OPTIMIZATION DESIGN OF MICRO-DIFFUSER/NOZZLE ELEMENTS AND DEVELOPMENT OF IMPLANTED DRUG DELIVERY MICROPUMP

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Abstract

A new valveless micro piezoelectric pump has been designed and fabricated. The pump consists of diffuser/nozzle elements connecting to a chamber with an oscillating diaphragm. The vibrating diaphragm produces an oscillating chamber volume, which together with the diffuser/nozzle elements creates a one-way fluid flow. ANSYS-CFD simulations of different diffuser/nozzle elements used in dynamic micropumps are presented. A micropump prototype with a chamber in diameter of 25 mm with conical diffuser/nozzle elements has fabricated and tested. A piezoelectric stack is used as the actuating element. The maximum liquid flow rate is 40 ml/min and the maximum pump pressure is 2.5 mH_2O.

Keywords: Micropump; Nozzle/Diffuser; Simulation; ANSYS; Micro Machining.

1. Introduction

A conventional diaphragm pump consists of two passive check valves connected to an oscillating diaphragm [Shoji,S.,1994] [Smits,J.G.,1990], which creates an oscillating chamber volume. Pumps with movable valves may suffer from problems such as a high-pressure drop across the valves, wear and fatigue of the movable parts. This may result in reduced lifetimes and reliability. There is a need for pumps with no movable parts.

The micro pump presented here is based on a new valveless pump principle using the different flow properties of diffuser/nozzle. ANSYS-CFD simulation method is used to optimize the design of the diffuser/nozzle elements. The valveless pump prototype is fabricated by micro machining methods, such as laser machining, EDM machining. The micropump prototype described here has properties such as simplicity and comparatively high pump volume, which makes it suitable for the applications, where high reliability and small size are required.

2. The Micropump Principle

The pump operation is based on the fluid flow rectifying properties of two diffuser/nozzle elements connected to a fluid cavity with an oscillating diaphragm. The nozzle/diffuser elements are shown schematically as Fig.1.

(a) (b)

Figure 1. Schematic cross-sectional views of (a) a diffuser and (b) a nozzle

A diffuser is defined as a conduit with an expanding cross-sectional area, and a nozzle is a conduit with decreasing cross-sectional area in the flow direction. The flow direction in the pump is based on the fact that a diffuser/nozzle element can be geometrically designed to have a lower pressure loss in the diffuser direction than in the nozzle direction for the same flow velocity [White, F. M., 1986]. For a complete pump cycle, a net volume is transported from the input of the pump despite the fact that the diffuser/nozzle conveys fluid in both directions.

Generally, the flow resistance coefficient ξ of the diffuser/nozzle flow shown in Fig.1 can be written as:

$$\xi = \frac{2\Delta p}{\rho v^2} \tag{1}$$

Where, Δp is the pressure drops along diffuser/nozzle, ρ the fluid density, v the mean flow velocity at the narrowest part of the diffuser/nozzle.

The diffuser/nozzle elements in the valveless pump are considered completely the same. The actuation membrane is actuated by the harmonic distributed force. During one period T, the mean volume output flow rate of the pump is:

$$Q = \frac{A}{T}\int_0^T | V_d - V_n | \, dt \qquad (2)$$

Where A is the cross-sectional area, V_d, V_n represent the mean flow velocities at the narrowest parts of the diffuser/nozzle respectively.

On the other hand, the maximum volume variability of the pump ΔV_m induced by deformation of the actuation membrane is:

$$\Delta V_m = \frac{A}{2}\int_0^T (V_d + V_n)\, dt \qquad (3)$$

The mean output flow rate is then calculated by:

$$Q = \frac{2\Delta V_m}{T}\,\frac{\sqrt{\xi_n/\xi_d} - 1}{\sqrt{\xi_n/\xi_d} + 1} \qquad (4)$$

From equation (4), if $\xi_n/\xi_d > 1$, the fluid will enter the pump chamber from diffuser and flow out from nozzle part.

