INVESTIGATION ON PERFORMANCE OF PVDF ACTUATED MICROPUMP WITH COMPLIANT DIAPHRAGM

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

ROOPA R

DEPARTMENT OF MECHANICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA
SURATHKAL, MANGALORE-575 025

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D E C L A R A T I O N

by the Ph.D. Research Scholar

I hereby declare that the Research Thesis entitled "**INVESTIGATION ON PERFORMANCE OF PVDF ACTUATED MICROPUMP WITH COMPLIANT DIAPHRAGM**" which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the **Degree of Doctor of Philosophy** in **Department of Mechanical Engineering** is a bonafide report of the research work carried out by me. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

Register Number: **135017ME13F07**
Name of the Research Scholar: **Roopa R**
Signature of the Research Scholar:

Department of Mechanical Engineering
National Institute of Technology Karnataka, Surathkal

Place: NITK, Surathkal

Date:

C E R T I F I C A T E

This is to certify that the Research Thesis entitled **"INVESTIGATION ON PERFORMANCE OF PVDF ACTUATED MICROPUMP WITH COMPLIANT DIAPHRAGM"** submitted by **Mrs. Roopa. R (Register Number: 135017ME13F07**) as the record of the research work carried out by her, is accepted as the Research Thesis submission in partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy.**

Dr. Navin Karanth P
Research Guide
Date:

Prof. S. M. Kulkarni
Research Guide
Date:

Chairman – DRPC
Date:

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ABSTRACT

Micropumps are promising devices which play an important role in microfluidic systems, which are widely used in biomedical fields, automobile applications, electronic cooling systems, chemical analysis, etc. Past research work has presented different types of micropump based on working principle, different actuator, valves, and different combination of micropumps. Based on the available literature, the piezoelectric actuation is extensively used for micropump. In the present work, Polyvinylidene Fluoride (PVDF) piezo polymer is used for micropump actuation.

The diaphragm is the key element of the reciprocating type of micropump. The flexible thin circular or rectangular plane diaphragms are used in most of the micropumps. Some of the general characteristics considered during diaphragm selection are stability, reliability, low hysteresis, size, weight, biocompatibility, and fabrication technique. Diaphragm with maximum deflection is required, which improves the micropump performance.

In this context, we have designed a compliant diaphragm based on compliance/flexure mechanism, in which three flexures are connected parallel to the actuating area of the diaphragm. The compliant diaphragm design is based on some of the important parameters like material, type of flexure, number of flexures, and perforations. Based on the resilience, three materials are considered for a compliant diaphragm, i.e., stainless steel, beryllium copper, and brass. The better deflection is obtained for brass material three flexure rectangle compliant diaphragm with minimum stress concentration. Further, the deflection can be improved by a decrease in the mass and stiffness of diaphragm. Therefore different perforation patterns are used in the diaphragm actuation area.

In the present work, the concept of single and bi-layer PVDF film is used to actuate the compliant diaphragms and plane diaphragm. The diaphragm deflection is improved with an increase in the PVDF film thickness, three different thickness single layer PVDF films are considered for the study. The effect of diaphragm deflection is better for bi-layer stacks (PESP configuration) with stacking done using lower thickness PVDF films of equal thickness. The analysis is carried out using COMSOL Multi-physics.

To predict the behavior of the micropump with compliant diaphragms and perforated compliant diaphragm, Simulink analytical micropump model is used. The main objective of using compliant diaphragm and perforation pattern compliant diaphragm is to improve the performance of micropump with low operating voltage.

In the present study, a new type of compliant diaphragms for micropump is designed, fabricated, and experimentally investigated. From the current work, it could be concluded that the use of flexures in diaphragm has improved the diaphragm deflection, i.e., twice that of the plane diaphragm at the same operating voltage. Further, the perforation patterns in diaphragm actuation area have given better deflection compared to the compliant diaphragm. The concept of stacking of PVDF film is done to achieve better performance of micropump. The micropump character, namely discharges and pressure difference with the plane diaphragm, compliant diaphragm, and perforation compliant diaphragm is investigated.

The discharge obtained for compliant diaphragm micropump is twice that of the plane diaphragm micropump at same operating voltage. Better discharge is achieved by using a bi-layer actuator in micropump. The discharge obtained in the plane diaphragm micropump is 14.3 ml/hr. The maximum discharge obtained in the compliant diaphragm micropump and perforated compliant diaphragm micropump is 47.3ml/hr and 49.8ml/hr at 140V respectively.

Keywords: Flexure, Compliant diaphragm, Polyvinylidene Fluoride (PVDF), Micropump, Diaphragm, Bi-layer

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ACRONYMS

ICPF	Ionic conducting polymer film
CD	Compliant diaphragm
PCD	Perforated compliant diaphragm
PD	Plane diaphragm
PDMS	Polydimethylsiloxane
PMMA	Polymethylmethacrylate
PVDF	Polyvinylidene Fluoride
PZT	Lead Zirconium Titanate
SMA	Shape memory alloy

NOMENCLATURE

A_D	Area of the diaphragm
D	Diffuse/nozzle element throat diameter
E	Young's modules
G	Shear modules
L	Length of flexure
t	Width of flexure
w	Thickness of flexure
α	Shear correction factor (i.e. $\alpha = 5/6$ for a rectangular section)
ΔP_d	Pressure difference in diffuser
ΔP_n	Pressure difference in nozzle
ρ	Density of the liquid
Q_n	Flow rates in the nozzle directions
Q_d	Flow rates in the diffuser directions
X	Central deflection of the diaphragm
k	Spring constant of the flexure
K_P	Correction factor
P	Continuous pressure

P_{atm}	Atmospheric pressure
M	Equivalent mass
K_h, K_l	Pressure loss coefficients of diffuser/nozzle
P_{out}	Micropump outlet pressure
P_{in}	Micropump inlet pressure
f	Frequency along with diaphragm deflection is considered
R	Radius of diaphragm
L_D	Diaphragm thickness
V_{in}	Applied input voltage
A_d	Cross section area of the diaphragm
F	Force on the diaphragm due to applied voltage
d_{31}	Piezoelectric strain constant for piezo actuator
tp	Thickness of piezoelectric actuator
w	Width of the flexures
L	Length of the flexures
n	Number of flexures

CHAPTER 1

INTRODUCTION

1.1 MICROFLUIDIC SYSTEM

Miniaturized pumping devices fabricated by micromachining/macro fabrication techniques are called as micropumps. Micropump is one of the primary components in microfluidic systems. Microfluidic devices are invariably necessary to transport a small amount of fluid from one region to another. Micropumps can control and deliver the mass flow rate very accurately. Microfluidic systems have numerous advantages like rapid responses, compact size, low-cost, high precision, the potential for mass fabrication, disposability, and portability compared to conventional macro-scale systems (Hsu et al. 2008). To satisfy the requirement based on the application area, different micropumps are presented during recent years. Micro-fluidic system consists of micropump, microsensor, reservoir, and necessary related circuits, as shown in Figure 1.1. Among the microfluidic components, the micropump plays an essential role because pumping is the key element of the microfluidic system.

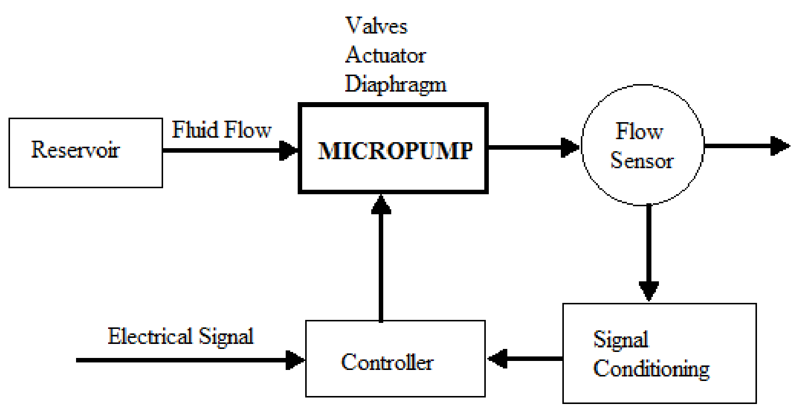


Figure 1.1 Block diagram of the microfluidic system (Nisar et al. 2008)

Micropumps are a very promising device used in the microfluidic system. Micropumps are widely used in the field of medical, biomedical applications such as injection of glucose for diabetes patients, insulin injection, blood transportation, DNA hybridization, drug delivery (Wan et al. 2001), for chemical and biological analysis, other applications are lab-on-chip, fuel cell, automobile application such as fuel cells (Ederer et al. 1997), cooling application like laptop cooling, high flux electronics cooling (Laser and Santiago 2004) (Ma et al. 2009), etc.

Micropumps have been developed over the years. Different micropumps are presented during recent years based on different working principles, actuation methods, valve type, chamber combination like serial and parallel, which have their advantages and disadvantages (Nguyen et al. 2002). The micropumps need to fulfill some specific requirements such as low power consumption for actuation, fast response, maximum flow rate, flow control, lightweight, etc. High volumetric flow rate, high resolution, low power consumption, reliability, bio-comparability are the essential requirements of the micropumps (Tsai and Sue 2007).

Micropumps are categorized into two types, mechanical and non-mechanical micropumps. Non-mechanical micropump does not involve any mechanical moving parts. Non-mechanical micropumps employ the properties of working fluid to generate the flow. Mechanical type micropumps have moving parts like check valves, membranes, or turbines for delivering a constant fluid flow in every cycle. Shoji et al. categorized the mechanical type micropump actuators into two types, i.e., external actuated micropump and integrated type actuators (Shoji and Esashi 1994). The most extensively used micropump is reciprocating/mechanical type micropump, which consists of moving parts like diaphragm and valves. The reciprocating type of micropump works on the principle of deflection of the diaphragm, which is in direct contact with working fluid. The mechanical type of micropumps requires mechanical actuators, which converts one form of energy into another form. The external actuator used in mechanical micropumps is piezoelectric actuator micropump, shape memory type actuator, pneumatic actuator, etc.

Some of the integrated actuators used in micropumps are thermo pneumatic actuators, electrostatic actuators, electromagnetic actuators, etc. There are two methods which can improve the pumping performance of mechanical type micropumps, one by magnifying the displacement, and the other is to increase the driving voltage (Wang et al. 2014).

1.1.1 Application of micropump

Now a day's MEMS technologies have been widely used in the microfluidic systems. Microfluidic system performance mainly depends on the efficiency of micropump. Different types of micropumps are designed based on their applications. Micropumps are widely used in the biomedical field such as blood transportation, insulin delivery to control the diabetic's blood sugar level, molecular separation such as DNA analysis, synthesis of nucleic acids for sequencing or synthesis, automotive industries for fuel injection, in chemical and biological sensing. Micropumps are used as electronic cooling systems like lab on chip, micro integrated circuits. Micropumps are used in automobiles for fuel injection. Table 1.1 shows some list of the researcher worked on different applications of micropump.

Table 1.1 Different applications of micropump

Author	Actuation type	Application
(Bourouina et al. 1997)	Electrostatic	Drug delivery
(Maillefer et al. 2001)	Piezoelectric	Disposable drug delivery
(Guo et al. 2003)	ICPF actuator	Bio medical
(Debesset et al. 2004)	Electroosmotic	Circular Chromatography
(Zhang and Wang 2006)	Piezo ring	Fuel delivery
(Ma et al. 2008)	Piezoelectric	Liquid cooling system
(Chiu and Liu 2009)	Electrolysis bubble actuator	Blood transportation
(Lee and Chen 2010)	Electromagnetic	Lab on chip
(Lee et al. 2013)	Capacitor actuated	Fuel cell
(Kim et al. 2012)	Electro-conjugated fluid tube	Forced liquid cooling system
(Seibel et al. 2008)	Electroosmotic	Lab on chip
(Salari et al. 2015)	Electrothermal	Lab on chip
(Ma et al. 2015)	Piezoelectric	Biomedical field

1.2 FACTORS INFLUENCING MICROPUMP PERFORMANCE

Several factors have to be considered at the design stage of micropump to optimize micropump performance. The performance of the micropump mainly depends on some input factors like actuator used, valve type, diaphragm material, and diaphragm type. The output parameter of micropump includes a maximum flow rate and back pressure. The parameter which affects the micropump performance is schematically represented in Figure 1.2.

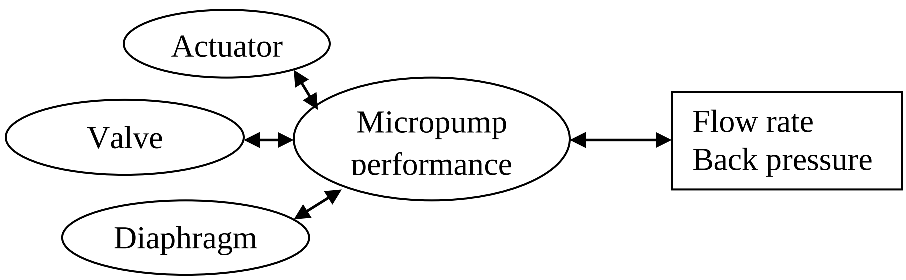


Figure 1.2 Parameters affect the micropump performance

1.2.1 Actuator

Actuators are the active parts of the micropump, which converts one form of input energy into another form. Actuators are the manageable work generating devices which come in different forms and shapes. A functional diagram of the actuator unit is shown in Figure 1.3. Actuator unit consists of a control unit, power supply, coupling mechanisms. The power unit continuously provides energy to the actuation unit. The coupling mechanism in actuator units acts as an interface between the actuator and the physical system. Pons (2005) classified the actuators based on the input energy domains, i.e., translational and rotation types. The actuator exerts force either in a linear or rotary mechanism, i.e., rack and pinion, levers, belt drives, gear drives, piston, and linkages.

Pons also classified the actuator into two types based on the working principle, i.e., translational and rotary type actuator. In the case of the translational type of actuator, the motion is always linear. Whereas in the case of the rotary type of actuator, the rotary motion is obtained from some external mechanism. Poole and booker classified actuators into different types based on the actuating effect and stimulus effects (Poole and Booker 2011). They suggested an easy and quick selection of actuator based on some criterions like actuating force, stimuli required for initiating motion, fabrication configuration with concerned technologies. Table 1.2 shows the classification of actuators based on the actuating effect and stimulus effect.

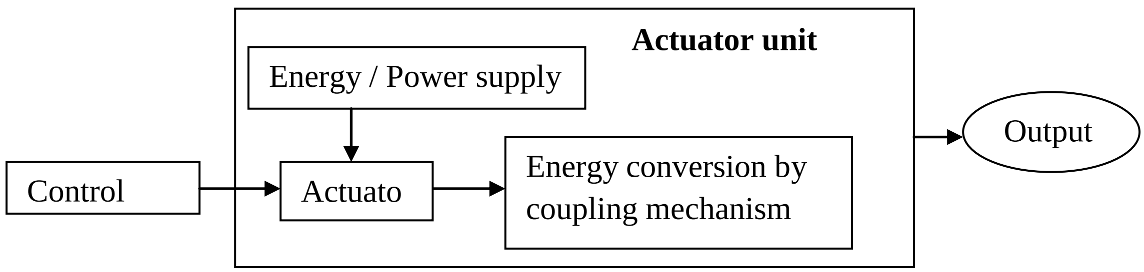


Figure 1.3 A Functional diagram of the actuator unit

Table 1.2 Classification of actuators based on actuating effect and stimulus effect

Based on actuating effect		**Based on stimulus effect**	
Type	Technology	Type	Technology
Molecular change	Shape memory alloy, **Piezoelectric**, Thermal expansion, Photostrictive, Active polymer, Electrostrictor	Electric field	**Piezoelectric**, Moving coil, Solenoid, Electrostatic, Electroheological fluids
Biological	Muscle	Chemical reaction	Active polymer muscle
Motor effect	Solenoid, Moving coil	Thermal change	Shape memory alloy, Thermal expansion
Pressurized fluid	Pneumatic, Hydraulic, Fluid mass flow	Mechanical	Hydraulic, Pneumatic, Fluid mass flow
Particle orientation change	Magnetorheological fluids, Electrorheological fluids	Magnetic field	Magnetic shape memory alloy, Magnetostrictor, Magnetorheological fluids
Electrostatic	Electrostatic	Optical change	Photostrictive

Actuators are available in different forms based on their fabrication configuration, without the addition of the discrete mechanical systems. To achieve better performance, actuators are configured into different type. Single layer, stacked (series, parallel) and dissipative damping actuators which comes under direct actuation configuration. Whereas bender, inchworm, traveling wave / peristaltic type of actuators come under indirect type of actuation method. Based on the energy supply Raab, Isermenn classified the actuators into two type's, i.e. conventional actuators and non-conventional actuators (Isermann 2005). Table 1.3 shows the different types of conventional and non-convention type of actuators. The purpose of the actuators is to provide physical motion for highly precise positioning tasks with a small stroke. Nowadays, the unconventional type actuators based on material behavior are widely used.

