Computational Analysis of a Piezo-electrically Actuated Valve-less Micropump for Micro-fluidic Applications

Rohit D. Bankar, Ajay L. Godase, Ashok B. Mule, Nikhil N. Gaikwad, Ranjitsinha R. Gidde

Abstract—**Computational analysis of a piezo-electrically actuated valve-less micropump is carried out for microfluidic applications. The effect of the operating parameter frequency on the performance of micropump is studied. The valve-less micropump consists of nozzle/diffuser elements; the pump chamber; a thin membrane (diaphragm) and a piezoelectric disc, PZT 5A of diameter 12 mm as the actuator. The complete electric–fluid–solidcoupling model is simulated with the commercial finite element analysis software COMSOL Multiphysics 5.0 to investigate the performance of the micropump.**

Index Terms—**Piezoelectic, PZT, Nozzle/Diffuser, Micropump**

I. INTRODUCTION

A micropump is one of the important devices in microfluidic applications, which can generate flow in the range of milliliters to microliters. A number of potential applications for micropumps are still being investigated, involving in drug delivery,biological detection, clinical analysis in medicine, etc.

A fixed geometry rectification pump, also known as a valve-less micropump is one of the most extensively investigated micropumps, which mainly consists of a flexible membrane propelling the flow and nozzle/diffuser elements for directing the flow.The oscillation of the diaphragm above pump chamber excited by the actuators propels the flow. A micropump requires an actuation mechanism to provide a pressure differential to transfer fluid from one point to another.The common actuation mechanisms include piezoelectric, electrostatic, thermo-pneumatic action, electromagnetic, shape memory alloy etc. Compared with other actuation mechanisms, thepiezoelectric actuation can provide a good reliability andmoderate pressure at low power consumption, which is preferred for medical applications [1]. Andersson et al. [2] designed a valve-less micropump for biological analysis and investigated the dependency on the properties of the pumped biological medium. The absence of moving parts, the simple planar design, and high pump performance in terms of pressure head and flow rate are some of the main advantages of such micropumps.Finite element analysis becomes a very attractive method to model the micro-devices used in microfluidic applications. Earlier studies on micropumps were mostly focused on the simulation of the functional elements, such as the micro-valves and actuators. Meiling Zhu et al. [3] did optimization of the design of geometric parameters of the piezo-electically actuated membrane by using 3D finite element method (FEM) to maximize piezoelectric actuation capability and ensure actuation reliability.Schalk Willem van der Merwe et al. [4]investigated the characteristics of a planar nozzle/diffuser based micropump using detailedcomputational fluid dynamics (CFD) analyses. Singh et al. [5] analyzed the performances of the nozzle/diffuser elements by using commercial software Fluent.

Therefore, in this study, a three-dimensional finite element modelof the valve-less piezoelectric micropump was built in COMSOL Multiphysics 5.0, including the pump diaphragm, the piezoelectricdisc, and the working fluid and analyzed the effect of constant actuation voltage of 30 V and thedifferent frequencies on the flow rate.This work, aims to design and study a piezoelectric valve-less micropump for microfluidic applications.

II. WORKING PRINCIPLE OF A PIEZOELECTRIC MICROPUMP

The schematic diagram showing the working principle of a piezo-electically actuated micropump is shown in Fig. 1-a and 1-b. A piezoelectric disc is glued with a diaphragm, which forces fluid through a small chamber. So there are basically two main parts of the micropump: a functional layer on which chamber and microchannels are engraved, and a diaphragm which is actuated by a PZT disc. In the supply mode (Fig. 1-a), the outward deflection of the membrane causes the chamber volume to increase, which results in decrease in pressure inside the chamber. In this situation, the fluid flows into the chamber through both inlet and outlet. However, since the kinetic energy of the fluid in the form of velocity is converted to potential energy in the form of the pressure in the diffuser, there is less loss of kinetic energy in the forward direction than in the reverse direction. Thus, the fluid flow from the inlet is greater than the fluid flow from the outlet. Therefore, the fluid is supplied into the chamber from the inlet. In the pump mode (Fig. 1-b), the reduction in the chamber volume creates higher pressure in the chamber. In this case, the fluid flows out from the chamber through both inlet and outlet. However, due to the difference in the loss of the kinetic energy, the fluid flowfrom the outlet is greater than the fluid flow from the inlet [6,7]. Thus, the net fluidflow from the inlet to the outlet is achieved.

