Numerical simulation and experimental study on valveless piezoelectric pump with triangular obstacles

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Abstract. A valve less piezoelectric pump with triangular obstacles is designed and manufactured, which uses piezoelectric vibrator as power source. The working principle and theoretical flow rate of the valveless piezoelectric pump are analyzed, and its flow rate expression is derived. The flow resistance characteristics of triangular obstacles are simulated by numerical simulation. Based on the mass fraction distribution of liquid water, the forward and reverse flow resistance of triangular obstacles and the influence of triangular obstacles on pumping capacity are analyzed. Finally, two groups of test prototypes of the valveless pump are made by using the engraving machine, and the flow measurement test is carried out. The experimental results show that the valveless piezoelectric pump with triangular obstacles can realize the valveless pumping function, and the pumping flow per unit time increases with the increase of triangular obstacles in the channel, and decreases with the increase of the distance between triangular obstacles and the channel. When the driving voltage is 140V and the driving frequency is 10Hz, the maximum output flow of the piezoelectric pump is 16.26ml/min.

Key words: Triangular block, Numerical simulation, Flow measurement.

1. Introduction

Piezoelectric pump is a device that uses the inverse piezoelectric effect of piezoelectric materials to convert electric energy into mechanical energy. Its power source relies on the piezoelectric vibrator to generate alternating bending vibration under alternating voltage, which makes the volume of pump cavity change, so as to inhale and discharge fluid [1]. Piezoelectric pump is divided into valved piezoelectric pump and valveless piezoelectric pump according to whether there is movable valve. Among them, the valve piezoelectric pump is used for hybrid drive, which has the advantages of large output flow and high pressure [2]. However, it has the disadvantages of poor valve follower and easy fatigue wear. Compared with the valveless piezoelectric pump, the valveless piezoelectric pump has the advantages of simple structure, small volume and easy miniaturization [3]. In addition, without the influence of one-way valve, at any time in the working process of the pump, the inlet and outlet are connected, and the requirements for the transmission medium are significantly reduced. Since Erik Stemme et al. Proposed the valveless piezoelectric pump with conical flow tube [4], the valveless piezoelectric pump has become one of the research hotspots. The valveless piezoelectric pump consists of many non valve one-way flow components, mainly including contraction tube / expansion
tube [5], Tesla valve [6] and "Y" flow tube [7]. The characteristics of this kind of valveless piezoelectric pump are: the non valve one-way flow parts are installed outside the pump cavity, and the fluid flows into and out of the pump cavity through the non valve one-way flow parts, so that the pump cavity space can be set with other structures to complete other functions, such as strengthening the pumping capacity and realizing the mixing structure. However, the above non valve one-way flow parts are complex as a whole, difficult to machine, long cycle, high cost, not easy to microminiaturize and so on, which greatly reduces the application of this kind of valveless pump in MEMS.

This paper presents a valve free piezoelectric pump with triangular in the runner, which has the advantages of simple structure, easy processing, low cost and easy miniaturization. In this paper, the piezoelectric pump with the prism block as the valve without moving parts is designed, which takes piezoelectric single crystal as the power source. Firstly, the structure and working principle of the pump and the theoretical flow of the pump are analyzed theoretically; Secondly, the pumping capacity of piezoelectric pump with prism obstruction is analyzed by numerical simulation analysis, and the influence of the obstruction on the pumping performance of piezoelectric pump is analyzed; Finally, the prototype of the Valveless piezoelectric pump is made by the precision Carver, and the pumping capacity test is carried out. The results of theoretical analysis and numerical simulation analysis are verified.

2. Structure and working principle

Fig. 1 shows the structure of the valveless piezoelectric pump with triangular prism obstruction, which is mainly composed of pump cover, pump body, piezoelectric vibrator, sealing ring, insulating layer, etc. The pump cover and the pump body are connected by bolts. In order to prevent liquid leakage, a sealing ring is set between the pump cover and the pump body. In order to enlarge the flow resistance difference between the forward and reverse flow of the pump, two triangular prismatic obstacles with the same geometric parameters are used to distribute in the inlet and outlet channels, so that the flow resistance coefficient decreases in the forward flow and increases in the reverse flow.

