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Effects of structural parameters and rigidity of driving diaphragm on flow characteristics of micro valveless pump*

XIE Hai-bo(谢海波)†, FU Xin(傅　新), YANG Hua-yong(杨华勇)
(*The State Key Laboratory of Fluid Power Transmission & Control, Zhejiang University, Hangzhou 310027, China*)
†E-mail: hbxie@zju.edu.cn

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Abstract: The structure and operating principle of micro valveless pump were investigated theoretically and experimentally. The mathematical model of pressure and flow rate within the micro nozzle/diffuser was established to analyze the effects of nozzle/diffuser parameters on the output flow rate of the micro valveless pump. The experiments were carried out with different structural parameters, driving frequencies, vibration amplitudes and stiffness of the driving diaphragms. Effects of the structural parameters and driving conditions on the operation performance of the pump are discussed in detail. The work provides useful reference for structure optimization selection of the driving diaphragm of micro valveless pump.

Key words: Micro valveless pump, MEMS, Driving diaphragm, Optimal design
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INTRODUCTION

The micro pump is key component of micro fluidic system. The integration of micro pump with other micro fluidic components can be widely used for minimal injection of medicament, fuel spray, cell separation technology, and as cooler for super integrated circuit etc. (Yin et al., 2000a). Micro pumps are commonly divided into micro valvate pump and micro valveless pump according to their having valve plate or not (Anders et al., 1996). A number of research works on micro valvate pump were recently reported. Industrial application of micro valvate pump, however, is very limited due to high manufacturing cost, complex processing technique and instability of flow parameters.

Compared with micro valvate pump, micro valveless pump is structurally much simpler (Jiang et al., 1998). The advantage of having no valve plates largely simplifies the manufacture processing and also largely reduces the cost. The structural characteristics and operating principle of the micro valveless pump are described in Fig.1 and Fig.2. When the driving diaphragm is moving down, pressure inside the pump is positive. The flow rates in the nozzle and diffuser are different due to the difference of the pressure distribution when $Q_{\text{diffuser}} > Q_{\text{nozzle}}$. When the driving diaphragm is moving up, however, pressure inside the pump is negative and the pressure distribution in the nozzle and diffuser is reversed, resulting in $Q_{\text{diffuser}} < Q_{\text{nozzle}}$. If the processes are periodically going on, the fluid can be pumped from the nozzle side to the diffuser side.

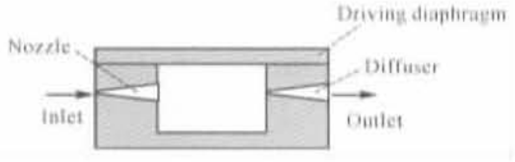

Fig.1 Schematic of micro valveless pump structure

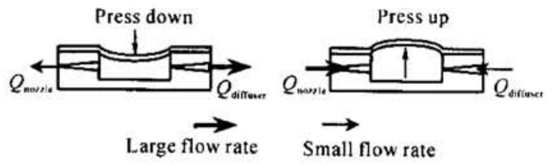

Fig.2 Operating principle of micro valveless pump

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THEORETICAL CALCULATION OF STRUCTURAL PARAMETERS

The structure of nozzle/diffuser is shown in Fig.3. The dimension of nozzle/diffuser can be described by three parameters: cone angle θ, length l and minimum sectional diameter d.

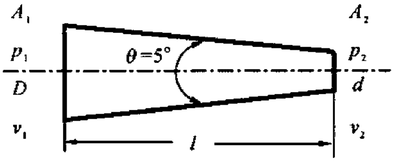


Fig.3 Parameters of nozzle/diffuser

According to hydrodynamics, when θ is about 5° – 7°, the dynamic flow resistance is minimum and therefore $\theta = 5°$ is selected in calculation as well as in experiment. The flow equation of clearance, and pressure distribution of nozzle is given by

$$p = p_1 - \Delta p \frac{\left(\frac{D}{h}\right)^2 - 1}{\left(\frac{D}{d}\right)^2 - 1} \tag{1}$$