Table 1.3 Classification of different actuator principles (Isermann 2005)

Conventional actuators		Unconventional actuators
Fluid energy	**Electro mechanic**	**Solid state actuators**
Hydraulic actuator, Pneumatic actuator	Electro motor (AC/DC), Step motor, Linear motor, Electromagnetic	**Piezoelectric**, Electrostrictive, Electrochemical, Memory metal, Thermo bimetal, Magnetostrictive

Actuators are classified into different types based on energy sources like electrical, mechanical, chemical, and solar radiations. Some actuators are capable of producing large displacement and force, whereas some actuators with less force and displacement. Zupan specified a certain strategy for selection of actuators based on the specific applications. The actuator attributes which are considered during actuator selection are efficiency, actuator density, volumetric power, actuation stress and strain, actuator modules, stroke work, and cycle work coefficient (Zupan et al. 2002). Figure 1.4 shows the maximum power to weight ratio versus actuator efficiency (power out / power in) in which the masked character of different actuators is given. Different actuators which come under different families are considered. Actuators of one family overlap with other family members but families are widely separated.

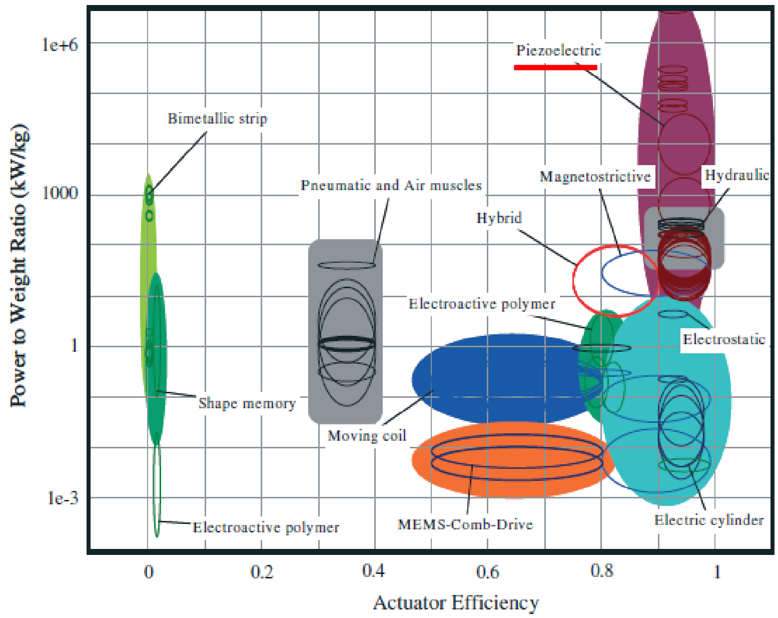


Figure 1.4 Power to weight ratio versus actuator efficiency of different actuators

It is also observed that the maximum power to weight ratio is obtained for piezoelectric and magnetostrictive actuator. Piezoelectric actuators have low weight and can be militarized easily. These features make piezo actuators most widely used in a compact system and MEMS applications. Poole and booker (2011) proposed a comparison of the varying performance of different actuator technologies based on parameters like force, frequency, and stroke. The two charts are shown in Figure 1.5, and Figure 1.6 which are developed based on the literature review in relevant research together with commercially available actuator data from suppliers. It is observed from the graph that piezoelectric actuators even though have a small stroke, exhibit high operating frequency and high force exertion compared to other actuators.

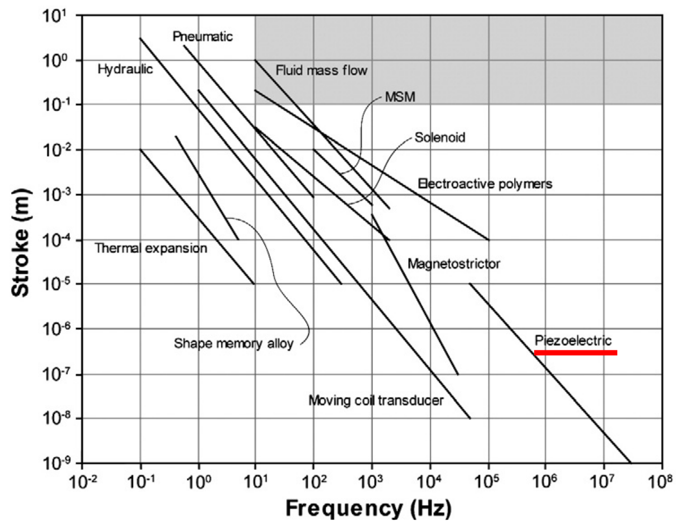


Figure 1.5 Frequency versus stroke (Poole and Booker 2011)

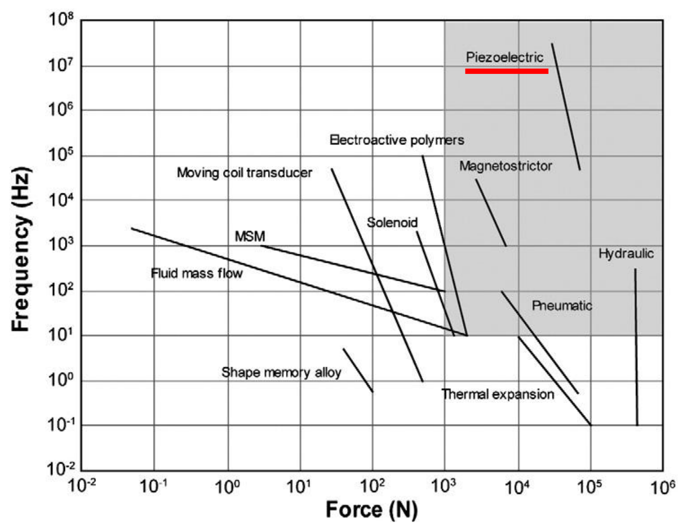


Figure 1.6 Force versus frequency (Poole and Booker 2011)

Piezoelectric actuators are widely used in micropump and MEMS applications. Furthermore details of the piezoelectric materials, working, properties, and different piezoelectric materials are explained in the below section.

1.2.1.1 Piezoelectric material

Certain material produces electricity when a mechanical load is applied and produced mechanical deformation when voltage is applied, this type of materials are called as piezoelectric materials. The development of mechanical strain when an electric field is applied to piezoelectric materials is called converse piezoelectric effect and vice versa of this is known as a direct piezoelectric effect. Naturally occurring materials like Rochelle salt, tourmaline and quartz and synthetic materials like barium titanate, PZT and PVDF exhibit piezoelectric effect.

Piezoelectric materials are available in ceramics and polymer form. Lead zirconate titanate (PZT) is a ceramic, which is more sensitive and can more easily be used for both high and low-frequency applications. The other ceramics that exhibit piezoelectric effect are leas-titanate ($PbTiO_2$) and lead zirconate ($PbZrO_3$). PZTs are more sensitive and can more easily be used for lower frequency applications. Piezoelectric ceramics can be generally loaded only in compression, as these materials typically suffer from low fracture toughness leading to asymmetric designs (Oates et al. 2004). Manufacturing of complex shapes from piezoceramics is far from cost-effectiveness. Machining quickly induces surface defects, which leads to a reduction in lifetime due to fracture (Van Den Ende et al. 2010).

The piezoelectric property in polymer and copolymers materials which exhibit piezoelectric effects are polyvinylidene fluoride (PVDF), PVDF with trifluoroethylene (TrFE) and tetrafluoroethylene (TFE) exhibit strong piezoelectric activity (Harrison and Ounaies 2002). Many synthetic piezo polymers like polypropylene, polystyrene, polymethylmethacry, semi-crystalline polyamides and amorphous polymers such as vinyl acetate have demonstrated piezoelectric properties. However, piezoelectric effect in these materials are relatively weak and sometimes unstable (Pantelis 1984).

In comparison to piezoceramics, the piezo polymers exhibit much lesser mechanical properties, as the polymer is more ductile compared to ceramics. The piezoelectric effect in semi-crystalline polymer like PVDF is known to exist at strains of up to 3% in stretching direction (Wang et al. 2006). In addition to piezoelectricity, polymers typically possess high dielectric breakdown and high operating field strength, and they can withstand much higher driving fields. Piezo polymers have low modules, lightweight, high electromechanical coupling coefficient, and ductility (Barsky et al. 1989). Piezo polymers are also stable because they can resist moisture, chemical, oxidants, and intense ultraviolet and nuclear radiations to some extents (Xu et al. 2009). Piezoelectric polymers could be considered as favorable materials for actuator applications due to their fast response, low operating voltages, and higher efficiencies of operation (Harrison and Ounaies 2002). Currently, PVDF is the commercially available piezoelectric polymer in the form of thin films of thickness ranging from 28 to 110µm. A thin layer of silver, nickel, copper or aluminum is deposited on both surfaces of the material in order to provide electrical conductivity for applying an electrical field. The features of the piezo polymer have led the researches to explore PVDF for a wide range of applications for sensors and actuators.

The material properties of PVDF and PZT are listed in mentioned in Table 1.4. Piezoelectric strain constant (d_{31}) for the piezopolymer is lower than that of the piezoceramic. Piezoelectric stress constants (g_{31}) of piezo polymer are much higher than the piezoceramics, this indicates that the piezo polymers are much better actuators than the ceramics. The specifications and details of PVDF films are given in Appendix I.

Table 1.4 Comparison between PVDF and PZT

Material properties	**PVDF (Polymer)**	**PZT (Ceramics)**
Young's Modules E (GPa)	4	53
Piezoelectric strain constant d_{31}(pC/N)	28	175
Piezoelectric stress constant g_{31} (Mv-m/N)	240	11
Relative dielectric constant (e/e_0)	13	1300
Density (Kg/m^3)	1780 (Light weight)	7500 (Heavy)
Flexibility	Good (Can be rolled)	Poor (Cannot be rolled)

Piezoelectri**c** actuation is the most popular and commonly used type of actuation for micropumps because of they of quick response, reliability, large deformation at a low operating voltage (Yang et al. 2006). The mounting procedure of the PZT disk is difficult, which requires a very well defined gluing process, an alternative screen printing and thin film deposition can be used for mounting.

PZT has been a promising candidate for these applications because of their excellent piezoelectric properties. However, PZT being a ceramic is brittle in nature, poses a problem for deposition and environmental hazardous element (lead) (Liangke Wu et al.

2014). Because of the complex mounting process, most of the silicon-based reciprocating micropump has used piezoelectric disc glued on the actuation membrane of the micropump. The piezoelectric polymer film such as polyvinylidene fluoride (PVDF) could be alternate candidates for micropump diaphragm actuation.

1.2.2 Valve

Valves are the essential elements of the micropumps which controls timing, routing and separation of the fluid within a microfluidic device. Valves are classified into two type's passive and active valves as shown in Figure 1.7. Another way to classify valves is to group them in fixed valves which have no moving element (also called as valveless) and check valves (valve with moving mechanical part). Microvalves are divided into different types based on their initial mode, i.e., normally open, normally closed and bi-stable valves. Active valve uses mechanical and non-mechanical moving parts, as well as the external system. Mechanical active valves use mechanical moving membranes which are coupled by magnetic, thermal or piezo actuation. In case of non-mechanical active valves hold movable membranes which are however actuated due to their functionalized smart materials such as phase change materials. External active valves are actuated by the aid of the external system. The closing and opening of active valves are operated using active external control. Non-mechanical active valves are relatively new and cheap compared to the traditional mechanical active valves. An external active valve uses an external system to control the valve operation. Build in valves, rotational valves, thin membrane valves actuated by external pneumatic air pressure, are some of the examples for the external active valve.

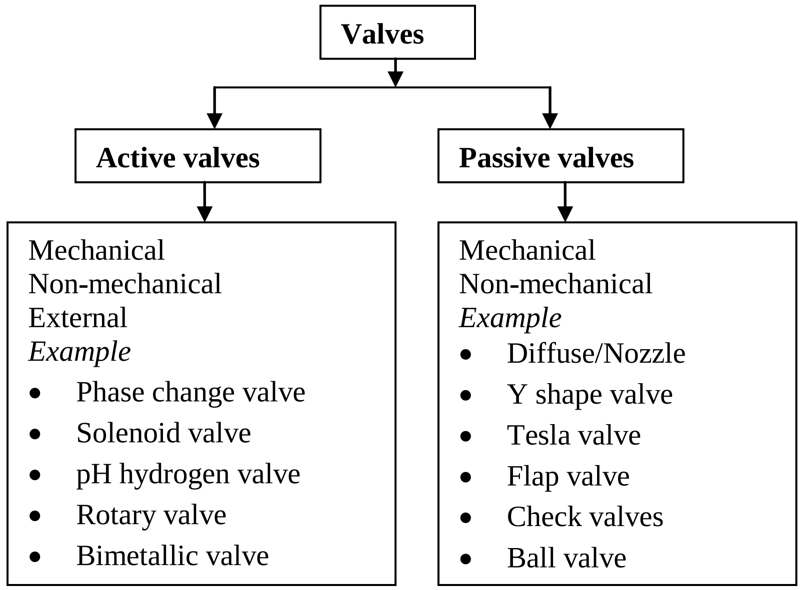


Figure 1.7 Classification of valves

Passive valves use mechanical and non-mechanical moving parts. In the passive valve micropump, the valve opening/closing action is always lagging behind the vibration of the actuator membrane. Mechanical passive valves or check valves are incorporated in the inlet and outlet of reciprocating micropumps. Mechanical moving parts in passive valves such as flaps, membranes, ball, etc. Mechanical passive valves are only open to forward pressure. The leakage in the mechanical passive check valve is more, which reduces the back pressure and flow rate of the micropump. Passive non-mechanical valves which have no mechanical moving parts. Diffuser/nozzle elements are widely used in inlet and outlet of the reciprocating micropump. In non-mechanical passive valves, the fluid flow rate is high and the leakage rate is less and is driven by the harmonic oscillation of diaphragm.

In the case of the active valve, type pump the fluid flow only in one direction. Due to external and internal pressure created inside the micropump chamber the cantilever valve turn off and on, which results in fluid movement. Active valve type micropumps are very fragile and costly due to their design and expensive fabrication process. Wear, fatigue and valve blocking are critical issues in active valve type micropumps. The non-mechanical passive valve is most promising flow controller which does not have any moving parts. Nonmechanical passive valves are also called as no moving parts (NMP) valve, i.e., Y shape valve, tesla valves, diffuser/nozzle valves. R Zengerle et al. (1992) presented an electrostatic micropump which consists of two passive check valves, the flap which is used is of the size $1 \times 1 mm^3$. Flap check valves are necessary for a reciprocating pump to indicate the fluid flow from input to output. Later Zengerle et al. (1995) designed a bidirectional silicon micropump with passive check valves. Electrostatic actuation was used to actuate passive check valves and diaphragm.

