A Valve-less Micro Pump driven by a Piezoelectric Actuator

Jigisha Thakkar
Production Engineering Dept.
Birla Vishwakarma Mahavidyalaya
Vallabh Vidya Nagar, India
jigishabhaskar@gmail.com

N J Manek
Production Engineering Dept.
Birla Vishwakarma Mahavidyalaya
Vallabh Vidya Nagar, India
njmanek@bvmengineering.ac.in

P M George
Mechanical Engineering Dept.
Birla Vishwakarma Mahavidyalaya
Vallabh Vidya Nagar, India
pmgeorge02@yahoo.com

Purvi Chahan
Production Engineering Dept.
Birla Vishwakarma Mahavidyalaya
Vallabh Vidya Nagar, India
pdechauhan@bvmengineering.ac.in

Abstract- A new valveless micro piezoelectric pump has been designed and fabricated. The pump with a check valve has a risk of reduction in performance and reliability due to wear and fatigue. Instead of passive check valves the pump uses two specially designed nozzle/diffuser elements which give a fluid directing effect. Diffuser/Nozzle element is connected 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. A micropump prototype with a rectangular chamber and conical diffuser nozzle elements has fabricated. A prototype of the piezoelectric stack is developed which is used as the actuating element.

Keyword- Micro pump, Nozzle/Diffuser element, Micro Machining

I. INTRODUCTION

While miniaturization is revolutionizing the world of sensors and various mechanical systems, a variety of chemical and biological procedures require devices that can deliver minute and accurately metered quantity of material. One of those devices is known as micropump. This need has stimulated extensive research in the field of microfluidics in last decade. The most potential application of micropump is the controlled drug delivery, precise fuel injection system and localized cooling of electronic devices.

The reciprocating micropump is one of the earliest presented micropumps, which mainly consists of flexible membrane propelling the flow and the micro valves directing the flow. The oscillation of membrane excited by the pump actuators propels the drug flow. However, the significant problems associated with this type of micropumps are: the fatigue of moving cantilever valves, the sensitivity to solid particles, high pressure loss of valves, and low driving frequency. In order to overcome these problems, the valveless micropump with diffuser/nozzle elements, also called fixed valves, was first presented [7]. The valveless micropump utilizes the difference of flow resistance across the diffuser element and nozzle element to achieve flow rectification. A new valveless micropump has proposed for pumping of both gas and liquid, and the dependence of the pump characteristic on the properties (i.e. density, pH, and ionic strength) of the pumped media was further investigated [1]. According to the experiment results, they concluded that the proposed valveless micropump can pump any sample in biology and biochemistry fields. Lot of research efforts have been made for the valve less micro pump [1].

Various mechanical micropumps with different actuating principle have been developed [2], such as thermopneumatic [3], electrostatic [4], shape memory alloy [5], electromagnetic [6] as well as piezoelectric [7]. The piezoelectric actuation presents its advantages of moderately pressure and displacement at simultaneously low power consumption, good reliability and energy efficiency [7].

This paper reports on the development of a reciprocating displacement diaphragm pump in which chamber is bonded by two nozzle/diffuser element. To vibrate the diaphragm piezoelectric actuator is designed. The proposed micro pump has the potential to be fabricated by traditional fabrication method such as electrical discharge machining (EDM).

II. THE PUMP DESIGN

A. Working Principle

The pump is of the reciprocating displacement type. It consists of a piezoelectric actuator unit, pump housing and two diffuser/nozzle elements. The pump operation is based on the fluid flow rectifying properties of the two nozzle/diffuser elements. Providing that the diffuser/nozzle element is correctly designed, the volume flow in the diffuser direction is
higher than the volume flow in the nozzle direction, assuming the same pressure drop across the fluid element. The pump cycle of the pump can be divided into a ‘supply mode’ and a ‘pump mode’ as shown in the Fig. 1. During the ‘supply mode’ the cavity volume increases and a larger amount of fluid flows into the cavity through the input element, which act as a diffuser, than through the input element, which acts as a nozzle. The result for the complete pump cycle of the diffuser/nozzle pump is that a net volume has been transported from the input to the output side of the pump.

Figure 1 Operation principle of valveless diffuser/nozzle pump [8]

B. Diffuser/Nozzle element

Diffuser is a duct with gradually expanding cross section and nozzle is a duct with gradually converging cross section. For the efficient operation of pump, diffuser is a key design parameter. The function of diffuser is to transform kinetic energy i.e. velocity to potential energy i.e. pressure. In general the two main types of diffusers conical and flat-walled have approximately the same diffuser capacity; however, the best performance for conical diffuser is achieved at a length which is 10 to 80% longer than for the best flat-walled design. The choice of diffuser type is basically dependent on the fabricated process. Conical diffuser as shown in Fig. 2 is selected for the proposed micro pump design.

Typical performance maps for conical diffusers at similar operating conditions [8] is given which gives the relation between Area Ratio (AR) and ratio of Length of diffuser by diameter at throat and Area Ratio is the ratio of Area at exit of diffuser to the Area at throat of the diffuser element. In order to achieve the best pump performance the diffuser element has to be designed for highest possible flow directing capability. To estimate the possible flow directing capability of diffuser element available information for macroscopic internal flow system with circular cross section was used. Considering it, area ratio is taken as 1.46 and for the diameter at throat as 0.7 mm, we get the value of \( \frac{L}{D_{throat}} \) as 10. The length of diffuser element is calculated as 7 mm.