And pressure distribution of diffuser can be expressed as

$$p = p_1 - \Delta p \frac{1 - \left(\frac{d}{h}\right)^2}{1 - \left(\frac{d}{D}\right)^2} \tag{2}$$

where h, sectional diameter of nozzle/diffuser

The flow rate of nozzle is given by the Bernoulli equation

$$\frac{p_1}{\gamma} + \frac{v_1^2}{2g} = \frac{v_2^2}{2g} + \sum \zeta \frac{v_2^2}{2g} \tag{3}$$

where $v_1 = v_2\left(\frac{d}{D}\right)^2$

$$\Delta p = p_1 - p_2$$

$$p_2 = 0$$

and

$$v_2 = \frac{1}{\sqrt{1 + \sum \zeta - \left(\frac{d}{D}\right)^4}} \sqrt{\frac{2p_1}{\rho}} \tag{4}$$

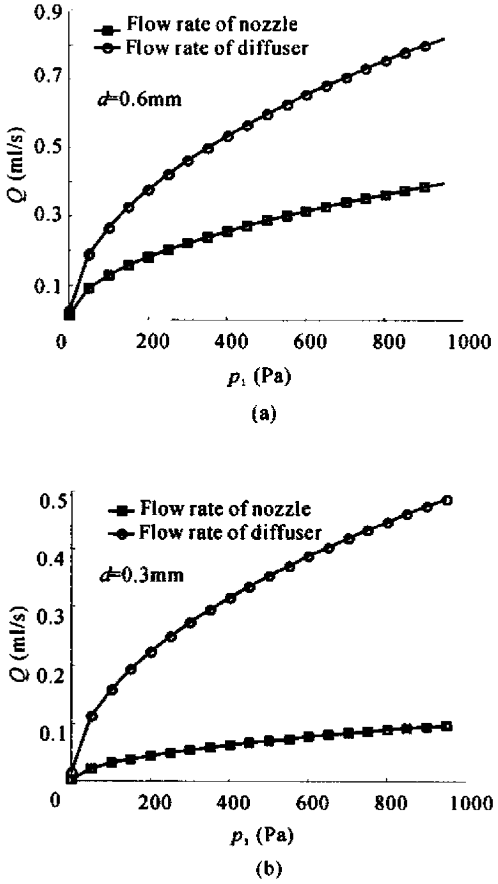
When $\theta = 5°$ and $\zeta = 0.0045$, the flow rate of nozzle Q can be expressed as

$$Q = v_2 A_2 = \frac{\pi d^2}{4} \frac{1}{\sqrt{1 + \sum \zeta - \left(\frac{d}{D}\right)^4}} \sqrt{\frac{2p_1}{\rho}} \tag{5}$$

and the flow rate of the diffuser can also be expressed as

$$Q = Av = C_V \frac{\pi D^2}{4} \sqrt{\frac{2p_1}{\rho}} \tag{6}$$

The mathematical model mentioned above is solved by MATLAB. The relationship between pressure and flow rate, related to θ, l and d has been numerically achieved. The typical simulation results under the condition of $d = 0.6$ mm, 0.3 mm and 0.2 mm are given in Fig.4, from which we can come to the following conclusions.



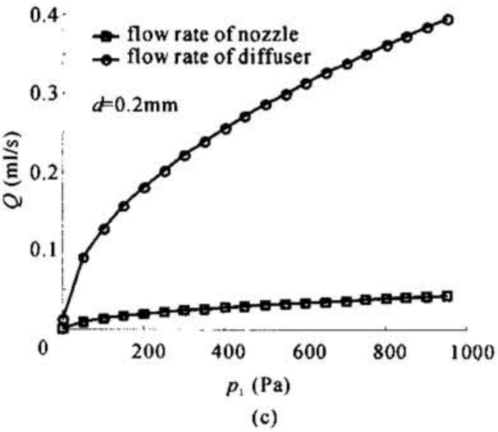


Fig.4 Simulation result of flow rate with different d
（a）$d = 0.6$mm；（b）$d = 0.3$mm；（c）$d = 0.2$mm

1. Decreasing d，reduces the flow rate in nozzle and diffuser，but increases the ratio of $Q_{\text{diffuser}}/Q_{\text{nozzle}}$.
2. With increasing θ，the flow rate in the diffuser increases faster than that in the nozzle；and the ratio of $Q_{\text{diffuser}}/Q_{\text{nozzle}}$ increases.
3. Increasing l，increases the flow rate in diffuser faster than that in the nozzle；and increases the ratio $Q_{\text{diffuser}}/Q_{\text{nozzle}}$.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Experimental set-up