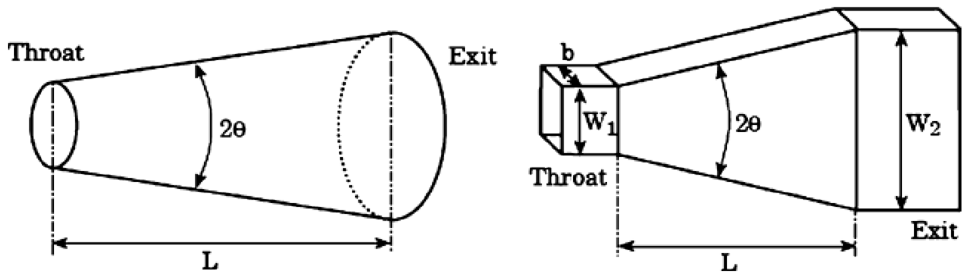
Koch et al. (1998) designed cantilever valves for a silicon micropump. The valve consists of a thin flap which bends into open state under low-pressure application on the free side, which leads to fluid flow. The two sides of the valve were fabricated by anisotropic KOH bulk etching, and the assembly was done by fusion bonding. C Yamahata (2005) presented a micropump with a ball valve in glass which is actuated by an external electromagnet. Polymer membrane is used with an embedded permanent magnet which gives rise to a large actuation stroke, bubble-tolerant, and self-priming. However, practical self-priming glass micropump capable of delivering high backpressure has not been reported so far. The powder blasting technique was used to fabricate the micropump.

T Pan (2005) designed a low-cost micropump made of PDMS material which consists of two ball valves, of microfluidic applications. Two functional PDMS layers were used, one consists of ball valves and actuating chamber, while the other consists of covering the chamber and a miniature permanent magnet for the actuation of the pump. The use of ball valves in micropumps leads to allow the liquid flow in one direction and blocks the liquid flow in the opposite direction. The steel ball used in these valves, the surface of the ball is smooth and the tube is tapered which provides little resistance to the movement of the ball inside the valve.

Ahn et al. (1995) presented a rotary valve micropump for the first time. The fast movement of the blades in the rotary valves leads to the fluid flow in micropumps. Polyimide is used for the fabrication of these valves, by a photolithography process. The rotary valve micropump is a mechanical type of pump. The pump with rotary valve can pump highly viscous fluids. Electromagnetic motor or integrated motors are used for the actuation of this type of pumps. Doepper et al. (1997) designed a two gear wheels valve for micropump. The gear wheels were fabricated by LIGA process, and the material used for the gear is an iron-nickel alloy.

Several critical properties which has to be considered while designing the valves are pressure drop, backward flow, switching speed of the valve have to be kept under control. Moreover, in case of valve type micropump the wear and fatigue are the critical issues. There may be a risk of valve blocking because of small particle, which degrades the micropump performance. This limits the use of valve type micropump. The main advantage of using valveless micropump is relatively simple in construction compared to valve type micropump. Due to the open valve structure, the pumping of liquid is easier in this type of micropump.

Diffuser/nozzle valves are most commonly used in reciprocating micropump because they are free from wear, fatigue, valve blocking, and ease fabrication. Diffuse nozzle elements are used as flow directing elements in valueless micropumps. The diffuser is the key element in reciprocating type micropump (Olsson 1998). In the diffuser, there is a gradual increase in the cross-section by a certain angle to raise the static pressure. Whereas in the case of nozzle element, there is a converging in the cross-section area. The maximum pressure is obtained for small opening angle (Olsson 1998). The diffuser elements are of two types conical diffuser, and flat type diffuser is shown in Figure 1.8 (a) and (b).



(a) (b)

Figure 1.8 Diffuser element (a) Conical diffuser (b) Flat diffuser (White 2010)

In general, the performances of the flat walled and conical diffuser are same and it decreases with blockage. The flat walled diffuser will give better performance when the length of the diffuser is limited, whereas in the case of conical diffuser better performance is achieved at a longer length. The parameters which are considered during the diffuser selection are aspect ratio, diverging angle and pressure recovery coefficient C_p. The flat walled diffuser may require an additional parameter to relate its cross section. Both the conical and flat type diffuser gives maximum performance at 8 to 9 percentage blockage. Figure 1.9 shows the stability map of the conical diffuser, which is divided into four basic regions. The region below the line ‘a’ represents the viscous study flow, no separation and moderately good performance the region between the line ‘aa’ and ‘bb’ is a transitory stall pattern with the unsteady flow. The region between ‘bb’ and ‘cc’ is a steady bi-stable stall from one wall only. The region above the line ‘cc’ is jet flow, in this region the wall separation is so gross and pervasive that the mainstream ignores the wall and passes on through at nearly constant area. The valve performance is extremely poor in this region. The best performance is obtained at higher C_p valve. The diffuser parameters like area ratio, divergence angle and slenderness can be selected based on the stability map.

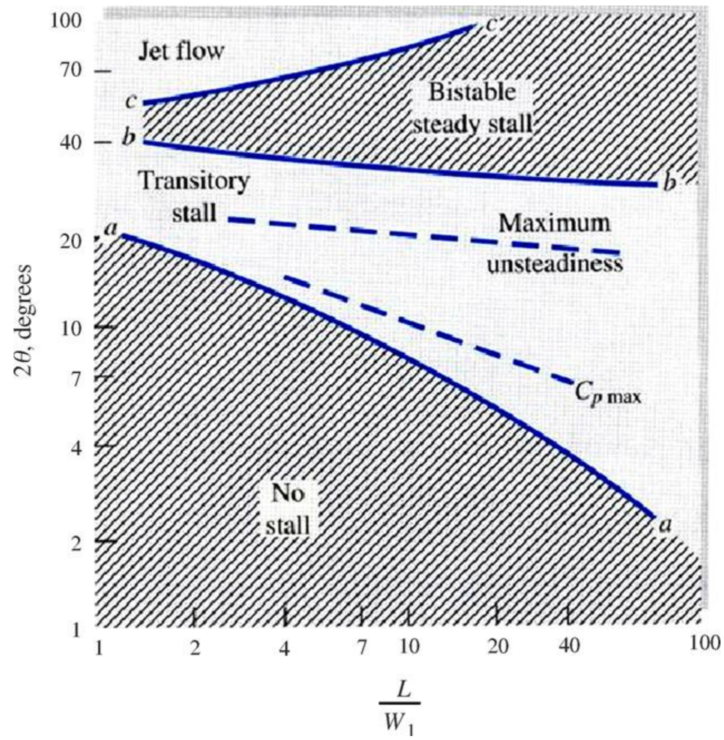


Figure 1.9 Stability map of the diffuser (White 2010)

Diffuser/nozzle valves are called as no moving parts valves. The working principle of diffuser/nozzle micropump is very simple. The diffuser element in valveless micropump is used as flow direction elements. The diffuser element will have an increased cross-section than the nozzle element less cross-section. The diffuser and nozzle, element decides the performance of the micropump. When the electric field is applied to the diaphragm of the pump, the pump chamber expands and contract this leads to the net flow of liquid from the inlet to the outlet through diffuser/nozzle. Stemme et al. (1993) presented a first valveless micropump using diffuser/nozzle elements as flow directing elements. Diffuser nozzle elements have been used in place of check valves, which are called as flow directing elements. Cylindrical brass body prototype was fabricated and tested with two different diffuser/nozzle geometries. The flow rate obtained by this micropump is 11ml/min at 100mbar outlet pressure for water and it was also able to pump air. Figure 1.10 Illustrate the working of valveless diffuser/nozzle micropump. During expansion mode, the volume of the pump chamber will increase (a). In

Contraction mode volume of the pump chamber will decrease (b). The arrow represents the flow of fluid.

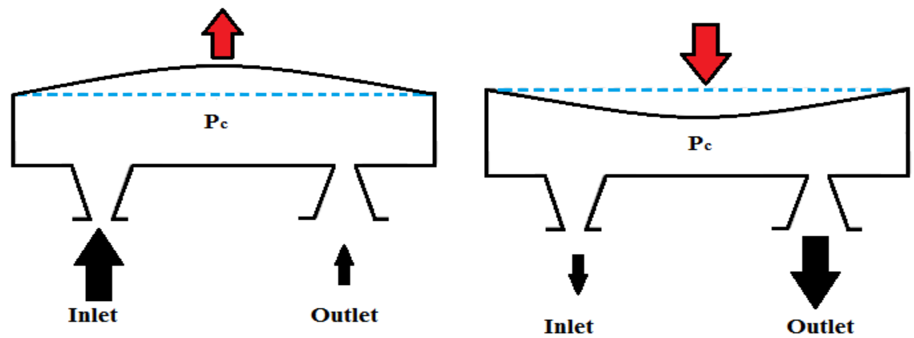


Figure 1.10 Working of valveless diffuse micropump (a) Expansion mode (b) Contraction mode

Later Olsson et al. (1995) (1996) designed a set-up of two valveless micropumps to reduce inlet and outlet pressure pulses and to improve the micropump flow rate. Foster et al. (1995)designed a planar micropump using complicated flow rectifying tesla valve. The fabrication process of tesla valves is difficult compared to diffuser/nozzle valves and tesla valves were not suitable to use with all type of liquids.

In case of the flat-walled diffuser, the length of the diffuser will be 10-80% shorter than that of the conical valves under the same performance flow. Yih-Lin Cheng proposed three-dimensional valveless micropumps with a flat-walled diffuser element (Cheng and Lin 2007).

X N Jiang (1998) proposed the flow model of valveless micropump with diffuser/nozzle elements. The cone angle of diffuser/nozzle, elements is 5^0, 7.5^0 ,10^0. Silicon micropump was fabricated. The main parameters such as the length of the valve and cone angles play an effect on the flow rate of the micropump. The Reynolds number in the microvalve is also an important factor in the case of valveless micropump. The flow rate is 28µl/min under the input power of 50 mW and 500 Hz.

The performance of diffuser/nozzle micropump with different angles was studied by Olsson (1995). Later Jiang et al. (1998) proposed the flow model of valveless micropump with diffuser/nozzle elements. The diffuser/nozzle components are extensively used in piezo-actuated micropump because of its advantages like easy fabrication, no clogging. Table 1.5 shows the list of researchers contributed to diffuser/nozzle micropump.

Table 1.5 List of researchers contributed to diffuser/nozzle micropump with their dimensions and performances

Author	Actuation	Size (mm)	Flow rate (µl/min)	Voltage (V)	Pressure (kPa)
(Stemme and Stemme 1993)	Piezoelectric	2500 mm^3	16000	100Hz	19
(Olsson et al. 1995)	Piezoelectric	830 mm^3	230	1318Hz	16
(Olsson et al. 1997)	Piezoelectric	730mm^3	8000	-	5
(Jiang et al. 1998)	Piezoelectric	-	28	4.8, 500Hz	1
(Jeong and Yang 2000a)	Piezoelectric	-	14	8, 4Hz	0
(Schabmueller et al. 2002)	Piezoelectric	144mm^3	1500	190V, 2400Hz	1
(Guo et al. 2003)	Bimetallic SMA	300mm^3	37.8	1.5,22Hz	-
(Shuxiang and Kinji 2004)	ICPF	1184 mm^3	700	6	-
(Yamahata et al. 2005b)	Electromagnetic	-	400	5, 50 Hz	0.02
(Kim et al. 2005)	Thermopneumatic	-	0.078	55	6
(Geipel et al. 2007)	Piezoelectric	330 mm^3	1800	27.8 Hz	60
(Geipel et al. 2008)	Piezoelectric	-	4.5	100	10
(Tayyaba et al. 2012)	Piezoelectric	-	501	105, 200 Hz	-
(Wei et al. 2014)	Piezoelectric	-	67	100, 600 kHz	-

1.2.3 Diaphragm

The diaphragm is a thin membrane used in the reciprocating type of micropump. In MEMS devices diaphragms are mainly used in sensors and actuators applications for high precision and good effective response. Diaphragm used in micropump can be of different shapes such as square, circular or rectangular shape. The different diaphragms materials which are used are glass, plastic, polyimide, silicon rubber, elastomers, PDMS, metals like brass, titanium, etc. Most of the micropumps reported are composed of silicon, glass and polymer materials. Polymer-based diaphragm is in high demand because of the low manufacturing cost, biocompatibility, simple and fast manufacturing, excellent physical and mechanical properties (Nisar et al. 2008). Biocompatible diaphragms are needed for biomedical applications.

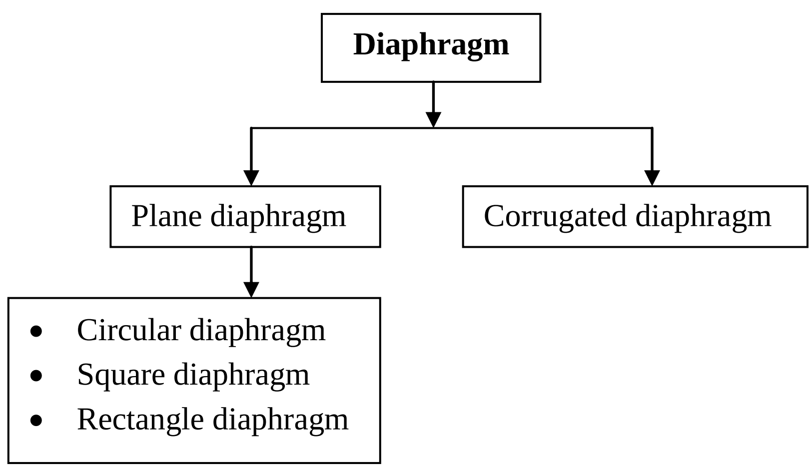


Figure 1.11 Different types of diaphragm used in micropump

Figure 1.11 shows the different type of diaphragms used in micropump. The main feature of the diaphragm is reliability, excellent stability, low creep and hysteresis, and good dynamic response. The characteristics which are considered during diaphragm design are geometry, weight, the effect of environmental conditions, working temperature range, frequency response requirements, effects of shocks, and vibration. Various design techniques can be followed to design the diaphragm with low-stress concentration and high deflection (Dissanayake et al. 2008). The residual stress in the plane diaphragm is more, so the deflection obtained from the plane diaphragm is less. Residual stress in the plane diaphragm can be reduced by using corrugation which increases the diaphragm deflection (Jeong and Yang 2000). The diaphragm deflection can be increased by releasing the stiffness and stress in the diaphragm. In addition, the operating voltage and mass of micropump diaphragm remain the important factor that determines the feasibility of the device. In most of the micropumps developed by earlier researchers have used the plane diaphragm and corrugated diaphragms.

The diaphragm displacements play a crucial role in determining the overall performance of the micropump. Circular diaphragms are widely used in MEMS, micropumps, micro motors and acoustic devices for a variety of actuation and sensing requirements (Deshpande and Saggere 2007). Anurekhasharma et al. (2008) showed the simple method for calculation of pull-in voltage for the square diaphragm, which can be used in MEMS applications. As the deflection of square diaphragm is less compared to circular diaphragms, most of the micropumps have used circular diaphragms.

Table 1.6 List of different diaphragm materials used in micropump

Author and year	Diaphragm material
(Stemme and Stemme 1993)	Brass
(Chan Jeong and Sik Yang 2000)	P+ Silicon
(Sim et al. 2003)	Silicon rubber
(Sim et al. 2005)	Parylene
(Yang et al. 2006)	Stainless steel
(Ma et al. 2008)	PDMS
(Lee and Chen 2010)	PDMS
(Ma et al. 2011)	Brass
(Sung et al. 2012)	Polyimide
(K. S. Lee et al. 2013)	Metalized polyamide
(Ma et al. 2015)	Brass

Use of corrugation in the diaphragm is another technique to realize the residual stress in the diaphragm and to get a maximum deflection. Most of the micropumps have used the plane diaphragm and corrugated diaphragms, which are fabricated using micromachining and bonding technique, which are not cost effective. From this point of view, it is very important to design a flexible diaphragm with less stiffness and high deflection, which can be fabricated easily. List of different types of diaphragm materials used in micropump by researchers is shown in Table 1.6.