![Figure 1. Structure and physical drawing of piezoelectric pump](image)

In the experiment, the sharp angle face of the triangular obstruction is distributed to the inlet of the pump, and the bottom face is distributed to the outlet of the pump. When the sinusoidal driving voltage is applied to the piezoelectric vibrator, the piezoelectric vibrator makes periodic reciprocating motion, which causes the volume and pressure inside the pump cavity to change periodically. When the vibration of the piezoelectric vibrator causes the pressure inside the pump cavity to increase, the pump sucks fluid from the flow pipes at both ends at the same time, Because the resistance produced by the sharp angle face is far less than that produced by the bottom face, the amount of liquid inhaled from the inlet of the pump is greater than that from the outlet, which is defined as the suction process of the pump. The opposite process is called pump discharge process. When the piezoelectric vibrator vibrates periodically, the valveless pump can absorb liquid from the outlet and discharge liquid from
the inlet for a long time, forcing the fluid in the pump cavity to flow in one direction and achieving the effect of pumping liquid.

### 3. Theoretical analysis

Because the pumping performance of the valveless piezoelectric pump depends on the forward and reverse flow resistance difference of the valve without moving parts, the output flow \( Q \) of the valveless piezoelectric pump obtained by Zhang Jianhui [8] and others through analysis can be expressed as:

\[
Q = \frac{\pi \omega_0 R^2 f}{\xi + 1} \sqrt{\frac{\xi - 1}{\xi}}
\]

\( \xi_p \) is the positive pressure loss coefficient; \( \xi_N \) is the reverse pressure loss coefficient; \( \omega_0 \) is the maximum amplitude of piezoelectric vibrator; \( R \) is the radius of piezoelectric vibrator; \( f \) is the working frequency.

Because the shape resistance of the prism is different from the edge, the total flow resistance of the prism group is different [9]. This kind of positive and negative flow resistance difference makes the valve free piezoelectric pump of the triangular block pump can pump the fluid one-way.

### 4. Simulation analysis

#### 4.1. Finite Element Modeling and Boundary Conditions

In order to prove the pumping capacity of the valveless piezoelectric pump in comparison with the results of theoretical analysis, the numerical simulation of the valveless piezoelectric pump is carried out. The boundary conditions of inlet and outlet are set as pressure inlet and pressure outlet, and the relative pressure is set as 0. The surface of piezoelectric vibrator is set as the moving wall, and the other solid walls meet the non-slip boundary conditions. In the pumping process of the valveless piezoelectric pump, the piezoelectric vibrator is used as the driving component. Under the driving of sinusoidal voltage, each point on the vibrator makes a certain sinusoidal motion. The dynamic mesh model is used to simulate the piezoelectric pump, which can effectively couple the motion characteristics of the piezoelectric vibrator and the fluid in one cycle [10]. Therefore, UDF program with dynamic boundary is written by using DEFINE_GRID_MOTION macro definition of dynamic grid in Fluent software.

#### 4.2. Numerical Simulation Results and Analysis

##### 4.2.1. Numerical Simulation Results and Analysis of Pumping Capacity

Initially, there is only one liquid in the pump body, which is set as liquid water. After the piezoelectric vibrator starts to vibrate, another kind of liquid water enters the piezoelectric pump through the inlet. Taking the second liquid mass fraction image of the whole cross section of the valveless piezoelectric pump, as shown in Fig. 2. It is found that the whole liquid moves from the inlet to the outlet to achieve the purpose of pumping.
4.2.2. numerical simulation results and analysis of the influence of triangular obstacles on pumping capacity. In order to analyze the influence of triangular obstacles on the pumping capacity of valveless piezoelectric pumps, two groups of valveless piezoelectric pumps were set up, namely: changing the number group, 1-4 triangular obstacles were set up respectively; By changing the spacing group with the flow channel, valveless piezoelectric pumps with 2, 2.25, 2.5 and 2.75 cm spacing were set respectively. The mass fraction of initial liquid water in the outlet section of each piezoelectric pump model at the same time is used as the criterion to determine the pumping flow rate per unit time. The smaller the mass fraction, the larger the pumping flow per unit time; On the contrary, the smaller the pumping flow per unit time, the mass fraction of initial liquid water in the outlet section after numerical simulation of piezoelectric pump model is shown in Fig. 3.