3. Simulation and Optimization of the Diffuser/nozzle Structure

According to F. M. White's fluid mechanism theory [White, F. M., 1986] for micro channels, for a diffuser flow at very low Reynolds number (at least within 1<Re<30), the resistance coefficient of the diffuser is described as:

$$\xi_d = \frac{A_d}{\mathrm{Re}} \qquad (5)$$

A_d is the function of both the angle α and the D_1/D_0, when $\alpha < 40^o$:

$$A_d = \frac{20}{(\tan\alpha)^{0.75}}\left(\frac{D_1}{D_0}\right)^{0.66} \qquad (6)$$

For a nozzle flow at very small Reynolds numbers (Re<30), the resistance coefficient of the nozzles is:

$$\xi_n = \frac{A_n}{\mathrm{Re}} \qquad (7)$$

Within the limits $\alpha < 40^o$, A_n is:

$$A_n = \frac{19}{n_0^{\,0.5}\tan\alpha^{\,0.75}} \qquad (8)$$

Where $n_0 = D_1^2 / D_0^2$

The above formulas can give theoretical guidance for selecting suitable nozzle/diffuser structure.

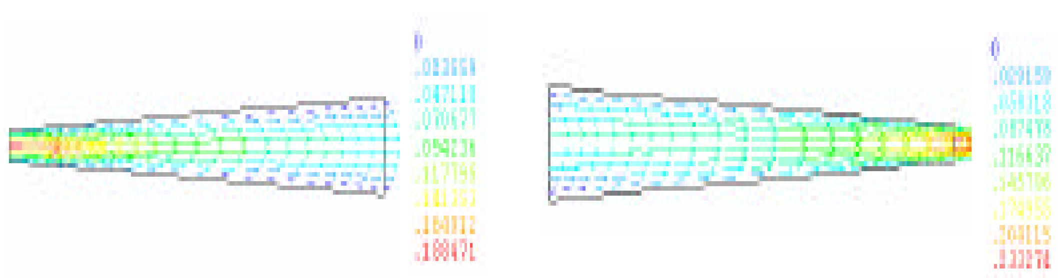
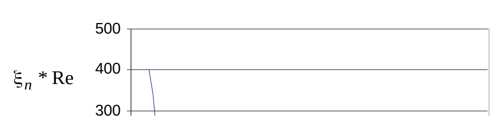


Figure 2. Flow patterns simulation for 2-dimensional model of a diffuser and a nozzle

The numerical simulations are done by using ANSYS-CFD software [ANSYS Inc., 1986]. Laminar flow situations is simulated using two-dimensional models, the D_0 is selected as 100 μm and the length L of the



nozzle/diffuser elements as 2 mm. The conical angles varied from 1º to 40º. The flow model calculates the velocity in inlet and outlet of the nozzle/diffuser at various pressures and various angles. The model is meshed with quadrilateral element using higher densities near the inlet and the outlet.

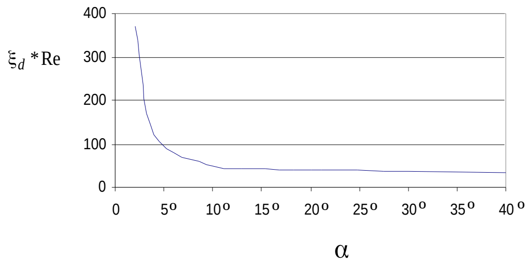


Figure 3. The relationship between ξ_d*Re and α

Figure 4. The relationship between ξ_n*Re and α

Fig.2. typically shows the simulated velocity change states of a typical nozzle/diffuser elements, the diverging and converging angles are 6º. By selecting the different conical angle (from 1º to 40º) and various pressures, the changing states of the resistances of ξ_d, ξ_n and ξ_n/ξ_d varying differently with α can be obtained as Fig. 3, Fig. 4 and Fig. 5 respectively. For a single nozzle or diffuser element, it shows the flow resistance coefficient is very large in the conical angle range of <10º, this is necessary for one direction flow function. From Fig.5, it shows, for achieving one direction flow function, α must be >5º, so that the ξ_n/ξ_d can be >1.5. The simulated diffuser/nozzle coefficient ratio has the similar changing trend as White's theory. From the simulation results, it shows that the conical angle of the nozzle/diffuser elements should be in the range of 5º-10º. Then the one direction flow function can be obtained.