1.3 CLASSIFICATION OF MICROPUMPS

Micropumps are generally classified into two basic categories: mechanical micropump (Reciprocating) and non-mechanical micropump (Continuous flow) are shown in Figure 1.12. Micropumps are further divided into sub-categories based on the actuation principle, diaphragm type, valves, fabrication techniques and fluid used. The selection criteria of micropump working principle depend on the suitable application.

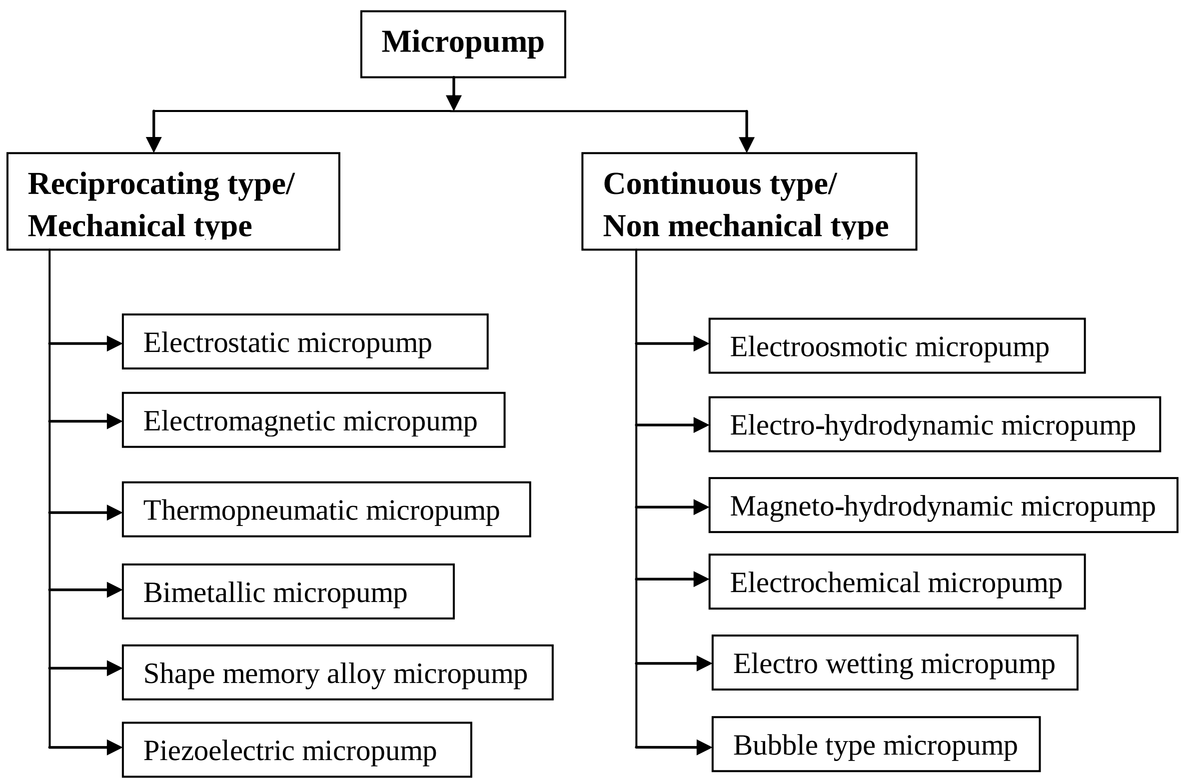


Figure 1.12 Classification of micropump

The function of the actuator in micropump is to transfer the input energy (i.e., Electrical, thermal, magnetic) into output work (i.e., Mechanical). Selection of actuator depends on the specific requirements of the applications. The diaphragm actuation and fluid flow are always coupled in micropumps. Micropump performance also depends on the type of the actuator and operating parameters of the actuators, such as driving voltages and frequency.

1.3.1 Reciprocating micropumps

Reciprocating micropump uses the oscillatory movement of mechanical parts to transfer mechanical energy into fluid movements. The gas or liquid from fluids in these micropumps is delivered in a series discrete volume, which makes up a pulsating flow. Classical representatives of the reciprocating type of micropump are piston type micropumps, diaphragm pumps, and peristaltic micropumps. The majority of micropumps found today are following one of these concepts. Reciprocating micropump also called as a displacement pump which uses the oscillatory movement of the diaphragm in most designs and check valves in few designs. Figure 1.13 shows the reciprocating type of micropump. The oscillating movement of diaphragm will transfer the mechanical energy into fluid movement in micropump (Woias 2001). This type of micropumps generally consists of a pumping chamber which is closed by a flexible diaphragm. The oscillatory movement of the diaphragm can be achieved by different actuating principles. The movement of the diaphragm generates a two-phase cycle, i.e. supply phase and pump phase. The reciprocating micropump operates in a periodic manner to produce the output flow.

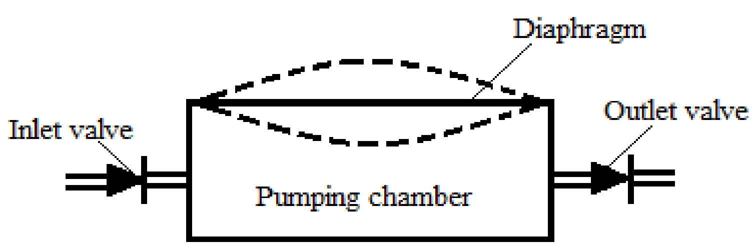


Figure 1.13 Reciprocating type of micropump

Reciprocating type of micropumps generally provides high flow rate compared to the continuous type of micropumps and operation principle is very simple. Reciprocating type of micropumps provides better flow rate so this type of pumps is used in most of the applications. This type of micropumps is governed by the actuation principle, diaphragm designs, diaphragm materials, valve type, operating parameters, and different micropump combinations. Different types of reciprocating micropumps are elaborately discussed below.

1.3.1.1 Electrostatic micropump

Electrostatic force is defined as the electrical force of repulsion or attraction induced by an electrical field. Electrostatic actuators are extremely fast response, operates at higher frequency, the electrostatic actuators work with very low power consumption. Zengerle used electrostatic actuation in micropump for the first time. The schematic of electrostatic actuated micropump is shown in Figure 1.14 (Zengerle et al. 1992). The electrostatic actuated micropump consists of a counter electrode in a capacitor like configuration and diaphragm. On the application of voltage, the capacitor electrode causes electrostatic attraction of diaphragm, which entirely comes in contact with the counter electrode. Once the voltage is discharged, the diaphragm returns to its rest position. Bidirectional pumping takes place in this type of micropump at high operating frequencies because of the time delay occurring between valve switching and diaphragm movement (Zengerle et al. 1995). The response time is fast and good reliability in electrostatic actuators and the major disadvantage of electrostatic actuated micropumps are complex structure and very small stroke. At higher actuating voltage there may be dielectric breakdown inside the capacitor. Degradation of actuator performance was frequently found in long term operation. Table 1.7 shows the list of the contribution of earlier research to electrostatic actuated micropumps.

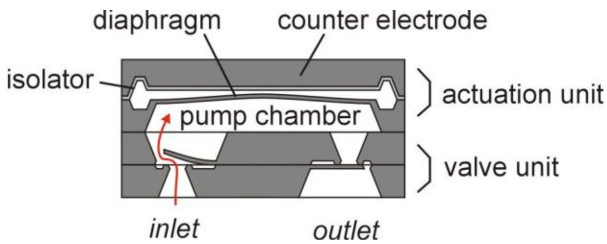


Figure 1.14 Schematic of electrostatic actuation micropump (Zengerle et al. 1995)

Table 1.7 Contribution of earlier researchers to electrostatic actuated micropumps

Author	**Size (mm)**	**Voltage (V)**	**Flow rate (µl/min)**	**Pressure (kPa)**
(Zengerle et al. 1992)	98mm^3	170, 25Hz	70	2.5
(Zengerle et al. 1995)	98mm^3	200, 300Hz	160	29
(Cabuz et al. n.d.) 2001	-	160, 30Hz	30	20
(MacHauf et al. 2005)	125mm^3	50, 1830Hz	1	-

1.3.1.2 Electromagnetic micropump

Electromagnetic actuators work on the external magnetic field, and it generally requires the permanent magnet to generate a sufficient force for the actuation. A typical magnetically actuated micropump consists of drive coils, permanent magnet, chamber with inlet and outlet valves, and flexible membrane/diaphragm. Figure 1.15 illustrates the schematic of magnetically actuated micropump. Set of coils or magnet is attached to the membrane as the current is driven through the coils the resulting magnetic field creates an attraction or repulsion between magnet and coil. The major advantage of electromagnetic actuation over other types of actuation is the large deflection capabilities. Electromagnetic actuation does not benefit from scaling down in size because electrostatic force reduces by cube of scaling factor. Only a few magnetic materials can be micromachined easily, therefore the microfabrication of this actuator is limited. The electric current requirement for driving the actuator is high therefore problems due to thermal effect are more in these micropumps. Table 1.8 shows the contribution of earlier research to electromagnetic actuated micropumps.

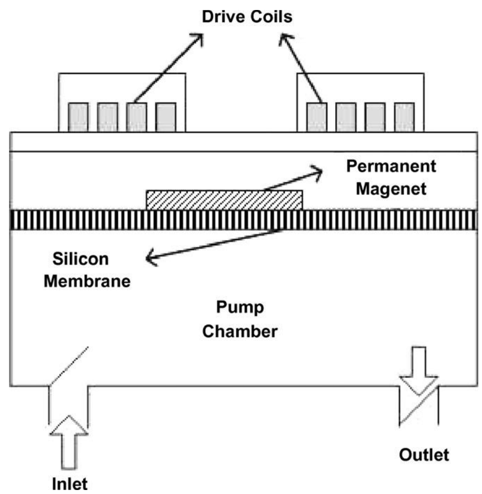


Figure 1.15 Schematic of magnetically actuated micropump (Nisar et al. 2008)

Table 1.8 Contribution of earlier researchers to electromagnetic actuated micropumps

Author	**Size (mm)**	**Flow rate (μl/min)**	**Pressure (kPa)**
(Santra et al. 2002)	3532 mm^3	260	0.6
(Pan et al. 2005)	600mm^3	260	3.6
(Yamahata et al. 2004)	4752mm^3	1000	2.5
(Yamahata et al. 2005c)	-	400	0.02
(Zhou and Amirouche 2011)	-	319.6	0.950

1.3.1.3 Thermopneumatic micropump

In a thermopneumatic actuator volume expansion of fluid is used for actuation. The fluid may be a liquid that turns into a gas or simply a gas that expands upon heating. Thermopneumatic actuator generates large pressure and relatively large stroke. Thermopneumatic actuators require high thermal energy for the operation and consume a lot of electrical power. Figure 1.16 shows the schematic of thermopneumatic actuated micropump designed by Van de Pol (1990). This type of micropump uses an air-filled chamber on the top of the micropump diaphragm that incorporates a heater resistor that is attached to the micropump diaphragm. The air enclosed inside the chamber will expand on heating air, which causes the downward motion of the diaphragm, comes to its original position on cooling. High temperature requirement and time taking for the cooling process will limits the actuation frequency is the main drawback of this type of actuators. Table 1.9 Contribution of earlier research to some thermopneumatic actuated micropumps.

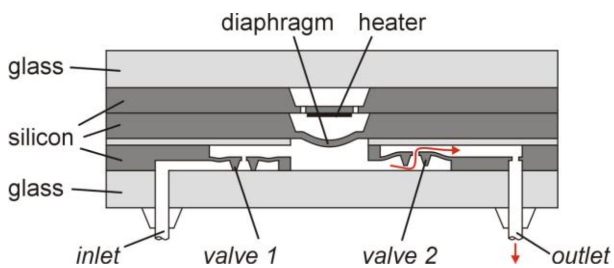


Figure 1.16 Schematic of thermopneumatic actuator micropump (Van de Pol et al. 1990)

Table 1.9 Contribution of earlier researchers to thermopneumatic actuated micropumps

Author	**Size (mm)**	**Voltage (V)**	**Flow rate (µl/min)**	**Pressure (kPa)**
(Van de Pol et al. 1990)	3000mm^3	60, 1Hz	34	5
(Chan Jeong and Sik Yang 2000)	-	8,4Hz	14	0
(Zimmermann et al. 2004)	-	10Hz	9	16
(Huang et al. 2006)	105.3mm^3	20V	3.3	-

1.3.1.4 Bimetallic micropump

Bimetallic actuators consist of two materials with different coefficient of thermal expansion are combined together and change in the temperature will lead to contract or expand the beam. When different materials are bonded together and subjected to the temperature variation, the thermal stresses are induced, which leads to the actuation. Large deflections are only achievable at high-temperature changes, but they are not suitable to operate at high frequencies. The deflection of diaphragm achieved is less because the thermal expansion coefficient of the materials involved is also less. Figure 1.17 shows the schematic of bimetallic actuated micropump. It consists of a bimetallic actuator which is attached to the heater, pump chamber, and inlet-outlet valve. This limits the use of such actuators in micropumps. Different degree of deformation is exhibited during heating of diaphragm material which is made up of bimetals. Table 1.10 shows the contribution of earlier researchers to bimetallic actuated micropumps.

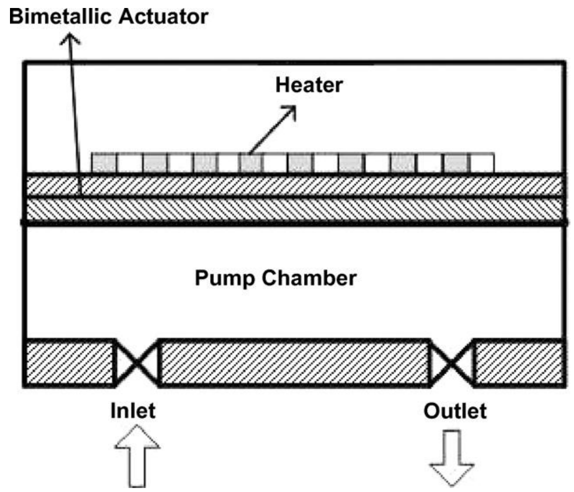


Figure 1.17 Schematic of bimetallic actuator micropump (Nisar et al. 2008)

Table 1.10 Contribution of earlier researchers to bimetallic actuated micropumps

Author	**Size (mm)**	**Voltage (V)**	**Flow rate (µl/min)**	**Pressure (kPa)**
(Zhan et al. 1996)	36mm^3	55, 0.5Hz	45	12
(Yue et al. 1996)	6.3mm^3	0.9Hz	43	-

1.3.1.5 Shape memory alloy (SMA) micropump

Shape memory alloys are capable of restoring its original shape right after the heating and cooling cycle. SAM works on the principle of phase transformation between the two solid phases. These two phase changes are called as martensite phase in low temperature and austenite phase at high temperature. The phase transition results in mechanical deformation and that are used for the actuation of micropump. The shape memory alloy commonly used, are Au/Cu, In/Ti and Ni/Ti. Schematic of shape memory alloy micropump is shown in Figure 1.18. For SAM actuator the power consumption required is high, and the response time is very slow. SMA actuated micropumps suffers from a low flow rate and insufficient bio-compatibility compared to other micropumps. Table

1.11 shows the contribution of earlier researchers to Shape Memory Alloy actuated micropumps.

