow, the greater the pump flow rate. The above formula ignores the influence of the cross-sectional mutation on the fluid resistance of the main channel. If the above influence is considered, there will be

$$E = \frac{S_i}{S}$$
 (*i* = 1, 3), (9)

where *E* is the transient impact coefficient and the smaller the value is, the greater the flow resistance is;  $S_i$  is the crosssectional area of each segment of the main flow; and *S* is the



FIGURE 1: The structure of the pump: (a) exploded view of the VPPSFT where 1: the flow tube A, 2: the flow tube B, 3: pump body, and 4: piezoelectric vibrator; (b) sectional view of the flow tube; (c) the larger version of the main runner of the flow tube.

maximum cross-sectional area of the flow passage. According to the design method of the arc segments, it can be deduced that the radius (R) of the arc segment and  $S_1$  are negatively correlated. In addition, the flow resistance in the main channel is sensitive to the change of R in the forward flow, while the main channel is insensitive to the change of R in the reverse flow. Therefore, with the increase in R, the flow resistance difference of forward-and-reverse flow decreases so does the flow rate of the pump.

#### 3. Simulation

Three groups of pumps with different arc segment radii are designed to verify the influence of arc segment radius on pump output performance, which are named pump A (R = 1.5 mm), pump B (R = 2 mm), and pump C (R = 3 mm), respectively. The design parameters are shown in Table 1. A 3D model of the flow domain was established. The fluid domain was meshed by an automatic mesh method with 220000 nodes. Transient analysis was selected for the analysis model. The boundary layer separation may exist in both forward flow and reverse flow, and circular jets may appear at the smallest diameter [32-34]. Thus, the Realizable K-Epsilon model can be used as a turbulence model. The material was set to water. The inlet boundary condition was set to pressure, and the outlet boundary condition was set to 0 Pa. The excitation signal of the pumps was all sinusoidal curves and acted on the bottom surface of the pump cavity in the fluid domain.

Figures 2 and 3 are the pressure diagrams of the scheduling and suction stages. It can be seen from the figures that no matter at that stage, the pressure in the flow tube first decreases and then increases. Figure 4 shows the simulation results of velocity streamline of the pumps, and the time points of the velocity flow diagram selected in the schedule stage and suction stage are t = (1/4)T and t = (3/4)T, respectively. The surrounding streamline in Figure 4 represents a vortex inside the pump, and the more turns the streamline exists, the greater the curl in the flow field. The phenomenons can be found from the picture. Large areas of

TABLE 1: Main size parameters of the pumps.

	Pump A	Pump B	Pump C	
S <sub>1</sub> (mm)	50.24	50.24	50.24	
S <sub>2</sub> (mm)	5.98	5.06	3.53	
S <sub>3</sub> (mm)	31.35	31.35	31.35	

vortices occur at both the inlet and outlet of the schedule stage and suction stage, which are caused by the defects of the flow tube structure with cross-sectional abrupt transitions. Therefore, this paper mainly discusses the relationship between the radius of the arc segment and the curl.

In these two stages, there are few vortices generated in the main runner of the flow tubes, and the curl of the flow field in the pump gradually increases with the increase in the radius. This is because that the instantaneous impact loss of the fluid entering the main runner from the inlet increases. Therefore, the flow velocity decreases as the radius increases, which causes the advance of the boundary separation point of the fluid in the main runner and the increase in the curl of the flow field in the pump.

#### 4. Experimental Setups

Three groups of streamlined pump bodies were fabricated by SLA. The piezoelectric vibrator is fixed to the pump body by epoxy resin, and the assembly of the pump is completed after eight-hour resin curing. Two experiments were carried out, one for flow rate and the other for piezoelectric vibrator amplitude. The main equipment includes functional signal generators (AFG1062, Tektronix, Beaverton, WA, USA), oscilloscopes (DSO-X2004a, Keysight, Santa Rose, CA, USA), power amplifiers (HVD-300D, NJFN, Nanjing, China), and laser displacement sensors (LK-H020, Keyence, Osaka, Japan).

The experimental schematic diagram is shown in Figure 5, and the traffic test platform is shown in Figure 6; the fluid medium is deionized water at the room temperature. The pump is fixed on the platform and connected with two beakers by two silicone rubber tubes. The pump

#### Shock and Vibration



FIGURE 2: The pressure diagrams of the pumps in the schedule stage.