Figure 2 Schematic diagram of Conical diffuser [8]

The dependence of the losses in a diffuser is shown in Fig. 3 for macroscopic, turbulent flow [9].

![Figure 3 Loss coefficient as a function of 2θ for conical diffuser [8]](image)

For achieving one direction flow function conical angle must be greater than 5°. From the White’s theory it shows that the conical angle of the nozzle/diffuser elements should be in the range of 5° - 10° then the one direction flow function can be obtained considering it and taking the reference of Fig 3 the value of conical angle of diffuser 2θ is selected as 10°, where the losses are minimum. Similarly the value of loss coefficient K can also be taken from the Fig. 3 as 0.4 at 10°. The relation between pressure loss coefficient (ξ), loss coefficient (K) and the area ratio is given (1).

\[
ξ = K \times \left( \frac{A_{throat}}{A_{exit}} \right)^2
\]

(1)

The diffuser elements have rounded inlet and sharp outlet in the diffuser direction in order to reduce the pressure loss, hence major pressure loss occurs in the bulk and diffuser region. For stationary flow total diffuser loss coefficient is 0.2-1. In the nozzle direction the inlet is sharp and outlet is rounded. As a result of this the pressure loss across in inlet and bulk nozzle region is less than that across rounded outlet. So the nozzle performance is independent of element geometry as long as basic design is followed and the total nozzle loss coefficient is 1 i.e. ξn = 1. From (1) we can calculate the value of diffuser loss coefficient ξd = 0.187.

To optimize the efficiency of the diffuser element the the nozzle/diffuser efficiency (\( \eta_{nd} \)) should be maximum and is defined by (2).

\[
\eta_{nd} = \frac{ξ_n}{ξ_d}
\]

(2)

If \( \eta_{nd} > 1 \) will cause a pumping action in the diffuser direction in a valveless micropump while \( \eta_{nd} < 1 \) will lead to pumping action in the nozzle direction. The case where \( \eta_{nd} = 1 \) corresponds to equal pressure drops in both the nozzle and the diffuser direction leading to no flow rectification [10]. From (2) the nozzle/diffuser efficiency is calculated as 5.33 and it is
greater than 1 so the pumping will be along the diffuser direction.

C. Pump Chamber Element

The pump chamber is made of stainless steel and fabricated by EDM. Stainless steel is widely used in medical equipment and instrumentation because of its good corrosion resistance and biocompatibility. In addition, using stainless steel for the pump chamber can improve the rigidity of the pump chamber [11]. Pump chamber has a rectangular cavity of length 24 mm, width 5 mm and depth of 0.3 mm. The dimensions of the pump chamber are chosen by considering the actuator design and the compressibility ($\beta$) requirement for the liquid pump. Photograph of the fabricated Nozzle/Diffuser element and the Pump chamber is shown in Fig. 4.

D. Diaphragm

The Pump membrane or a diaphragm has a thickness of 0.15 mm of aluminum material. The diaphragm closes the cavity of pump chamber and it is bonded with the centre disk of the actuator. The reason for taking 0.15 mm thickness is as diaphragm oscillates by applying alternating excitation voltage to the actuator. We get larger the deformation magnitude and stroke volume if the pump membrane (diaphragm) is thin [12]. Hence the pump membrane should be as thin as possible to improve the pump flow. However limitation of fabrication process and the membrane strength is considered.

E. Actuator Element

When the electric field is applied between these two terminals of disc, there will be displacement in vertical direction. In the design of PZT stack, identical PZT discs are placed one over other such that positive terminal of first disc will come into contact with positive terminal of second PZT disc. The same arrangement is followed for placing another disc whose negative terminal comes into contact with negative terminal of the next disc. This kind of arrangement of discs forms a stack with parallel connection of PZT discs. It is required to make a firm joint between two successive discs. This joint should maintain a conducting path between two positive or two negative terminals of the discs. To provide gluing effect as well as to maintain conducting path, silver conducting cement is used as a paste in between two discs. A thin copper plate of thickness 0.5 mm and length 30 mm is placed in between the discs and then silver conducting cement is spread evenly on this copper plate. The next PZT disc is placed such that it is aligned in vertical direction with the previous disc. The same procedure is followed for further discs. The copper plates on one side of stack are connected with positive terminal of the disc, while the copper plates on the other side of the stack are connected to the negative terminal of the disc. The copper plates for positive and negative terminals are joined together as shown in Fig. 5. With the help of this kind of arrangement, ultimately two terminals are carried out as positive and negative from the stack where electric field is applied. This electric field is available to each and every disc and hence every disc is getting 0.02 $\mu$m displacement. We have used 10 PZT discs, giving 10 times displacement [13]. Photograph of a Fabricated PZT Actuator is shown in Fig. 5.