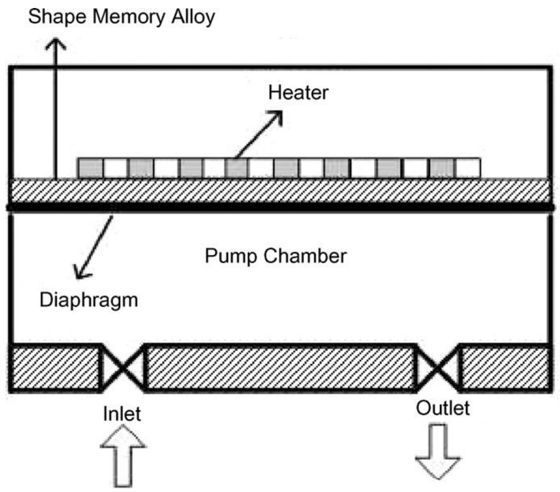


Figure 1.18 Schematic of shape memory alloy actuated micropump (Nisar et al. 2008)

Table 1.11 Contribution of earlier researchers to SMA actuated micropumps

Author	**Size (mm)**	**Voltage (V)**	**Flow rate (µl/min)**	**Pressure (kPa)**
(Benard et al. 1998)	-	6	49	4.23
(Xu et al. 1999)	$54mm^3$	-	340	100
(Guo et al. 2008)	-	6	400	-

1.3.1.6 Piezoelectric micropump

Piezoelectri**c** actuation is the most popular and commonly used earliest mechanism type of actuation for micropumps. Because they normally have high output force and short response time. In the case of piezoelectric actuation is operated at relatively high frequencies, but the induced voltage has to be high up to a certain level. The piezoelectric materials such as PZT, PVDF, and polymer-metal composites are used for the actuation of micropump. Figure 1.19 shows the schematic of piezoelectric micropump. The piezoelectric micropump consists of the piezo actuator, diaphragm which may be glass, metal or elastomer and inlet-outlet valves. Table.1.12 shows performance parameters of some piezoelectric actuated micropumps.

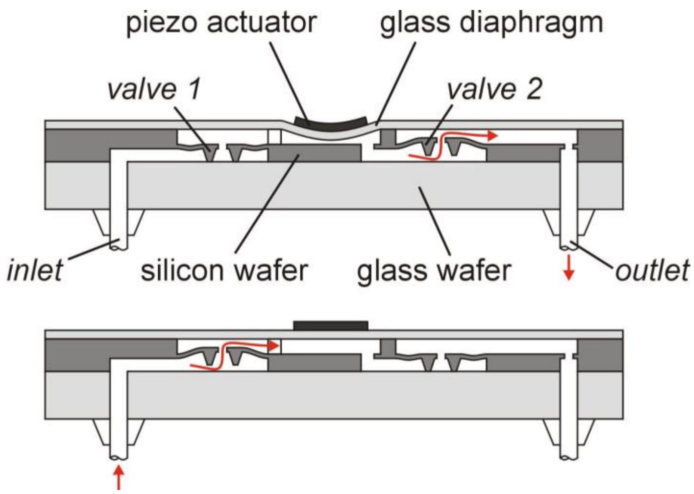


Figure 1.19 Schematic of piezoelectric actuated micropump (Van Lintel et al. 1988)

Table 1.12 Contribution of earlier researchers to piezoelectric actuated micropumps

Author	**Size (mm)**	**Voltage (V)**	**Flow rate (µl/min)**	**Pressure (kPa)**
(Van Lintel et al. 1988)	4100mm^3	125, 0.1Hz	0.6	24
(Stemme and Stemme 1993)	2500mm^3	20, 110HZ	4400	21
(Koch et al. 1998)	-	600, 200Hz	0.12	1.8
(Schabmueller et al. 2002)	122.4mm^3	190, 2400Hz	1500	1
(Kan et al. 2005)	-	50, 800Hz	3500	23
(Feng and Kim 2005)	160	80, 60K Hz	3.2	0.12
(Geipel et al. 2007)	-	100, 1Hz	4.5	10
(Ma et al. 2006)	2240mm^3	67.2, 208Hz	1800	208
(Doll et al. 2006)	330mm^3	- , 27.8Hz	1800	60
(Hsu et al. 2008b)	-	140, 450Hz	50.2	1.8
(Suzuki et al. 2007)	-	100, 87Hz	336	2.4
(Liu et al. 2011)	-	3 Hz	260	10
(Juliana et al. 2012)	-	16, 673Hz	4980	-

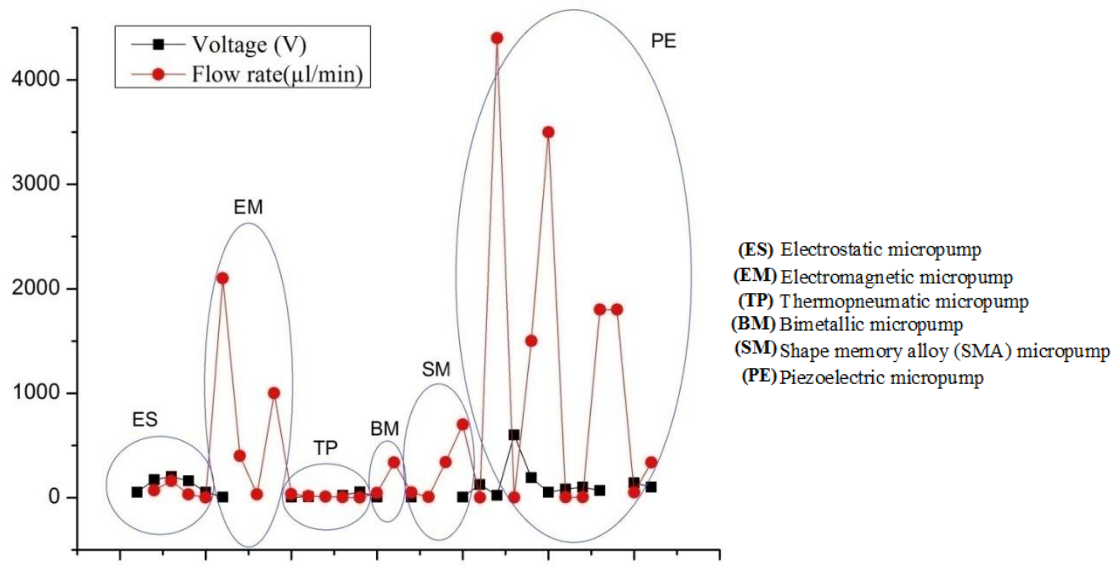


Figure 1.20 Comparison of flow rate and operating voltages in different type of mechanical type of micropumps

The important factors which are considered for selection of the reciprocating type of micropump are flow rate and voltage. Voltage is an important parameter of the micropump which determines the electrical and other components for micropump operation. Figure 1.20 shows the comparison of flow rate and operating voltage of different type of reciprocating micropumps. It can be observed that the maximum flow rate is obtained for piezoelectric micropump and electromagnetic micropump at lower operating voltage.

1.3.2 Continuous flow micropumps

Micropumps which directly transfer the non-mechanical energy into a continuous fluid movement are called continuous flow micropumps (Woias et al., 2001). Mechanical moving parts are not required in continuous flow micropumps. These types of micropumps do not need physical actuators. Several devices with different forms of primary energy have been developed, reaching from electrohydrodynamic to electroosmotic, magnetohydrodynamic and ultrasonic to electrochemical displacement micropumps. The design principles of these micropumps are very different, depending on the actuation principle. Continuous flow micropumps provide a much steadier flow rate than reciprocating micropumps, but they are not suitable for handling high-viscosity liquids and higher flow rate micropumps. Moreover, the actuation mechanisms are such that they interfere with the pumping liquid. Different types of continuous flow micropumps are elaborately discussed below.

1.3.2.1 Electroosmotic micropump

Electroosmosis also called the electrokinetic phenomenon, which can be used to pump electrolyte solutions. In electroosmosis, an ionic solution moves relative to stationary charged surfaces when an electric field is applied externally. When an ionic solution comes in contact with solid surfaces, an instantaneous electrical charge is acquired by the solid surfaces. When an external electric field is applied along the length of the channel, a thin layer of cation-rich fluid adjacent to the solid surfaces start moving towards the cathode. This boundary layer like motion eventually sets the bulk liquid into motion through viscous interaction. Figure 1.21 shows the schematic of electroosmotic flow micropump. Fused silica is commonly used in microchannel manufacturing because negatively charged surface attracts the positively charged ions of the solutions. The working principle of electroosmotic micropumps simple and can be easily controlled by switching the external electric field. The electroosmotic micropumps have advantages like it does not involve any moving parts and valves. The disadvantage of electroosmotic micropump is an electrically conductive solution and high power consumption. Table 1.13 Contribution of earlier researchers to electroosmotic actuated micropumps

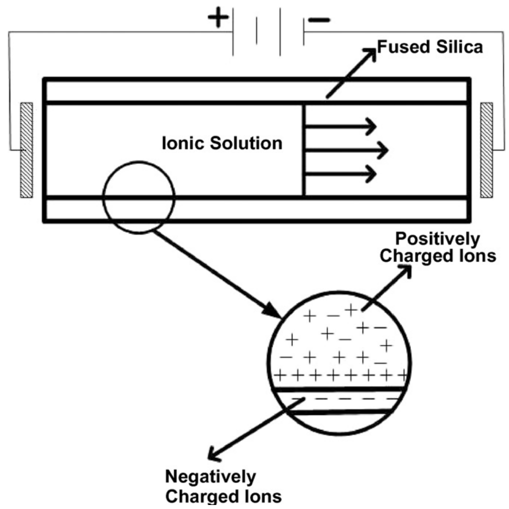


Figure 1.21 Schematic of electroosmotic flow in micropump (Nisar et al. 2008)

Table 1.13 Contribution of earlier researchers to electroosmotic actuated micropumps

Author	Size (mm)	Voltage (V)	Flow rate (µl/min)	Pressure (kPa)
(Zeng et al. 2001)	-	2k	3.6	2026.5
(Chen and Santiago 2002)	-	1k	15	33
(Takemori et al. 2005)	-	3k	0.47	72
(Wang et al. 2006a)	-	6k	2.9	304

1.3.2.2 Electrohydrodynamic micropump

In electro hydrodynamic actuated micropump the transduction of electrical to mechanical energy is electric field acting on induced charges in the fluid. The fluid flow in electrohydrodynamic micropump is controlled by the interaction of electric field acting on induced charges in a fluid. Fluids which are of low conductivity and dielectric in nature are used in EHD micropumps. In EHD micropumps, the two permeable electrodes will be in direct contact with the working fluid. From one or both electrodes, ions are injected into the working fluid by electrochemical reaction. There is a fluid flow motion between the emitter and the collector due to the pressure gradient developed between the electrodes. EHD micropump consists of dielectric fluid, emitter, collector, and input-output. Schematic of electrohydrodynamic micropump is shown in Figure 1.22. The

Contribution of earlier researchers to electrohydrodynamic micropump is listed in Table 1.14.

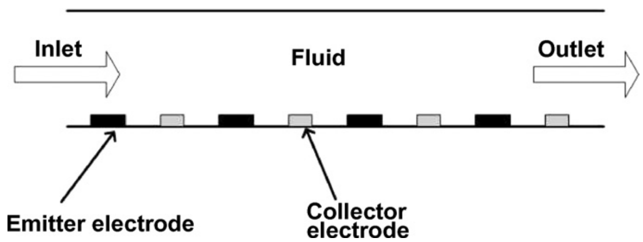


Figure 1.22 Schematic of electrohydrodynamic micropump (Nisar et al. 2008)

Table 1.14 Contribution of earlier researchers to electrohydrodynamic micropump

Author	**Size (mm)**	**Voltage (V)**	**Flow rate (µl/min)**	**Pressure (kPa)**
(Richter and Sandmaier 1990)	3mm×3mm	600	14000	0.43
(Fuhr et al. 1992)	-	40	2	-
(Darabi et al. 2002)	638.4mm^3	250	-	0.78

1.3.2.3 Magnetohydrodynamic micropump

Magnetohydrodynamic micropumps drive fluid flow in conductive liquids which are subjected to perpendicular applied electric and magnetic fields across the microchannels. The magnetohydrodynamic theory is based on the interaction of the electrically conductive fluid with a magnetic field. The structure of magnetohydrodynamic micropump is relatively simple with microchannels, two insulator walls bounded by electrodes and a permanent magnet for generating the magnetic field. The schematic of the magnetohydrodynamic micropump is shown in Figure 1.23. Contribution of earlier researchers to electro hydrodynamics micropump is shown in Table 1.15.

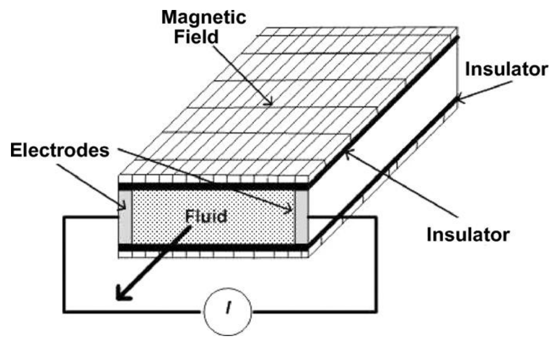


Figure 1.23 Schematic of magnetohydrodynamic micropump (Nisar et al. 2008)

Table 1.15 Contribution of earlier researchers to magnetohydrodynamic micropump

Author	Size (mm)	Voltage (V)	Flow rate (µl/min)	Pressure (kPa)
(Jang and Lee 2000)	-	60	63	0.17
(Huang et al. 2000)	-	15	1200	-
(Lemoff and Lee 2003)	-	25	6.1	-
(Wang et al. 2004)	-	-	-	-

1.3.2.4 Electrochemical micropump

Electrochemical micropumps utilize the bubbling force that is generated by electrochemical reaction during electrolysis of water. Bi-directional pumping can be achieved by reserving the actuating current, which makes the hydrogen and oxygen bubbles reacting back to the water. The pumped fluid volume can be measured by estimating the gas volume with the measurement of the conductivity between the electrodes placed in micropump. The concept of using electrochemical actuation for micropump was first found by S Bohm et al. (2000). Micropump consists of a reservoir filled with an electrolyte, fluid channel, inlet-outlet reservoir, and immersed electrodes to generate gas bubbles by current supply. Figure 1.24 shows the schematic illustration of electrochemical actuation micropump. The limitation of electrochemical micropump is that the generated bubbles might collapse and become water leading to the unsteady and unreliable release of fluid. Contribution of earlier researchers to electrochemical micropump is shown in Table 1.16.

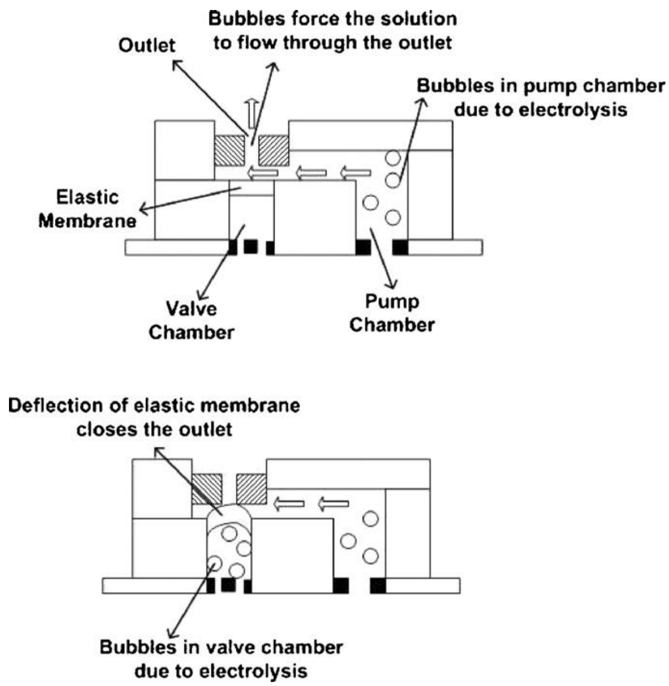


Figure 1.24 Schematic illustration of electrochemical actuation micropump (Nisar et al. 2008)

Table 1.16 Contribution of earlier researchers to electrochemical micropump

Author	Size	Voltage (V)	Flow rate (µl/min)	Pressure (kPa)
(Bohm et al. 2000)	-	-	0.0012	-
(Yoshimi et al. 2004)	10µm diameter	3	-	-

1.3.2.5 Electro wetting micropump

Electrowetting micropump involves a change in the wet ability due to the applied electric field. The fluid transport is due to surface tension in electrowetting micropumps. Surface tension is an inertial force which dominates at the microscale. Voltage is applied on the dielectric layer, a decrease in the interfacial energy of the solid and liquid surface, which results in fluid flow. Continuous electrowetting is usually applied to adjust the surface tension between two immiscible liquids, liquid phase metal like mercury and electrolyte are used. The interface between these two is referred as electric double layer shown in the schematic of electrowetting micropump Figure 1.25. Due to photo nation effect on the mercury surface, the electrical potential between the right end of mercury droplet and the cathode of the electrode pair is higher than the counter electric potential on the left side. The surface tension difference besides a mercury droplet, thus pushes the droplet towards the right. Continuous electro wetting involves no heating of the liquid, demonstrate faster speed and low power consumption. Contribution of earlier researchers to electrowetting micropump is shown in Table 1.17.