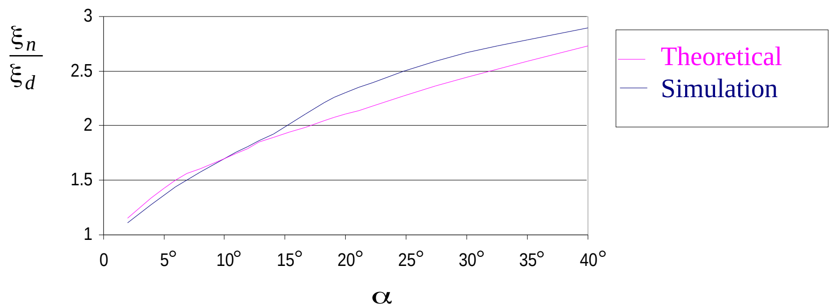


Figure 5. The relationship between ξ_n/ξ_d and α

4. Development of Valveless Micropump Prototype

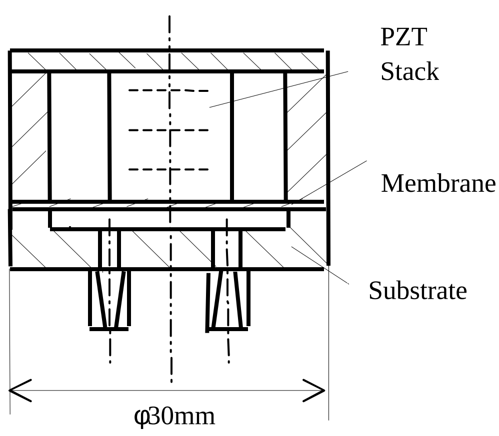


Figure 6. The diagram of the piezoelectric micro pump

Many micro pumps [Y.H. Mu, 1998, Lintel, H.T.G.V., 1988, Schoot, B.H.V.D., 1992] are developed by using piezoelectric disks as actuating elements, they need to bond the piezoelectric disks to the membranes by epoxy, the thickness of the epoxy should be as thin as possible, but it is difficult to achieve, this will greatly affect the actuating results. So these structures can not obtain high oscillating amplitude for the limited deformation of a single layer piezoelectric disk. One efficient way is to use piezoelectric stacks, which can produce tens of times deformation amplitude, this method can ignore the effect of the epoxy bonding. The prototype of micropump is shown in Fig. 6. It contains a chamber substrate, which is made of medical polymer and the nozzle/diffuser elements that are bonded to the chamber.

The nozzle/diffuser elements are fabricated by microelectro-discharge machine (EDM) system; its model is M-ED72W, a new product of Matsushita Electric Industrial Corporation Ltd. The fabricated microelectrode and corresponding nozzle hole are shown as Fig.7 and Fig.8 respectively, its structure parameters are selected according to the above simulation results.

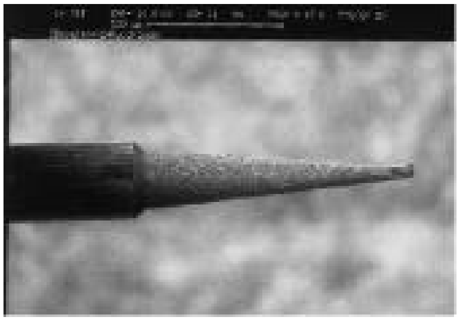


Figure 7. The SEM picture of the electrode fabricated by micro-EDM

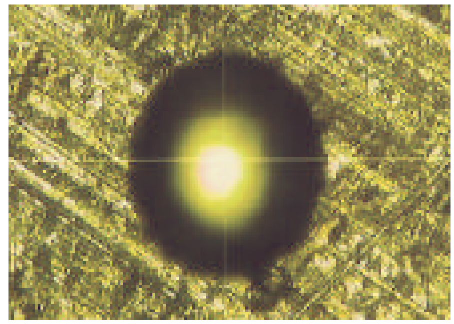


Figure 8. The picture of fabricated nozzle under optical microscope(×200)

5. Measurement Results

Deformation measurements at the center of the membrane are taken with a laser interferometer. The resolution of this type of interferometer is nominally a quarter of a wavelength or 158 nm for a helium neon laser with a wavelength of 633 nm. The deformation of an $11 \times 11 \times 18$ mm^3 sized PZT stack is approximately 15 μm for a voltage of 100 V and frequencies of 100 Hz to 5 kHz. The micro pump is tested with water. The pump rate is tested by measuring time and the output volume. A maximum pump rate of 40 *ml/min* is achieved at frequency of 200 Hz. The maximum backpressure of 2.5 mH_2O is achieved.

6. Discussions and Conclusions

This new pump has many advantages: simplicity, and high reliability; capability of pumping fluids with solid particle contents; miniaturizeability. With the diaphragm diameter of 25 mm, it demonstrated the pumping rate of about 40 ml/min and maximum pump pressures of about 2.5 mH_2O. We are planning to make a micropump to a miniaturized scale (3-5 mm), so that it can be used as an implanted component for the medical application.

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