The displacement achieved under the application of applied voltage is calculated with (3) as follows,

$$\Delta l = d_{33}.n.V $$

where, $\Delta l$ is displacement in meter and $d_{33}$ is strain coefficient. For an applied voltage of 400 Volts and $d_{33}$ as $425 \times 10^{-12}$ Columb/Newton, the displacement achieved is 1.7 micrometers for 10 number of PZT discs.

F. Power supply Module

The displacement of PZT stack is directly proportional to the applied electric field. Since the co-efficient is in terms of $425 \times 10^{-12}$ meter/Volts, high voltage of the order of Kilovolts will be required for PZT discs to get the displacement in terms of few micrometers. So, it is required to have a high voltage source. A DC to DC converter is utilized for this purpose. With the help of 12 volts DC generated from a power supply, DC to DC converter generates 0.4 Kilovolts. This high voltage is required to be switched in the form of on and off such that required frequency of this high voltage can be applied to the PZT stack to achieve pumping action.

III. ASSEMBLY OF MICRO PUMP

A prototype micropump with diffuser/nozzle elements bonded on one side of the pump chamber using epoxy and diaphragm closes the cavity of pump chamber on the other side. Diaphragm is bonded with the centre disk of the actuator which oscillates by applying alternating excitation voltage to the actuator. In order to hold the pump chamber and actuator stable the housing of acrylic is fabricated. The photograph of a fabricated piezoelectric micropump is shown in Fig. 6.
The pump flow rate is calculated with (4) as follows,

\[ Q = V_s \times f \]  \hspace{1cm} (4)

Where \( V_s \) is a stroke volume by (5)

\[ V_s = l \times w \times \Delta l \]  \hspace{1cm} (5)

Where ‘l’ is 24 mm, which is the length of the pump chamber, w is 5 mm the width of the pump chamber and \( \Delta l \) is the diaphragm displacement. Considering the frequency as 1 KHz we get pump flow rate from (4) as 12.24 mlit/min. for calculating compression ratio (6) is used as follows,

\[ \beta = \frac{V_s}{V} \]  \hspace{1cm} (6)

The chamber volume \( V \) is 36 mm³, so we get Compression ratio \( \beta \) as 5.66×10⁻³, which is more than the minimum value 10⁻⁶ required for the liquid micropump.

IV. EXPERIMENTAL SET-UP

The experimental set-up for testing the pump is shown in Fig. 7. The flow rate of the pump can be obtained by measuring the length traversed by the liquid column in a small I.V tube in a predetermined period of time. The pump head is determined by measuring the height difference between the liquid column and the reservoir.

De-ionized filtered water is used as the pumping medium for testing the pump. As the leakage and dead volume is still significant (due to the limitation of machining process), the prototype pump is not self-priming. A syringe is used for filling the pump with water and sucking out any gas bubbles entrapped in the pump chamber prior to testing the pump [11].

### TABLE I. MICROPUMP DESIGN AND CHARACTERISTICS

<table>
<thead>
<tr>
<th>Material of chamber</th>
<th>stainless steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of chamber</td>
<td>24 mm</td>
</tr>
<tr>
<td>Width of chamber</td>
<td>5 mm</td>
</tr>
<tr>
<td>Thickness of chamber</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Volume of the chamber</td>
<td>36 mm³</td>
</tr>
<tr>
<td>Material of Diaphragm</td>
<td>Aluminum</td>
</tr>
<tr>
<td>Diaphragm thickness</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>PZT Disc Diameter</td>
<td>15 mm</td>
</tr>
<tr>
<td>PZT Disc thickness</td>
<td>3 mm</td>
</tr>
<tr>
<td>Diffuser throat diameter</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>Diffuser exist diameter</td>
<td>1.022 mm</td>
</tr>
<tr>
<td>Length of Diffuser element</td>
<td>7 mm</td>
</tr>
<tr>
<td>Operating Voltage(switch DC)</td>
<td>400V</td>
</tr>
<tr>
<td>Frequency</td>
<td>1 KHz</td>
</tr>
<tr>
<td>Stroke volume (Vs)</td>
<td>0.204 mm³</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>5.66×10⁻³</td>
</tr>
<tr>
<td>Volume Flow</td>
<td>12.24 mlit/min</td>
</tr>
<tr>
<td>Average velocity</td>
<td>441.55 mm/sec</td>
</tr>
<tr>
<td>Angle of conical diffuser</td>
<td>10</td>
</tr>
<tr>
<td>Pressure loss coefficient</td>
<td>0.4</td>
</tr>
<tr>
<td>Diffuser loss coefficient</td>
<td>0.187</td>
</tr>
<tr>
<td>Nozzle loss coefficient</td>
<td>1</td>
</tr>
<tr>
<td>Nozzle/Diffuser efficiency</td>
<td>5.33</td>
</tr>
</tbody>
</table>

V. CONCLUSION

The design and working principle of a valve less micropump and its actuator is described. The reciprocating displacement micropump has a diaphragm which utilizes a piezoelectric stack as the actuation mechanism. Stainless steel and aluminum is used as the material for the pump housing and diaphragm respectively. Due to its relatively simple design, the micropump can be fabricated by conventional machining technology.

REFERENCES