In order to observe the circumfluence in the nozzle/diffuser，the micro valveless pump was fabricated with transparent material，polymethylmethacrylate. Three different elastic materials such as rubber film，latex film and thin latex film were used to fabricate the driving diaphragm so that the effects of the diaphragm rigidity on the characteristics of the flowing fluid can be evaluated. The experiment system shown in Fig. 5 consists of a micro vibratile device，signal-generator，measuring cylinder and capillary glass tube. The micro vibratile device is a Mini Shaker 4800 from Brüel & kjær Company in Denmark. The output parameters of the shaker are 0 – 3 mm，0 – 15 N and 0 – 5 kHz. The pump flow rate is measured by the cylinder. The capillary glass tube is used to evaluate the delivery capacity. The output pressure is calibrated by the water column height.

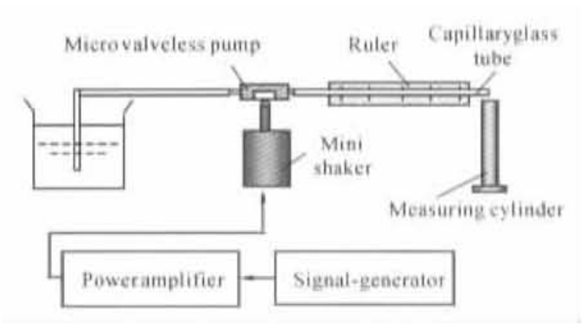


Fig.5 Set-up of experiment

Experimental results and discussions

The flow characteristics of two model pumps with minimum sectional diameters of 0.6 mm and 0.3 mm were experimentally investigated. The measurement results of flow rate and output pressure under the different conditions of driving frequency and vibration amplitude are given as follows：

Fig.6 on the effects of driving frequency on the output flow rate of the pump shows nonlinear relation between flow rate and driving frequency. The change of minimum sectional diameter d also led to a shift in flow rate. When the frequency was < 12 Hz，the flow rate increase of the $d = 0.3$ mm pump was a little larger than that of the $d = 0.6$ mm. But when the frequency was > 12 Hz，the flow rate decrease of the $d = 0.3$ mm pump was also a little larger than that of the $d = 0.6$ mm pump. This phenomenon indicated that smaller d led to higher pump efficien-

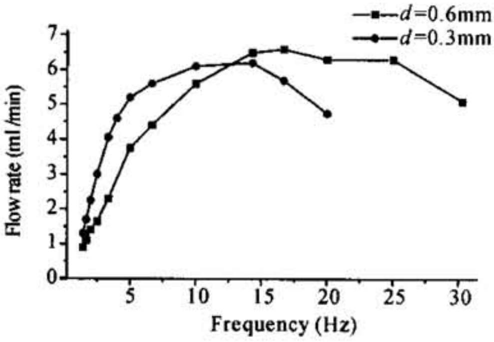


Fig.6 Flow rate/frequency

cy. As the output flow rate reached its peak value, however, the absolute flow rate depended not only on the efficiency of the pump but also on the diameters of the nozzle/diffuser. On this occasion, the effects of the efficiency are subject to the diameters, resulting in the output flow rate of the $d = 0.6$ mm pump exceeding that of the $d = 0.3$ mm pump.

Fig. 7 shows the shifts of output pressures versus minimum sectional diameter d and driving frequency. It can be seen that the output pressure of $d = 0.3$ mm pump is much higher than that of $d = 0.6$ mm pump, which indicates that diminishing d could achieve higher-pressure output. On the other hand, $d = 0.3$ mm pump reaches output pressure peak at a much lower driving frequency than $d = 0.6$ mm pump does, which means that the relation between the output pressures and driving frequency is related to the minimum sectional-diameter. Smaller d leads steeper rise of the output pressure, and maximum pressure output can be reached at the lower driving frequency as well.