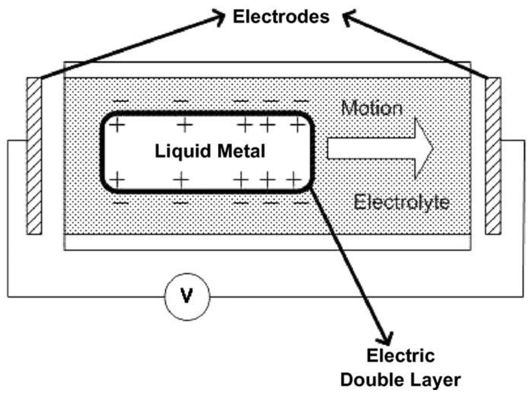


Figure 1.25 Schematic of electrowetting micropump (Nisar et al. 2008)

Table 1.17 Contribution of earlier researchers to electrowetting micropump

Author	Size	Voltage (V)	Flow rate (µl/min)	Pressure (kPa)
(Yun et al. 2002)	-	2.3	170	0.7

1.3.2.6 Bubble type micropump

Microbubble is generated in this type of micropumps to create pumping pressure in channel or chamber. The pumping effect is based on the periodic expansion and collapse of microbubbles. The bubbles in this micropump are generated by a heating process which is not preferred in many applications. Schematic of bubble type micropump is shown in Figure 1.26. Microbubbles were generated in the micropump chamber to create a pumping effect. Due to the expansion of the bubble, the flow rate at the diffuser was large than at nozzle. When the pumping bubble collapses the flow rate at diffuse is less than at nozzle. A net flow was generated from nozzle to diffuser by periodically controlled voltage input during each cycle consisting of bubble expansion and collapse. Contribution of earlier researchers to bubble type micropump is shown in Table 1.18.

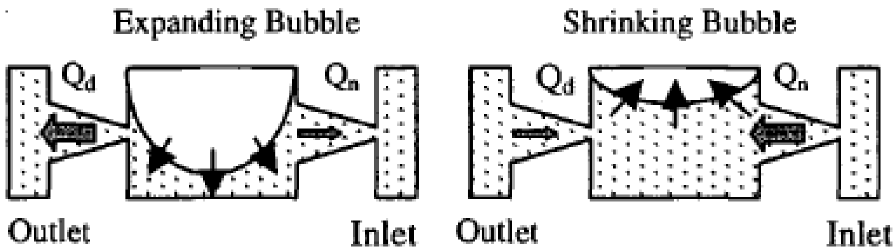


Figure 1.26 Schematic of bubble type micropump (Tsai and Lin 2002)

Table 1.18 Contribution of earlier researchers to bubble type micropump

Author	Size	Voltage (V)	Flow rate (µl/min)	Pressure (kPa)
(Tsai and Lin 2002)	-	20	5	0.38
(Zahn et al. 2004)	-	-	0.12	3.9

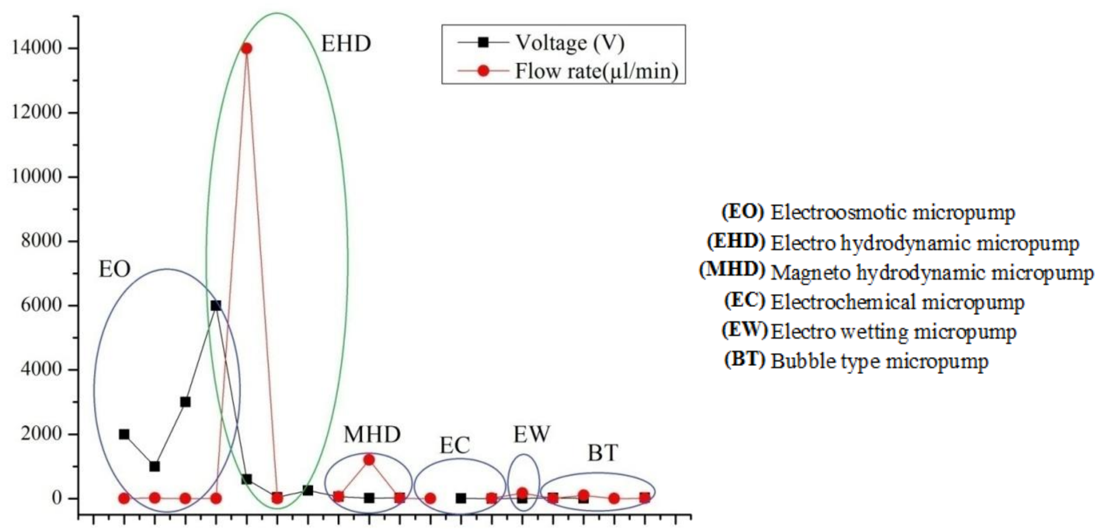


Figure 1.27 Comparison of flow rate and voltage in the different nonmechanical type of micropump

Figure 1.27 shows the comparison of flow rate and operating voltage of different type of continuous type micropumps. The maximum flow rate is obtained for electrohydrodynamic micropump at lower operating voltage compared to other type micropump. The structure of most of the mechanical and non-mechanical micropumps reported above has its advantages and disadvantages. The important factors considered for the selection of micropump type are flow rate, pressure, size, and operating voltage. Electrohydrodynamic and magnetohydrodynamic micropump produce high flow rate compared to other types of micropump. Comparisons of different type of mechanical and non-mechanical micropump with respect to voltage and flow rate in micropump are presented. Based on the application the type of micropumps can be selected. Working fluid properties also influence the flow rate and must be taken into account in choosing the micropump type. Size of the micropump and manufacturing process is an important parameter as it influences the micropump application field. Piezoelectric micropump reports better performance in terms of flow rate with better self pumping ability compared to other types of micropump. Therefore piezoelectric actuators are considered for further to analyze the diaphragm deflection and micropump performance.

1.4 MICROPUMP PERFORMANCE ENCHANTMENT METHODS

In addition to basic pump parameters like actuation principle, the other parameters which are considered for micropump are diaphragm design, actuator design, valve design, a combination of micropump are an important parameter used for the design of reciprocating micropumps. Most of the micropumps are characterized by their simple structure and small size. The drawback of this simple structure is low back pressure and fluid flow. The flow rate and back pressure of a single chamber micropump (SCM) cannot be improved very much by varying parameters like the diameter of a diaphragm, the thickness of diaphragm, actuating principle, and valve type used. To achieve higher performance in micropump, some of the enhanced geometrical design and optimization of valves, actuator, and diaphragm were presented by new researchers. The effective methods like a serial, parallel, series combination of micropump can be used to get the desired flow rate and back pressure without increasing the voltage. The different micropump performance enhancement methods are shown in Figure1.28.

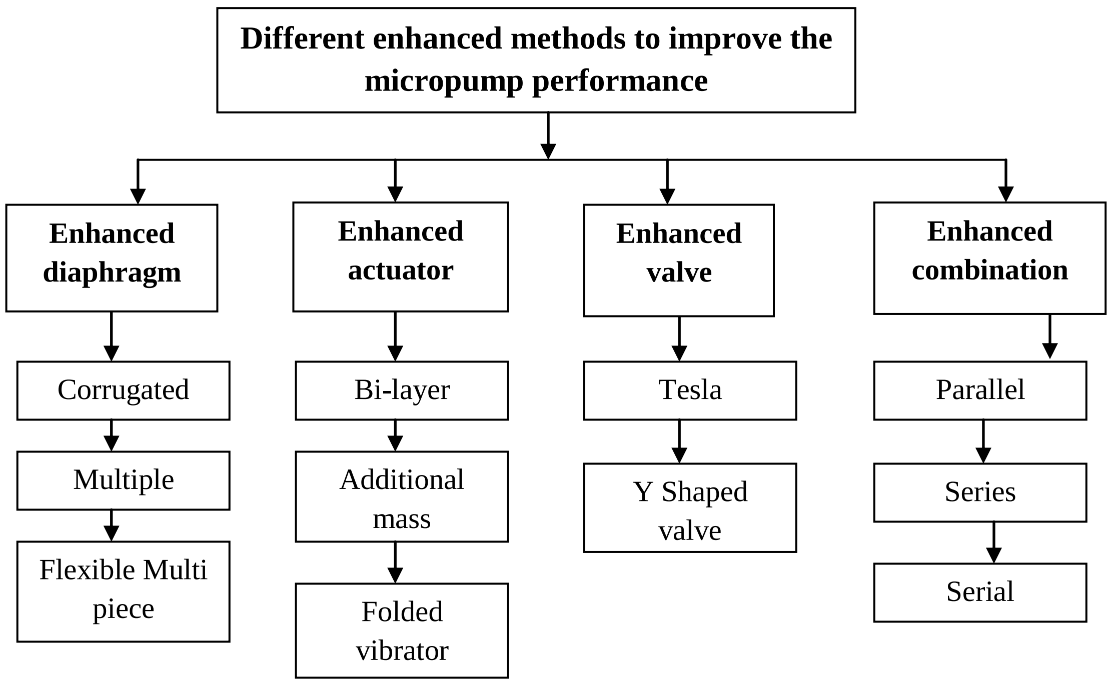


Figure 1.28 Different performance enhancement methods of micropump

1.4.1 Enhanced diaphragm design

Diaphragms play an important role in transferring oscillating action to fluid flow action in mechanical type micropumps. In the case of plane diaphragm however, stress is large which can lead to undesirable effects on diaphragm deflection. To design new diaphragms with higher displacement and low-stress various enhancement methods where considered. Oscillatory motion of the diaphragm obtains the fluid flow in mechanical type micropump. At the same time, fluid plays a key role in offering resistance to the oscillation of the diaphragm. Flat diaphragms in circular and square shape are commonly used in micropumps. Some of the researches have worked on enhanced diaphragm design to improve the diaphragm deflection which influences the micropump performance, some of them are presented below. Reduction in the deflection of the plane diaphragm is due to residual tensile stress, while bucking is due to compressive stress (Ding et al. 1990). To reduce the residual stress in plane diaphragm corrugations diaphragms where designed.

C J Van et al. (2000) modeled the corrugated diaphragm for the first time. The deflection of the corrugated diaphragm was more compared to the plane diaphragm at the same voltage (Mullem et al. 1991). Introduction of rectangular corrugation into the diaphragm will lead to the large deflection performance of the diaphragm. Scheeper P R et al. (1994) fabricated the silicon nitride circular corrugated diaphragm for microphones. For small corrugation depth the mechanical sensitivity increases due to the reduction of the initial diaphragm stress. Whereas in case of large corrugation depths mechanical sensitivity decreases due to the stiffening effect of the corrugation.

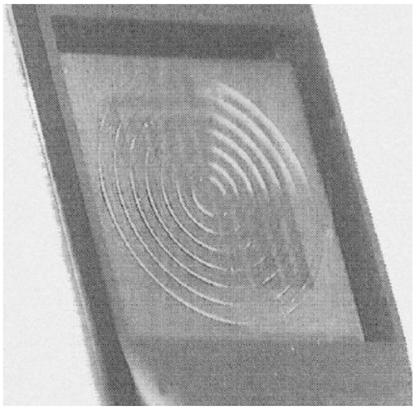


Figure 1.29 Corrugated diaphragm (Chan Jeong and Sik Yang 2000)

E H Yang et al. (1995) fabricated electrostatic actuated corrugated P+ silicon diaphragm for micropump Figure 1.29 show the fabricated silicon corrugated diaphragm. Ok Chan Jeong (2000) used the corrugated P+ silicon diaphragm in thermo pneumatic micropump. Displacement was compared with the flat diaphragm, the deflection of the corrugated diaphragm was three times greater than the flat diaphragm because corrugation of the diaphragm will release the residual stress in the diaphragm. The flow rate of micropump was 3.3 times more than the flat diaphragm micropump. The obtained maximum flow rate of the corrugated diaphragm micropump was 14µl/min. In the case of corrugated diaphragms, the fabrication is difficult, and it is specified to use with only some type of actuators (Yang et al. 1995).

Micropump with multiple diaphragms were designed by some researches to improve the micropump performance. C Cabuz et al. (2001) designed an electrostatic actuated dual diaphragm gas micropump for the first time. The pump consists of two diaphragms with a very thin metal electrode with a dielectric. The upper and lower diaphragm consists of perforations which act as inlet and outlet. The maximum flow rate obtained was 30ml/min at 8 mW voltage.

Z Zhang et al. (2013) presented the integration of the sensor and the conventional piezoelectric pump with double actuation. The segmenting electrode method is used in micropump for self-sensing of flow rate. The electrode of the piezoelectric element is divided into two units one is driving unit and sensing unit.

Nam D N et al. (2012) designed flexible and self-sensing ionic polymer metal composite (IPMC) material as a diaphragm for micropump is shown in Figure 1.30. Unlike the conventional design of using a single piece of IPMC material, they used several IPMC actuators to drive elastic films. The new design helps to produce large deflection and increase the durability of diaphragm compared to plane diaphragm micropump. The deflection obtained from this new design is 0.4mm at 3V, whereas in conventional design the deflection was 0.2mm.

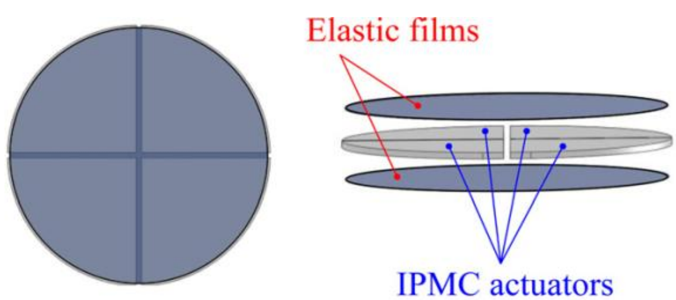


Figure 1.30 Diaphragm IPMC actuators

1.4.2 Enhanced actuator design

As explained early different types of actuators can be used for micropump applications. Some of the recent work done on the mechanical type micropumps, in which different actuation techniques used to increase the displacement of the diaphragm via micropump performance. The enhanced actuator designs to improve the diaphragm deflection and micropump performance are presented below.

Park et al. (2013) designed a piezoelectric micropump for Direct Methanol Fuel Cell (DMFC) which works based on resonance and fluid inertia. The resonance mechanism is used to oscillate the pumping chamber. The additional resonant mass was connected to the piezo actuator to magnify the diaphragm displacement as shown in Figure 1.31. The experimental investigation of prototype reported the flow rate of 3.71ml/min and maximum pumping pressure was 14kPa.