According to the comparison in Fig. 3 (a), with the increase of triangular obstacles in the flow channel, the pumping flow of the valve free piezoelectric pump increases in unit time; Compared with Fig. 3 (b), the distance between the triangular block and the runner increases, the pumping flow rate of the valve free piezoelectric pump decreases in unit time.

5. Experimental study
In order to verify the results of numerical simulation, the pumping capacity of the valveless pump and the influence of triangular obstacles on the pumping capacity are proved. Two groups of sample pumps were made. They are: change the number group, set up 1-4 triangular prism obstacles respectively; By changing the spacing group with the flow channel, valveless piezoelectric pumps with 2, 2.25, 2.5 and 2.75 cm spacing were set respectively. The sample pump adopts double crystal
piezoelectric vibrator. The base layer is made of brass with a radius of 17.5 mm and a thickness of 0.2 mm. The radius of piezoelectric ceramic layer is 15 mm and a thickness of 0.1 mm. The pump cavity height is 2 mm.

In this experiment, distilled water was used as the test medium, the peak to peak driving voltage was 140V, and the working frequency was 10Hz. The output flow curves of the above two groups of sample pumps in unit time were recorded, as shown in Figure 4.

![Figure 4](image)

(a) Change quantity group  (b) Distance group with runner

Figure 4. Output flow curve of sample pump in unit time

It can be seen from Fig. 5 that the valveless piezoelectric pump with triangular obstacles can realize the pumping function; The influence law of triangular obstacles on the pumping capacity is consistent with the change trend of numerical simulation analysis results. According to the comparison of Fig. 5 (a), with the increasing of triangular obstacles in the channel, the pumping flow per unit time of valveless piezoelectric pump is increasing; It can be seen from the comparison of Fig. 5 (b) that the pumping flow per unit time of valveless piezoelectric pump decreases with the increase of the distance between the triangular obstacles in the channel and the channel. When the driving frequency is 10Hz, the peak to peak value of the driving voltage is 140V, and the output flow of the sample pump with four triangular obstacles and 2mm distance from the channel reaches the maximum value of 16.26ml/min.

6. Conclusion

In this paper, the pumping function of valveless piezoelectric pump is realized by setting triangular obstacles in the flow channel. The pressure loss equation of the forward and reverse flow around the choke is analyzed theoretically, and the flow rate expression of the pump is derived. The conclusion that the triangular prism obstruction has an effect on the flow rate per unit time of the valveless piezoelectric pump is obtained. The flow field of a valveless piezoelectric pump with triangular obstacles is numerically simulated and analyzed. According to the mass fraction distribution of liquid water, it is judged that the pump has good pumping capacity. Two groups of sample pumps are set up to analyze the influence of triangular obstacles on the pumping capacity; Two groups of valveless piezoelectric pump prototypes with triangular prism obstacles were designed and manufactured. The flow measurement experiments were carried out to verify the theoretical analysis and numerical simulation results. The results of flow test show that the triangular obstacles have the characteristics of unequal flow resistance in forward and reverse directions, and can realize valveless pumping; With the increase of the triangular obstacles in the channel, the pumping flow per unit time of the valveless piezoelectric pump increases. With the increase of the distance between the triangular obstacles and the channel, the pumping flow per unit time of the valveless piezoelectric pump decreases. When the driving voltage is 140V and the driving frequency is 10Hz, the maximum output flow of the piezoelectric pump is 16.26ml/min. The pump realizes the integration of triangular prism obstruction and flow channel, effectively saves the pump cavity space, and sets other structures to complete other functions.
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