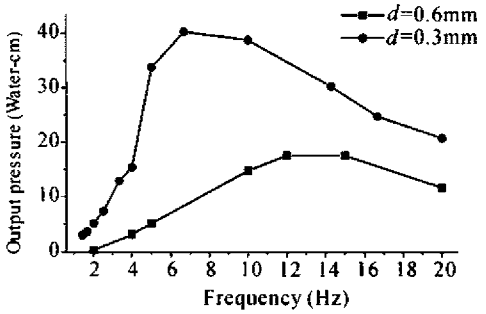


Fig.7 Output pressure/frequency

Fig.8 shows the change of flow rate with different amplitude at the same driving frequency. From the figure, it can be seen that the flow rate increases with the increment of amplitude, but the shifts of the flow rate are nonlinear.

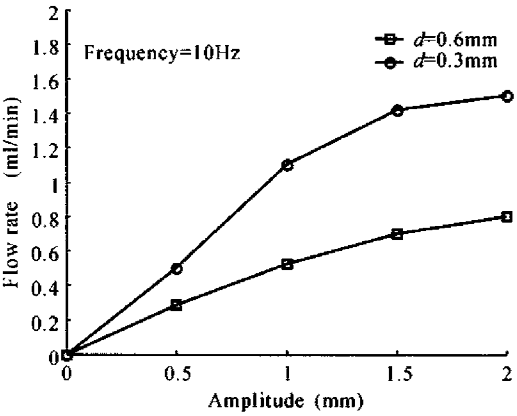


Fig.8 Flow rate/amplitude

In the experiment, three types of driving diaphragms with different rigidity were used to analyze the driving characteristic. The results in Fig.9 show that stiffer driving diaphragm results in better delivery capacity. For the same driving diaphragm, however, delivery capacity fluctuates irregularly with the shift of the driving frequency. Fluctuation of the delivery capacity can be explained as due to the coupling of driving frequency and the pipe-period of the micro pump. That is, when the motion of the driving diaphragm is in the same direction with the transient pressure generated by the pump itself, the delivery capacity reaches its crest; otherwise, the delivery capacity goes down gradually to the wave trough (Fu et al., 1999; Douglas et al., 1992).

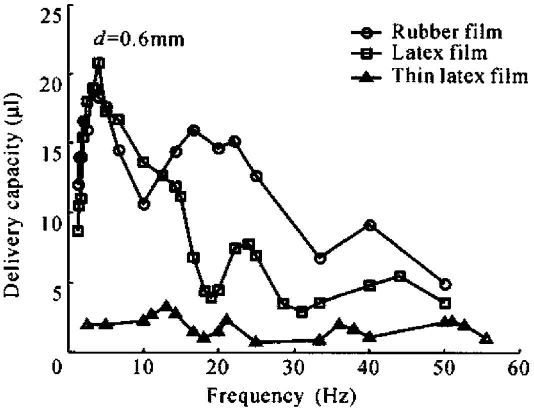


Fig.9 Influence of stiffness of driving diagram on delivery capacity

COMPARISON OF MICRO VALVATE AND VALVELESS PUMP

Compared with the micro valvate pump, micro valveless pump has a number of advantages. Firstly, it has no valve plate, which largely reduces fabricating and bonding costs. Secondly, it has better flow performance, which can be proved by comparing the results presented in this paper with the experimental observation of Yin Zhizhong (Yin et al., 2000b) whose work confirmed inactivity of the micro valvate pump at lower driving frequency due to the low natural frequency of the valve plate. Finally, advantages of the micro valveless pump are also clearly seen in the parametric design, flow resistance and micro flow visualization.

CONCLUSIONS

As a new kind of high efficiency micro fluidic machine, the micro valveless pump has the advantages of simple structure, low cost, and excellent controllability. It is in fact widely accepted that the micro valveless pump is becoming the most potential micro power supply for micro fluidic system. In this paper, the flow pattern and the influence of working parameters on output characteristic of micro valveless pump is given, from which we can come to the following conclusions.

1. The driving frequency, vibration amplitude and rigidity of driving diaphragm are the main factors that greatly influence the output performance. In the controllable frequency range, the increasing of driving frequency and vibration amplitude will increase the flow rate and output pressure of the pump. When the motion of the driving diaphragm is in the same direction as that of the transient pressure generated by the pump itself, the delivery capacity reaches its wave crest. Besides, increasing the driving diaphragm rigidity is the most effective means to expand the controllable flow rate range.
2. The structural parameters of the nozzle/diffuser are also key factors determining the flow performance of the pump.
3. The micro valveless pump operated by the diffuser/nozzle is especially suitable for the MEMS products that require frictionless transmission.

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