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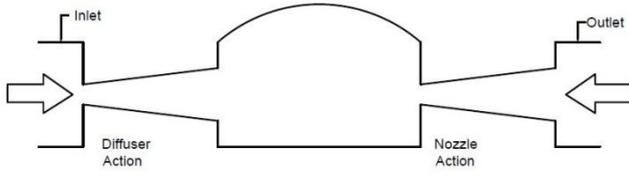
Fig. 1-a. Supply mode

Fig. 1-b. Pump mode

III. THEORETICAL ANALYSIS

The performance of a valve-less micropump depends on the properties of the rectification elements (nozzle/diffuser) [8].

1. Flow rectification efficiency

The pressure loss coefficient for flows through the nozzle/diffuser element is defined as[9]:

$$K = \frac{\Delta P}{\rho v^2 / 2} \qquad (1)$$

Where ΔP is the pressure drop across the nozzle/diffuser direction, ρ is the fluid density, and v is the mean velocity of the fluid flow in the nozzle/diffuser elements.

The pressure loss coefficient across the nozzle/diffuser element is the sum of the pressure drops through the three parts, namely, the sudden contraction at the entrance, the sudden expansion at the exit, and the gradual expansion or contractionalong the length of the nozzle/diffuser element. Thus, the pressure loss coefficients across the diffuser direction and the nozzle direction are expressed as:

$$K_d = K_{d,en.} + K_{d,l.} + K_{d,ex.}\left(\frac{A_1}{A_2}\right)^2 \qquad (2)$$

$$K_n = K_{n,ex.} + \left(K_{n,l} + K_{n,en.}\right)\left(\frac{A_1}{A_2}\right)^2 \qquad (3)$$

Where $A_1$is the narrowest cross-sectionarea andA_2 is the largestcross-section area of the nozzle/diffuser element, respectively.
The diffuser efficiency of the nozzle/diffuser elements is defined as the ratio of the pressure loss coefficient across the nozzle direction to that in the diffuser direction:

$$\eta = \frac{K_n}{K_d} \qquad (4)$$

Where, $K_d$and$K_n$are pressure loss coefficients across the diffuser direction and the nozzle direction respectively.If the pressure loss coefficient in the nozzle direction is higher than that in the diffuser direction, i.e., $\eta > 1$, a forward flow from the inlet to the outlet is caused. In contrast, $\eta < 1$ willlead to a backward flow from the outlet to the inlet.
The flow rectification efficiency of the valve-less

micropump is expressed as:

$$\varepsilon = \frac{Q_+ - Q_-}{Q_+ + Q_-} \qquad (5)$$

Where $Q_+$and $Q_-$are the flow rate in the forward and the backward directions respectively.The flow rectification efficiency reveals the ability of the micropump to generate flow in the forward or backward direction. The higher the ε is, the better flowrectification in forward direction.

2. Governing equations
A piezoelectric disc is utilized as the actuator. PZT-5A, a special type of piezoelectricmaterial, is used in the computational analysis.
The coupled electro-mechanical constitutive equations for the actuator in stress charge form [10] is as given below:

$$\left.\begin{array}{l} T = C_E.S - e^t.E \\ D = e.S - \varepsilon_s.E \end{array}\right\} \qquad (6)$$