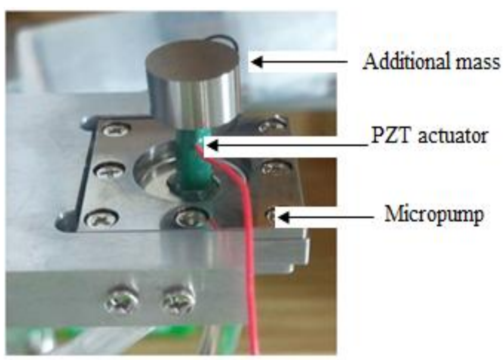


Figure 1.31 Prototype of micropump with additional mass (Park et al. 2013)

Wang et al. (2014) developed a micropump with folded vibrator with piezoelectric sheets, which serves as the resonantly-driven actuator. The vibrator provides uniform strain distribution in piezoelectric sheets surfaces to improve their utilizing efficiency. Figure 1.32 shows the prototype of micropump with folded vibrator with dimensions of 20mm×20mm×28mm. Folded vibrator which is attached to micropump will magnify the displacement of the piezoelectric actuator and enlarges the actuating force through the resonant drive. The experimental finding shows the maximum flow rate of 118ml/min and maximum back pressure of 22.5kPa for 120V at the resonance frequency of 361 Hz.

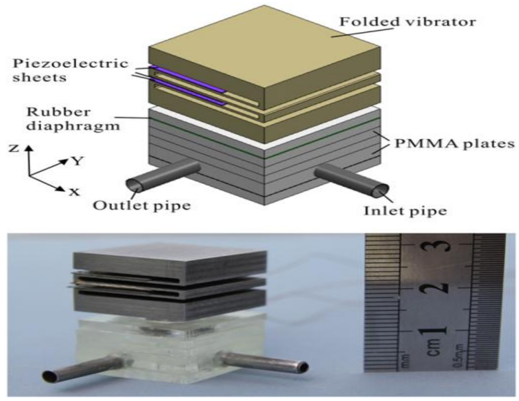


Figure 1.32 Prototype of micropump with a folded vibrator (Wang et al. 2014)

Pan et al. (2015) designed a dual-frequency micropump to improve the performance of a piezoelectric micropump. The dual frequency driving method uses the first and third harmonics of the square wave voltage to have a ratio of 1:3 bending resonant frequencies. The vibrator was made by the rectangular metal beam with a piezoelectric sheet adhered on it. The prototype of piezoelectric duel frequency drive micropump is shown in Figure 1.33. The maximum flow rate reported was 163.7ml/min and back pressure of 29.7 kPa for 400V driving voltage at 445.5Hz.

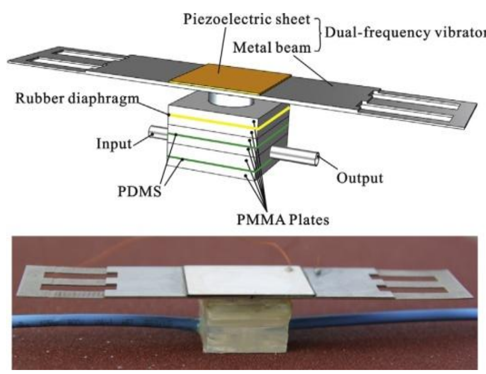


Figure 1.33 Prototype of piezoelectric dual frequency drive micropump (Pan et al. 2015)

1.4. 3 Enhanced valve design

Valve in micropump plays an important role in both mechanical and non-mechanical micropumps. As explained earlier non-moving valves are more suitable for the reciprocating type of micropumps. Different enhanced valve designs used to improve the micropump performances are presented below.

Ivano Izzo et al. (2007) designed new valves with vortex area based on the fluid dynamic pattern in standard diffuse/nozzle valve to enhance the micropump performance. The results showed that the use of recirculation diffuse nozzle microvalves had increased the micropump flow rate by 2.9 times and pressure head by 1.6 times compared standard diffuser/nozzle valves.

Kai-Shing Yang et al. (2010) found that the diffuser/nozzle micropump suffer from low efficiency, an enhanced structure is presented to diffuser/nozzle to improve the performance of micropump. Enhanced structure designed by kai-shing are fish skin type, fin type, and obstacle type and compared with conventional diffuser/nozzle. A dramatic increase in pressure drop in the valves when the obstacle and fin structure were introduced in the valves. In this case, due to the fish skin outward wavy surface, trapping of the liquid within this structure will take place.

Guan Yanfang et al. (2008) presented a micropump with an enhanced structure like fin type, sawtooth and obstacle type microchannel with PDMS-glass-silicon-PDMS sandwich. In obstacle structure, there will be more pressure drop compared to other structure, this high-pressure drop leads to a sharp rise in the flow resistance. Thus the less flow rate is obtained when the obstacle structure is used in pump, i.e. 19.79mm^3/s. The efficiency ratio of the obstacle structure also similar as that of the fin structure, significant pressure drop (flow resistance) offsets its superiority at the low operating frequency, thus leading to a smaller flow rate through the test range. The maximum amplitude of the conventional micro nozzle/diffuser and obstacle added structure are 23.49μm and 15.85μm. The maximum flow rate of the sawtooth channel pump is

63.6µl/min at 200Hz and 1328.8Pa and 45.1µl/min at 60 Hz and 681Pa for traditional diffuser micropump.

Jianhui et al. (2007) presented a new piezoelectric pump with Y - shape pipes. The pump comprised of two Y shaped pipes which serve as an inlet-outlet of the micropump. The shape of the pipe is just like Y so it is called a Y-shape pipe. This pipe is called positive pipes which have one inlet and base pipe works as an outlet. Vice versa it's called as negative when they are interchanged. The Y-shaped pipe can be a square or circular, but square Y-shaped pipes can be easily processed and their structure is small.

Later Huang et al. (2010) designed a new type of piezoelectric valveless micropump with combined Y and cone shape. CFX finite element software was used to simulate the fluid flow state in the valveless piezoelectric pump which uses the combined shape of Y and cone valve. The maximum flow rate obtained with the combined shape of Y and cone is 43.9ml/min at 100V, 15Hz power supply.

The tesla valve concept was first applied in a micropump by Dodge et al. (1995). These valves are more advantages compared to conventional check valves in microscale. Tesla valves can be easily fabricated. Telsa valves are bifurcated channels which have fixed type valves or no moving parts (NMP) valves are more attractive due to valves simplicity and fabrication. Telsa valve is used in the micropump for the first time and the fabrication is done using an RIE method and width was 114µm of the depth of etching is 60µm.

T Q Truong et al. (2003) proposed a complete design optimization of the tesla valve and a method to construct the geometry of the tesla valves. The main parameter to evaluate the performance of these valves is the diodicity. Tesla valves can be easily fabricated on silicon substrates. S M Thompson et al. (2014) designed a multiple identical tesla valve in series, i.e. multi-stage tesla valve (MSTV).

Using a relief valve design at the inlet and outlet of the diffuser nozzle the improvement is found by Karnath et al. (2012). Use of relief value in the diffuser/nozzle will maximize the micropump pump efficiency. Based on the earlier work the relief at the throat of diffuser/nozzle is further used for micropump.

From the above discussion, we can conclude that the flow rate obtained by the enhanced diffuser/nozzle valve is high compared to standard diffuser/nozzle valves. The fabrication of this enhanced NMP valves is difficult and these valves cannot be used for all type of fluids. Most of the micropumps have used plane diffuser/nozzle as flow directing elements, because of its advantages like easy fabrication, less failure risk, no additional moving parts.

1.4.4 Multiple chamber micropump / Peristaltic micropump

Single chamber micropumps are commonly used in most of the applications. The flow rate and back pressure of the single chamber micropumps cannot be improved by simultaneously changing the diameter and thickness of the actuator at a given operating voltage. With the rise of actuator diameter the flow rate increases while the back pressure decreases. Peristaltic micropumps were used to increase the back pressure performance of micropump. In peristaltic micropump, the operation of actuator members generates the calving effect to direct the liquid flow. In case peristaltic micropumps fluid flow from one chamber to another is due to voltage application and removal, which makes the membrane to deflect alternatively.

The micropump which works on the principle of peristaltic motion of pump chamber area called peristaltic micropumps. For the limited maximum driving voltage, it is difficult to increase the performance of the micropump by varying the other parameters of the pumps (actuator diameter, thickness, valves, etc.). The pump performance can be further increased by using more number of micropump in a different arrangement. In peristaltic micropump, the micropump chamber squeezes the fluid from one chamber to another in the desired direction. The peristaltic micropump requires three or more pump chamber with the oscillating membrane in some cases passive valves are also used. Different combination peristaltic micropumps were designed to enhance flow rate i.e. parallel type micropump, series type micropump, and serial type micropump.

Guo et al. (1999) proposed a new type of capsule micropump actuated by Ionic Conducting Polymer Film actuator. In case of capsule type of micropump, the micropumps are connected one above another, i.e. parallel connection. The micropump was experimentally studied and flow rate obtained was 4.5ml/min. These capsule type micropumps were suitable to use in medical and biotechnology application.

In the case of series peristaltic micropumps, the pumps are connected in series with piezo-actuated members. The sequential controlled application of voltage to the micropumps will make the fluid to flow inside and outside the chamber. Amos Ullmann et al. (1998) presented the different combination modes possible for the operation of such pumps such as a series connection and a parallel connection to obtain the desired flow rate and backpressure. Peristaltic pumps have many advantages in microfluidic applications, this type which eliminated the need for moving parts such as valves and is capable of self-priming and bidirectional transportation (Jang and Kan 2007).

Teymoori et al. (2005) designed electrostatic peristaltic micropump for drug delivery application. The pumping mode of this type of micropump is based on the peristaltic motion. The flow rate obtained was 9.1μl/min, which was suitable for drug delivery applications. Yi- Chu Hsu et al. (2008) designed a three chamber four phase actuation sequence peristaltic micropump which are connected via straight tapered microchannels. The flow rate and back pressure obtained for diffuser type micropump and conventional type micropump is 114.8μl/min at 9.2kPa and 262.4μl/min at 3.9kPa respectively.

Y H Guu et al. (2008) fabricated the piezoelectric (PZT) actuated parallel type of micropump for the first time. The maximum flow rate obtained was 91μl/min at 140V and 20Hz. The obtained flow rate of the double parallel type of micropump was 1.5 times more than that of single micropump, and twice that for the triple parallel micropump.

H Yang et al. (2008) designed a portable piezo-actuated valveless peristaltic micropump and obtained flow rate about 365µl/min at 24V, 50Hz frequency. J Kan et al. (2008) proposed a serial connection multi-chamber piezoelectric micropumps (SCMCP) to achieve high performance at low actuation voltage. The output performance of this type of serial connection micropumps is equal to that of several single chamber piezoelectric pumps. The pumping performance of micropumps also depends on the number of chambers.

Flow rate and back pressure of the micropump can be enhanced to a certain extent level, but when compared to parallel type pumps the performance is less. The back pressure and flow rate of the micropump can be increased by increasing the number of chambers. Azarbadegan et al. (2010) studied the characteristics of a double-chamber series valveless micropump using a one-dimensional non-linear model.

Kim et al. (2013) proposed electrostatically driven valueless double sided peristaltic micropump for gas chromatography. Micropump works based on sequencing actuation using 4 electrodes. The maximum flow rate obtained was 27.19µl/min at 100V DC supply. The literature review on the multi-chamber micropump has proved that the parallel combination micropump enhance the flow rate. Whereas in the case of series combination micropump improves both flow rate and backpressure compared to single chamber micropump. Many research has been done on peristaltic pumps, the drawback of this type of micropump is scale size which is difficult to implement in real-time applications. Malfunction in pumping diaphragm or chamber in peristaltic micropump will deal with the failure of whole peristaltic device (Ou et al. 2012).

From the above literature review, it can be found that the different types of micropumps were designed to improve the micropump performance. The performance enhancement new methods have their drawbacks like this method cannot be useful in MEMS application, since the size of the micropump is large compared to the conventional type of micropumps. Wear, fatigue and valve blockage are critical issues in valve type micropumps. The important properties like valve blockage, backward flow and valve operating speed should be easily controllable which cannot be possible in valve type micropump.

Most of the micropumps have used plane diaphragms. The residual stress in the plane diaphragm is more, so the deflection obtained from the plane diaphragm is less. The total stress in the plane diaphragms mainly depends on the residual stress, tensile stress, and bending stress thus residual stress cannot be neglected. Deflection of the plane diaphragm can be improved by designing the new type of diaphragms. As the performance of the reciprocating micropump mainly depends on the diaphragm deflection, it is widely recognized that high deflection diaphragms are required for micropump and other MEMS applications. The literature only reports a limited number of works on diaphragm design. In addition, the operating voltage and mass of micropump remain the important factor that determines the feasibility of the device. The use of flexure hinges and flexure based compliant mechanisms are considered for the diaphragm design. The literature review and details of the compliant mechanism, flexure hinges, and application of flexure based compliant mechanism are presented in the below section.

1.5 COMPLIANT MECHANISMS

A compliant (or flexible) mechanism is a mechanism that is composed of at least one component that is sensibly deformable (flexible or compliant) compared to the other rigid links (Lobontiu 2002). A compliant mechanism is a device that moves solely by deformation, typically by utilizing flexures in the place of conventional bearings. The compliant mechanism is based on smooth manipulators (Goldfarb and Celanovic, 1999). Compliant mechanisms are considered to be the subclass of flexible mechanisms that undergo large deformations (King and Xu 1996). Compliant mechanisms are single-piece flexible structures that deliver the desired motion by undergoing elastic deformation as opposed to jointed rigid body motions of conventional mechanisms. Different definitions were given to the compliant mechanism by different authors as mentioned above.

Compliance in design leads to jointless, no-assembly, monolithic mechanical devices and is particularly suited for application with a small range of motions (Kota S et al. 2001). Compliant mechanisms are the flexible mechanisms that transfer an input force or displacement to another point through elastic body deformation. There may be monolithic (single-piece) or jointless structures. Use of this compliant mechanism some of the mobility from the deflection of flexible members rather than from movable joints. Compliant mechanism transfers motion, force or energy (Howell et al. 2013).

Compliant mechanisms offer several advantages compared to rigid body mechanisms. Compliant mechanisms are used in both macroscale and microscale application. Some macroscale application like high lateral stiffness application, optical mount, precision alignment, output platform for the spatial mechanism, serial flexure base, hybrid amplifier, spatial hybrid flexure base and in load cell, etc. Microscale application of flexure mechanisms like microcantilever, scratch drive actuator, inertia sensor, single flexure microcomponent, tilt mirror and other multi flexures compliant microsystem, etc. (Lobontiu 2002).

Compliant mechanisms provide guided motion via elastic deformation. Their ability to produce repeatable/precise frictionless motion makes them a common choice in precision positioning devices, frictionless bearings, biomedical devices and robotic arm (Lobontiu 2002). The compliant mechanism transforms an input form of energy like mechanical, electrical, thermal, magnetic, etc. into output motion. Schematic of the compliant mechanism is shown in Figure 1.34.

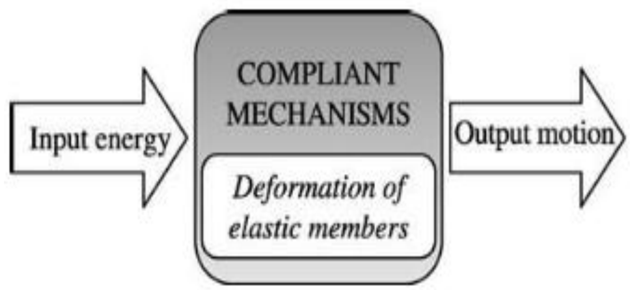


Figure 1.34 Schematic representation of compliant mechanism in terms of its energy trade (Lobontiu 2002)

Flexure hinge is a thin member that produces relative motion/rotation between two adjacent rigid members through flexing (bending) (Lobontiu 2002). Flexural hinge consists of an elastically flexible, slender region between two rigid links as shown in Figure 1.35. Some of the advantages of flexural hinges are no friction losses, easy to fabricate, can be used in small scale application like MEMS. Flexural hinges can be easily machined by using the manufacturing processes like end-milling, electro-discharge machining (EDM), laser cutting, and photolithography techniques for microelectromechanical systems (MEMS). Some of the application of flexural hinges in an automobile for example speed sensor, position sensor, airbags, suspension system, etc. Mechanisms that are based on flexural hinges are also beneficiary in the biomedical industry for biomedical devices like biopsy devices, orthotic devices, vascular catheters, etc.