FIGURE 3: The pressure diagrams of the pumps in the suction stage.



FIGURE 4: The velocity streamline diagrams of these pumps in different stages: (a) the schedule stage; (b) the suction stage.

#### Shock and Vibration



FIGURE 5: The experimental schematic diagram.



FIGURE 6: Traffic test platform.

chamber and all tubes are fulfilled with water, and the fluid level in each beaker keeps the same when the pump is not working. The driving voltage of the piezoelectric vibrator is 100 Vrms, the driving frequency of the signal generator is changed, and the flow rate curve at different frequencies is obtained. Meanwhile, the displacement of the piezoelectric vibrator center is measured by the laser displacement sensor, and the curve of the amplitude changes with frequency is obtained.

## 5. Results and Discussion

The experimental results of the flow rate are shown in Figure 7. The maximum flow rate of pump A, pump B, and pump C is 110.04 mL/min at 120 Hz, 114.03 mL/min at 115 Hz, and 116.78 mL/min at 155 Hz, respectively.

From the figure above, it can be found that the maximum flow of the pump increases with the increase in the radius of the arc segment. This can be summarized as the following reasons. In the forward flow, the fluid is in

the positive pressure gradient in the arc segment. At this time, with the increase in radius, the transient impact coefficient of the fluid will increase when the fluid enters the main runner from the inlet, which leads to an augment of the flow resistance of the forward flow. In the reverse flow, the fluid is in the reverse pressure gradient in the arc segment. The pressure drag of the fluid will decrease as the radius increases, which causes the flow resistance of the reverse flow to decrease. The pumping flow rate is positively correlated with the flow resistance difference of forward-and-reverse flow. Therefore, the maximum flow rate of the pump increases with the increase in the radius. This result is consistent with the theoretical analysis.

Figure 8 shows the amplitude data of each pump vibrator tested in the experiment. The maximum amplitude of pump A, pump B, and pump C is 0.0705 mm at 25 Hz, 0.1015 mm at 70 Hz, and 0.062 mm at 95 Hz, respectively.

Furthermore, it was found that the changes in amplitude are oscillatory with the increase in frequency. The amplitude



FIGURE 7: The flow rate measuring results of the pumps.



FIGURE 8: The comparison of amplitude and flow with frequency: (a) pump A; (b) pump B; (c) pump C.

of the piezoelectric vibrator and the flow rate of the pump are almost the same trend as the frequency. However, there are exceptions, with the increase in the amplitude, the flow rate of pump A decreases when the driving frequency is 30–50 Hz. It shows that the relationship between the flow rate and the amplitude is also affected by the structure of the flow tube. However, overall, the amplitude is positively correlated with the flow rate.

# 6. Conclusions

In this paper, the influence of the change of the arc segment radius to the pump performance was investigated. On the basis of the theoretical analysis, three groups of VPPSFT were designed. The internal flow field of the VPPSFT was calculated through the FEM method, and the results showed that the curl of the flow field in the pump increases with the increase in the radius. Three prototype pumps were made to test the output performance. The results of the experiments demonstrate that the maximum flow rate of the pumps increased with the increase in the radius, and the maximum flow rate was about 116.78 mL/min, and the trend of amplitude changing with frequency was basically the same as that of flow rate changing with frequency. This study improves the performance of the valveless piezoelectric pump and provides reference for the structure design of VPPSFT.

# **Data Availability**

Some information used to support this study is as follows: the maximum flow rates of pump A, pump B, and pump C are 110.04 mL/min at 120 Hz, 114.03 mL/min at 115 Hz, and 116.78 mL/min at 155 Hz, respectively. The driving voltage amplitude of the piezoelectric vibrator is 100 V.

# **Conflicts of Interest**

The authors declare that they have no conflicts of interest.

# **Authors' Contributions**

K. B. conceived and designed the experiment; Z. H. designed the 3D model of the flow tube, explained the experimental results, and wrote the manuscript; J. D. and F. Z. contributed to the background of the study; J. Z. proposed the idea and designed the experiment; X. C. and L. L. revised the spelling and grammar of the manuscript; Z. C. provided the experimental data.

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