Where T is the mechanical stress tensor, S is the mechanical strain tensor,$C_E$is elastic stiffness constant tensor at constant electric field, $e^t$is the piezoelectric constant tensor, Eis the electric field vector, Dis the electric charge displacement vector,eis the piezoelectric coupling coefficient for stress charge form,ε_s is the electric permittivity.
The polydimethylsiloxane (PDMS)membrane in the piezoelectric valve-less micropump is integrated with surrounding walls; as a result, it can be considered as a clamped plate.
The governing equation of forced vibration of a thin clamped plate[11]can be expressed as:

$$D\nabla^4 W + \rho_P \frac{\partial^2 W}{\partial t^2} = f_e - P \qquad (7)$$

Where,

$$D = \frac{Et_m^3}{12(1 - v^2)} \qquad (8)$$

Where D is the plate stiffness,$\nabla^4$is the two-dimensional double Laplacian operator, Eis the Elastic modulus, vis the Poisons ratio of the membrane, t_m is the thickness of the membrane, and$\rho_p$is the density of the membrane. $f_e$is the periodic actuating force, and P is the dynamic pressure exerted on the membrane by the liquid.In this case, the pump membrane is assumed to be clamped.
The flow can be considered as an incompressible laminar flow, which can be described using the Navier–Stokes equation (9) and the mass continuity equation (10)[11].

$$\rho_L \frac{D\vec{V}}{Dt} = \rho_L \vec{g} + \mu \nabla^2 \vec{V} - \nabla P \qquad (9)$$

$$\frac{\partial \rho_L}{\partial t} + (\vec{V}.\nabla)\rho_L = 0 \qquad (10)$$

Where,$\rho_L$is the density of the liquid; $\vec{V}$is the velocity vector; μ is the viscosity of the liquid. The boundary conditions for fluid model are no-slip at Fluid–Wall interface and Fluid-Membrane interfaces, and free surface boundary conditions at the inlet/outletof the micropump.

IV. DESIGN OF MICROPUMP

1. Structural design of piezoelectric actuator

The material used for the construction of piezoelectric transducer requires high reliability, a wide frequency response range, and a linear response to applied voltage with reasonably low cost. In this study, we have used PZT-5A disc with external diameter of 12 mm. The structure of the piezoelectric transducer is shown in Fig. 2. It consists of three elements: a PZT piezoelectric layer, a connecting layer (glue), and a brass disc. A PDMS diaphragm is bonded to this PZT disc. The diaphragm is actuated due to piezoelectric effect induced in the PZT disc. The dimensions of the PZT actuator are shown in Table 1.
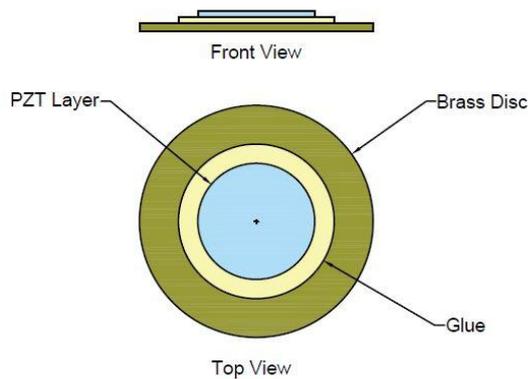

Fig. 2. Structure of piezoelectric transducer

Table 1. Dimension parameters of piezoelectric actuator

Sr.No.	Parameter	Values (mm)
1.	PZT layer diameter	7.5
2.	PZT layer thickness	0.2
3.	Brass disc external diameter	12
4.	Brass disc thickness	0.14
5.	PDMS diaphragm diameter	12
6.	PDMS diaphragm thickness	0.15

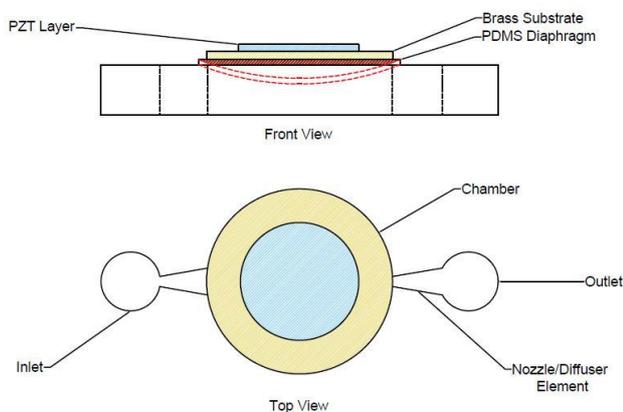### 2. Structural design of functional layer