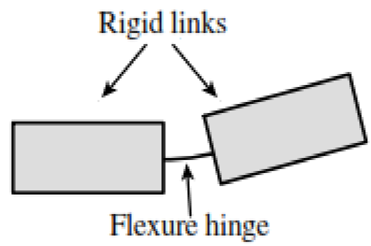
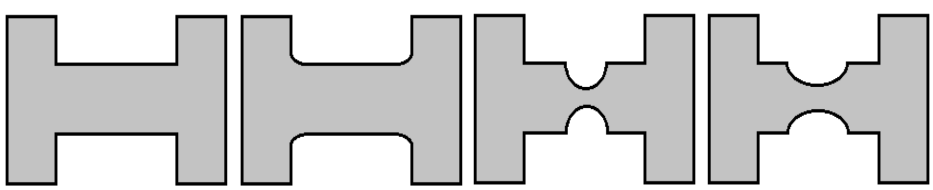


Figure 1.35 Flexure hinge (Lobontiu 2002)

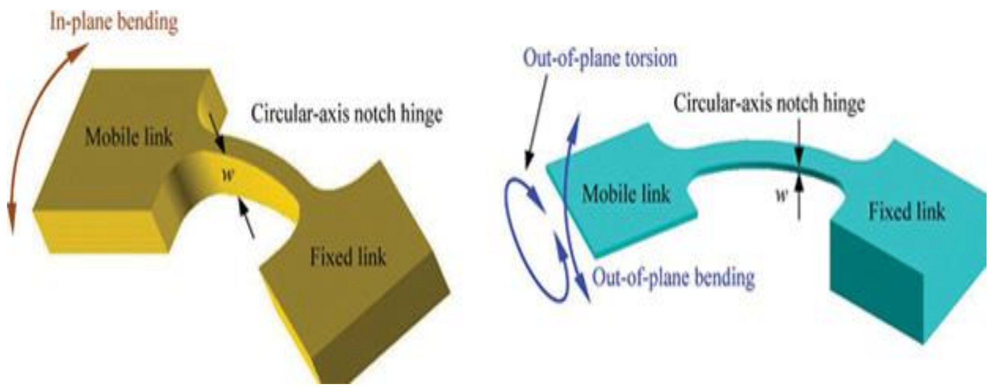
Flexures and flexure-based mechanisms are frequently to be found in instrumentation and machinery across a broad range of scientific application. Specifically, these elements are used to connect rigid links in a way that provides stiff constraints in some directions, while, as a result of high compliance, enabling relatively free motion in other. Consequently, flexure mechanisms can be used in any application requiring precise motion control, particularly for small translations and rotations (Hazelton 2002). Flexures are classified into different types i.e. rectangular flexure, corner fillet flexure, circular cut out flexure and elliptical cutout flexures which are shown in the Figure 1.36 (a), (b), (c) and (d) respectively.



(a) (b) (c) (d)

Figure 1.36 Flexures type (a) Rectangular flexure (b) Corner fillet flexure (c) Circular cutout flexure (d) Elliptical cutout flexure

Based on the load applied to the flexure planes, it is further classified into two types i.e. in-plane flexure and out-of-plane flexure. The active and resistive loads are in planar in case of in-plane flexures application whereas in case of out-of-plane flexure application the loads are in the perpendicular direction as shown in the Figure 1.37 (a) and (b). The out-of-plane compliance occurs as a result of errors caused by the positioning of external loads or defective actuation or manufacturing and assembly (Lobontiu 2002). Based on application i.e. in-plane compliance or out-of-plane compliance external loading position can be changed.



(a) (b)

Figure 1.37 Flexure hinge (a) In-plane motion (b) Out-of-plane motion (Lobontiu N 2014).

Some of the application of in-plane motion flexures is microgripper, precision positioning stage, tilt mirrors for MEMS optical, micro switches, etc. The out-of-plane motion flexures are used in micromirrors, RF switches, diaphragms, etc. The flexural diaphragm has out-of-plane motion, so rectangular hinges are more suitable for this application. Corner fillet and circular fillet hinges are more suitable for in-plane compliant mechanism. Rectangular cross-section flexures have the simplest geometry and easily fabricated compared to all other hinges.

Flexure hinges allow rotation between two adjacent stiff members by the elastic deformation of a flexible connection (Friedrich et al. 2015). A flexure system consists of rigid bodies that are joined together by flexible elements (i.e., compliant members or flexible, spring-like joints). These flexures/ elements are directionally compliant and thus behave like bearing elements in that they guide the system's rigid bodies to move in prescribed directions called the degree of freedom. The main advantages of compliant mechanisms are high resolution and repeatability, require no lubrication, cost reduction, experience minimal friction and wear, a significant reduction in weight, easily maintained increased performance and ease with which they are miniaturized (Howell et al. 2013). Some of the applications and literature review on compliant mechanism and flexures are presented below.

Weinberg et al. (2000) proposed a lumped-parameter model for FPW devices, which are rectangular plates or diaphragms with structural and piezoelectric layer and with inter digitized conducting comb for driving and sensing, that configuration is often used in micromechanical chemical sensors.

Kota et al. (2001) presented the distributed compliant mechanism using flexure links and no joints for improved readability, performance and ease fabrication. Some of the MEMS devices with a distributed compliant mechanism where designed, fabricated and tested. Compliant wiper blades, a four-bar mechanism with lumped compliance, micro compliant crimping mechanism, compliant based actuator systems for comb drives are some of the tested devices.

Shilpiekandula et al. (2008) designed a diaphragm with flexures for precision angular positioning application. Presented lumped parameter model and state space analysis model of precision angular positioning diaphragm.

Later Zhihong et al. (2008) presented a mass sensitive biosensor utilizing a flexural vibration mode of a micromachined piezoelectric micro-diaphragm. Deyuan Zhang et al. (2014) used flexural hinges for microvalves application. M Nashrul et al. (2009) designed a high precision microgripper for micromanipulation. The microgripper design was based on a hybrid flexure based compliant mechanism. Performed finite element analysis of microgripper and experimented with microgripper prototype, which was fabricated by the electro-discharge machining process. Compliant flexures provided new and better solutions for MEMS devices.

Later different type of circular cut out and elliptical cut out flexure hinges were designed (Chen et al. 2011). Benliang et al. (2013) designed the flexure-based on topology optimization of flexure hinges to maximize the compliance of flexure in the desired direction meanwhile minimize the compliance in other directions.

As explained above compliant mechanisms are widely used in MEMS applications. From the literature on the compliant mechanism, it can be concluded that compliant mechanisms have more advantages compared to rigid body mechanisms. In the present work, the new diaphragm is designed for the micropump application using compliant mechanism (Flexure element). Flexures are commonly used for providing motion in the direction normal to the flexure plane. Flexures in diaphragms are mainly used to provide out-of-plane motion. A parallel mechanism is formed when two or more flexures area connected in parallel to rigid link. The parameters which are considered for compliant diaphragm are material, compliance, stiffness of flexures, type of flexure, and the number of flexures. The new diaphragm is designed based on the compliant mechanisms, which consists of actuation area and outer boundary which are connected by flexure joint. For further improvement in the diaphragm deflection, the perforation patterns were introduced to the diaphragm actuating area. Effect of perforation shapes, size, and the number of perforations in the actuating area are studied. The preliminary design and modeling of the compliant diaphragm and the perforated compliant diaphragm are presented in Chapter 2.

1.6 MODELING OF DIAPHRAGM AND MICROPUMP

The behavior of micropump and diaphragm is better understood by the characteristic performance study. Either analysis based or experimental based approach can be used for the characteristic study. The experimental based approach study is a lengthy process because it involves design, prototype, fabrication, testing, and manufacturing. This approach is time-consuming, parameter variation cannot be done easily, failure is recognized after manufacturing, and stress inside the body cannot be measured easily. Analysis based approach is also called as computer aided engineering (CAE). In analysis based approach the materials are characterized by modeling its behavior using governing equations. The governing equations used in the analysis can be solved by using numerical methods, which involves the definition of concept, Computer Aided Design (CAD) model, simulation and optimization process. In the analysis approach parameter variation and design, the alteration can be done easily. Once the developed model is validated in analysis, the product can be directly manufactured. The analysis approach is very cost efficient compared to experimental based approach.

Finite element analysis is commonly used in the structure, fluid flow, coupled filed problem, heat transfer problem, MEMS problem, etc. to understand the stress and performance analysis of the design. The behavior of the piezoelectric actuator and diaphragm has to be analyzed before its real-time application. FE analysis of piezoelectric phenomena requires coupled-field or multiphysics analysis approach for solving problems which involve coupled interaction between the disciplines like mechanical and electrical engineering. The characteristic behavior of compliant diaphragm can be achieved either by experimental or by an analytical approach. The experimental approach involves the definition of the concept, design, prototype fabrication, testing, and manufacturing. The disadvantage of this procedure is time-consuming, lengthy process, parameters cannot be changed easily, failure may be recognized later, etc. The analytical-based approach works based on constitutive equations, these constitutive equations can be solved by numerical methods. Some commercial FE software's like COMSOL, ANSYS, ABAQUS, and INTELISUITE, etc. are widely used packages. For piezoelectric actuators the couple filed analysis is required for which multiphysics software's has to be used. Some of the researchers worked on different analytical and modeling methods of diaphragm and micropump are discussed below.

Sim et al. (2003) used ANSYS tool to study the deformation shape of the silicone diaphragm at different pressure application. The analytical results were compared with the simulation results, the obtained maximum deflection was 57µm which coincides with calculated analytical results.

Li S et al. (2003) designed analytical analyses of circular PZT actuator for valveless micropump. Nguyen et al. (2008) analyzed the static and vibration characteristics of the IPMC diaphragm using finite element NASTRAN. D Ngoc et al. (2012) presented the ANSYS finite element model to study the IPMC diaphragm deflection and stress analysis for different step input voltages. Shape effect of the IPMC diaphragms was studied using ANSYS Finite element analysis, circular shape, and square shape diaphragms where considered.

Other than the finite element approach, many researchers have used different methods for micropump analysis. An analytical model to predict the maximum flow rate and the maximum pump pressure at zero pump pressure and zero pump flow was presented before (Stemme et al. 1993). Later an enhanced analytical model and valveless dynamic micropump model were developed by Ullmann (2001). The model was based on continuity equations, volumetric displacement, diffuser/nozzle parameters, and frequency inputs. The output flow rate is calculated for different voltage.

Wan et al. (2001) presented an electrical equivalent circuit for piezoelectric micropump using hydraulic resistance, inductance and capacitance elements from electrical formulas. The authors examined the power consumption estimation of piezoelectric micropump from the equivalent electric circuit. In the electric circuit, the transformer is considered to relate the electrical domain to the mechanical domain, the membrane is represented as spring, liquid in the chamber as oscillating mass considered as damping from the liquid in the chamber and effective capacitance of PZT disc is considered for the equivalent electric circuit.

C Yamahata et al. (2005) presented an analytical solution of the hydraulic system is reducible to a second order equation to propose an equivalent fluidic model similar to the electric model. The fluidic elements of the pump were replaced by RLC equivalent circuit with diodes. Reciprocating micropump with passive check valves was represented as an equivalent electrical model.

S Hayamizu et al. (2003) proposed an equivalent circuit model of bi-directional valveless silicon micropump to optimize the pump chamber, inlet/outlet structure and flow channels. . The flow rate obtained was 393 nl/s and 323nl/s for forward and backward directions, respectively.

H K Ma et al. (2008) presents the theoretical analysis of the pump chamber and valve to study the performance of one side actuating diaphragm micropump. They successfully developed one side actuating diaphragm micropump for a cooling system. Hsu et al. (2008) presented a numerical model of peristaltic micropump using an electronic-hydraulic analogy circuit simulation package (Circuit Make 6.2Pro). The author represented the simplistic model of actuator membrane mechanism into the electric circuit to simulate the micropump and to compare with the experimental results. The maximum flow rate and back pressure obtained by conventional and diffuser-type micropump is 262.4µl/min at 3.9kPa and 114.8µl/min at 9.2kPa respectively. Deshpande et al. (2007) presented an analytical model and working equations for static deflections of the piezoelectric actuator with the multi-layered circular diaphragm. Markus et al. (2010) designed analytical modeling for ideal circular bending actuators for high-performance micropump based on Classic Laminated Plate Theory (CLPT).

Simulink model for valveless micropump was developed based on the Ullmann model (Ramaswamy et al. 2011.) (Navin Karanth thesis 2012). Micropump diaphragm and optimization of diaphragm geometry were performed. The dynamic micropump performance was calculated from the Simulink model. Based on the above review on diaphragm and micropump modeling, in the present work Simulink model has been used for the performance analysis of compliant diaphragm and perforated compliant diaphragm micropump. This model consists of five input parameter blocks. The micropump design is based on the details provided by Ullmann (2001). To study the behavior of the piezoelectric material and diaphragms design FE analysis method is carried out in COMSOL 5.2 multiphysics software. The Simulink model developed is validated based on the parameters published in the earlier research works. The details of the Simulink model of the micropump used for the compliant diaphragm and perforated compliant diaphragm micropump are discussed in Chapter 2.

1.7 OBJECTIVE AND SCOPE OF RESEARCH WORK

It is evident from the available literature survey that not much work has been done on the design of diaphragm for micropump using compliant features. In this regard, the use of flexure elements in the diaphragm is a new alternative to improve the diaphragm deflection for micropump application. In the present work, an attempt is made to improve the central deflection of the diaphragm using compliant flexure. Single and bi-layer stacked actuation is proposed to enhance performance.

Effect of diaphragm material, number of flexures attached to the diaphragm is studied and compared with the plane diaphragm. Different flexure elements are considered to select the suitable flexure for the out-of-plane compliant diaphragm. Different diaphragms with a different number of flexures are considered for the study. The compliance of the diaphragm can be further improved by introducing perforations in the diaphragm actuating area. An attempt is made to improve the deflection of the compliant diaphragm by introducing perforation patterns in actuating area.

Moreover, perforated pattern is used in the diaphragm for deflection improvement, the different number of perforations are considered. Single layer and bi-layer PVDF film are considered for the diaphragm actuation. The compliant diaphragm and perforation diaphragm deflection is experimentally validated and compared with plane diaphragm performance. The newly designed compliant diaphragm and perforation pattern compliant diaphragm is used for micropump performance study. In this study, a compliant diaphragm for valueless micropump is designed for the simplicity and ease of fabrication. Based on this, the following objectives and scope are defined for the present research work.

1.7.1 OBJECTIVES

The objectives of the proposed investigation are as follows:

1. To model a compliant diaphragm and investigate the effect of material, effect of different flexures, the number of flexures and perforations on the compliance of the diaphragm.
2. To identify optimum material, flexure geometry, and the number of flexures and perforations for maximum compliance of the diaphragm from preliminary design and modeling studies.
3. To fabricate optimum feature compliant diaphragms and a valveless micropump.
4. To measure the discharge and pressure of the compliant diaphragm micropump for proposed single and bi-layer actuation.

1.7.2 SCOPE OF THE WORK

The envisaged work considers design and optimization the geometry of compliant diaphragms of three materials Beryllium copper, Brass and SS 304 and simulates the deflection of these diaphragms actuated by piezo films of different thicknesses. The single layer Polyvinylidene fluoride (PVDF) piezo films of thickness 28µm, 52µm and 110µm and bi-layer PVDF film of 28µm and 52µm thickness are considered. To simulate the deflection of the compliant diaphragm using staggered and non-staggered perforations, optimize the staggering pattern and number of perforations. Performance analysis of compliant diaphragm micropump is performed using Simulink.

To fabricate the compliant diaphragm and perforated compliant diaphragm based on the optimized results and to experimental validate. Fabricate the micropump prototype in mesoscale and develop experimental setup. Experimental validation of plane diaphragm, compliant diaphragms and perforated compliant diaphragm micropump with a single layer and bi-layer PVDF actuation.

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