Fig. 3. Schematic diagram of functional layer of micropump

In this study, a valve-less micropump with nozzle/diffuser elements is designed, which utilizes the difference of the flow resistance across the diffuser element and the nozzle element for directing the flow. The functional layer is made of acrylic material which includes two nozzle/diffuser elements, one pump chamber, one inlet chamber and one outlet chamber. The schematic diagram of functional layer is shown in Fig. 3

2.1 Nozzle/Diffuser element

The section of microchannel following the direction of the increase of cross-section area is called diffuser, while the section following the direction of decrease of cross-section area is called nozzle. Two nozzle/diffuser elements have the same geometrical dimensions. The diffuser and the nozzle are used as the inlet and outlet of the micropump chamber respectively.

For easy integrating with other MEMS devices and high performance, the planar nozzle/diffuser element is used. At smaller divergence angle, the rectification efficiency is low as both nozzle and diffuser offer the same resistance and thus the net flow rate increases with increase in divergence angle. Similarly, at much higher divergence angles, the flow separation may occur which leads to the reduction in the net flow rate. Therefore, output of micropump also depends on the geometrical dimensions of the nozzle/diffuser element.

Fig. 4 shows the basic dimension parameters of the planar nozzle/diffuser element. These basic dimensions involve the divergence angle 2θ, the channel length L, and the width of the nozzle W1. The values of these dimensions for the proposed micropump are shown in Table 2.
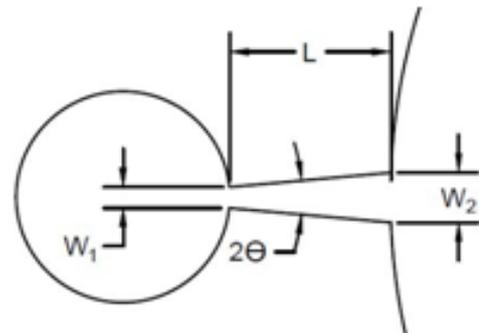

Fig. 4. Schematic diagram of nozzle/diffuser element

Table 2. Dimension parameters of nozzle/diffuser element

Sr.No.	Dimension parameter	Value
1.	Divergence angle (2θ) (degree)	10
2.	Width at nozzle (W1) (micron)	200
3.	Microchannel length (L1) (mm)	1.5

2.2 Pump chamber

The pump chamber is the central section of the functional layer where fluid gets stored during suction mode and this stored fluid is forced to outlet during discharge mode. The diameter and depth of the chamber should be such that to conform to the diameter and the thickness of the piezoelectric actuator with sufficient space for storing fluid. For this study, we have used functional layer with pump chamber of diameter 12 mm and depth 500 micron.

2.3 Inlet and outlet

The diameters of the inlet and the outlet chambers are to

conform to the diameters of the inlet and outlet pipes respectively. On functional layer,we have engraved inlet and outlet chambers of diameter 2 mm each.
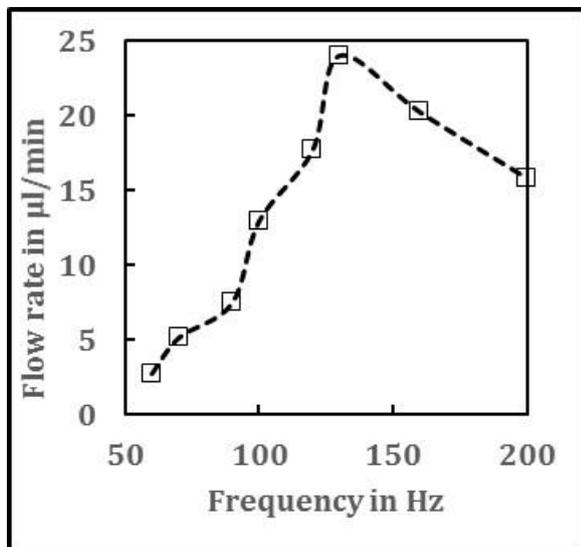
V. COMPUTATIONAL ANALYSES AND RESULTS

Fig. 5. Flow rate as a function of actuation frequency
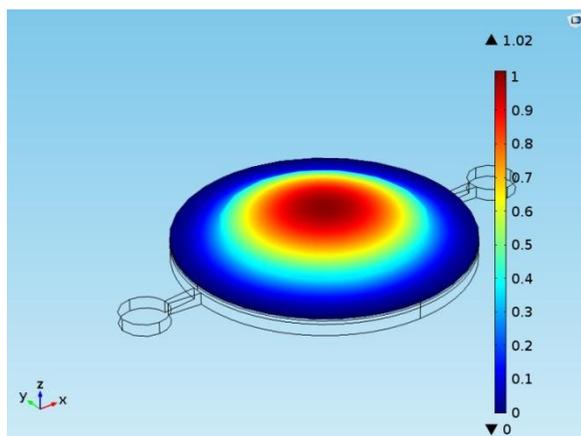

Fig. 6. Total displacement at actuation frequency 130 Hz

The computational analyses are carried out on the proposed micropump design using COMSOL Multiphysics software for the calculation of maximum flow rate at the outlet of the micropump. Water is considered as the working fluid. Also, the total displacement of the PDMS diaphragm is obtained from simulations at the actuation frequency, at which we get the maximum flow rate of discharge.

We have given constant supply of 30 V AC to the piezoelectric actuator and the actuation frequency is varied from 10 Hz to 200 Hz. The plot of flow rate as a function of actuation frequency is shown in Fig. 5. The flow rates obtained at frequencies of 60 Hz, 100 Hz, 130 Hz, 160 Hz and 200 Hz are 2.77 µl/min, 12.95 µl/min, 24.00 µl/min, 20.25 µl/min and 15.84 µl/min respectively. The maximum flow rate of 24 µl/min is obtained at outlet of micropump at actuation frequency 130 Hz.
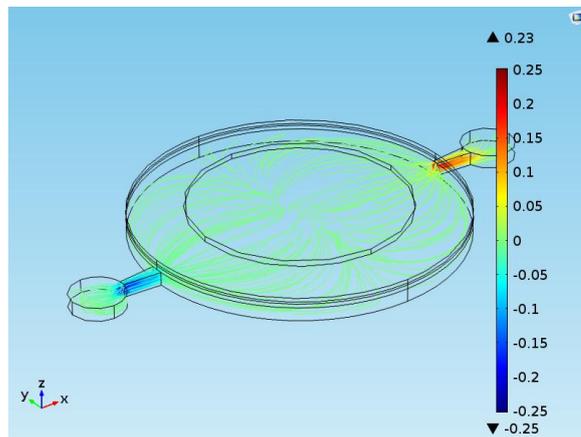

Fig. 7. Streamline velocity distribution inside the pump chamber

Fig. 6 shows the total displacement of the piezoelectric actuator at frequency 130 Hz, where maximum flow rate is obtained. The maximum central displacement obtained at 130 Hz is 1.02 µm.

The distribution of streamline velocities inside the pump chamber at 130 Hz frequency is shown in Fig. 7. From figure, the maximum streamline velocity of 0.23 m/sec obtained at the nozzle section of outlet.

VI. CONCLUSIONS

The working principle of piezoelectric micropump has been studied and the micropump is designed for piezoelectric disc of 12 mm diameter. The driving parameters of the piezoelectric transducer have been determined and their effects on flow rate of micropump, displacement of actuator and streamline velocities are investigated using computational analyses. The results of computational analyses can be summarized as below:

1.The maximum flow rate at the outlet of micropump at 30 V supply is obtained at 130 Hz frequency. The maximum flow rate obtained is 24 µl/min.

2. The maximum central displacement of piezoelectric actuator at 30 V voltage and 130 Hz frequency is 1.02 µm.

3. The maximum streamline velocity is 0.23 m/sec for 30 V at 130 Hz supply condition.

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