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Design Analysis and Characterization of a Piezoelectric Actuated Microvalve for Drug Delivery Applications

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Abstract—one of the stumbling blocks for successful miniaturization and commercialization of fully integrated micro fluidic systems was the development of reliable micro valves. In this study, a micro valve is designed and analyzed by employing two analytical software's namely ANSYS and FLUENT. This work gives also a brief overview of micro valves, actuation mechanisms and focuses on piezoelectric as one type of actuation mechanisms. Applications of the micro valves include flow regulation, on/off switching and sealing of liquids, gases or vacuums. Even though great progress has been made during the last 20 years, there is plenty of room for further improving the performance of existing micro valves. Results showed that maximum displacement is at the forward of the beam and FLUENT software demonstrated the logical response about behavior of fluid passing through channel of the micro valve system

Keywords—Micro valve, piezoelectric, analytical analysis, miniaturization

I. INTRODUCTION

Since the first integrated circuit was invented by Kilby (the Nobel Prize winner in Physics in 2000) in 1958 miniaturization has become an important research topic in both electronic and non-electronic devices. In the late 1970s, miniaturization was extended to mechanical devices with electronics, which is now known as micro electromechanical systems (MEMS). [1] Besides miniaturization of electronics and mechanical devices, micro fluidics is among the greatest engineering challenges of the century. Microsystems technology has the potential to digitalize the fluidic devices. [2]

A. Micro fluidic systems & MEMS

In the last two decades, MEMS technologies have been applied to the needs of biomedical industry giving rise to a new emerging field called Micro fluidics. Micro fluidics deals with design and development of miniature devices, which can sense, pump, mix, monitor and control small volumes of fluids. The development of micro fluidic systems has rapidly expanded to a wide variety of fields. Principal applications of micro fluidic systems are for chemical analysis, biological and chemical sensing, drug delivery, molecular separation such as DNA analysis, amplification, sequencing or synthesis of nucleic acids and for environmental monitoring. Micro fluidics is also an essential part of precision control systems for automotive, aerospace and machine tool industries. [3]

They are widely employed in areas from biomedical and drug delivery to space and fuel cell micro fluidic systems. These systems have been reduced in size to micro scale for the realization of a fully integrated micro fluidic system, such as lab-on-a-chip (LOC) or a micro total analysis system (μ TAS). Major advantages of miniaturization are the drastic decrease in chemical reaction time and less consumption of expensive chemical reagents, as well as enhancement of reliability. [1]

B. Micro valve

A fundamental component of any micro fluidic systems is the micro valve. In recent years, a great deal of research has been conducted to design and develop micro valves for different fluidic systems. These systems involve the integration of many individual steps performed in chemical analysis. This requires the ability to control the large flow precisely and efficient transport of reagents and samples throughout different parts of the system with lowest amount of gas leakage. [4]

Micro valves are an important part of many fluidic operations were a fluid flow has to be controlled. A micro machined valve usually presents three parts: the actuation, the micromechanical structure that opens/closes the fluid flow and the fluidic connections (inlet/outlet). Different types of actuators have been used such as electromagnetic, thermal, piezoelectric or electrostatic. In the operation of micro valves Portability (reduced size as well as lightweight), low power consumption and friendly use are still challenges for a micro valve. [2] Micro valves found today can be roughly categorized as shown in table 1. Most of them generally fall into one of two major categories: *active* micro valves, using *mechanical* and *non-mechanical* moving parts, as well as *external systems*, and *passive* micro valves, using *mechanical* and *non-mechanical* moving parts. [1]

In this work categorization of *active* micro valves are given that involve three subgroups according to their actuation originality. Traditionally, (1) *mechanical* active micro valves are accomplished using the MEMS based bulk or surface micro-machining technologies, where mechanically movable membranes are coupled to magnetic, electric, piezoelectric or thermal actuation methods. Unconventionally, (2) *non-mechanical* active micro valves can be operated by the use of smart or intelligent materials. These non-mechanical active micro valves may hold movable membranes, which are, however, actuated due to their functionalized smart materials such as phase change or rheological materials.

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In addition, (3) *external* active micro valves are actuated by the aid of external systems such as built-in modular or pneumatic means. Sometimes, passive micro valves are regarded as a part of

Micro pumps in many other reviews additionally, based on their initial mode, micro valves can be divided into normally open, normally closed and bistable micro valves. [1]

Active micro valves—mechanical

Various actuation principles are adopted to actuate mechanical moving parts in active micro valves. Figure 1 illustrates the actuation principles widely employed in micro valve structures (or micro actuators including micro pumps). Most active micro valves couple a flexible membrane to magnetic, electric, piezoelectric, thermal or other actuation methods. Traditionally, these active micro valves are accomplished using MEMS-based bulk or surface micromachining technologies, which have been well established in the MEMS field during the last two decades. [1]

Passive micro valve-mechanical

Most passive micro valves, or check valves, are incorporated in inlets and outlets of reciprocal displacement micro pumps as mechanical moving parts, such as flaps, membranes spherical balls, or mobile structures. Passive valves only open to forward pressure, showing diode like characteristics. The one-way behavior of these check valves significantly affects the pumping performance of a reciprocal displacement micro pump. Leakage in the check valves reduces backpressure and pumping rate in the micro pump. [1]

C. Piezoelectric

Piezoelectricity is the ability of certain crystals to produce mechanical stress or stretching with an applied electric field. Piezoelectric actuations are widely used in micro pumps, since the piezoelectric effect can generate both extremely big bending force (several MPa) and small displacements (with less than 0.1% strain). [1]

Piezoelectric actuation stands out for its potential low-power consumption and high actuation forces, but suffers from drawbacks like relatively high actuation voltages, complex fabrication and small dis-placements. Reducing piezo film thickness can lead to lower actuation voltages, but at the expense of lower forces. In order to obtain high-force and low-voltage actuation, one needs large piezoelectric actuators. However, the large size limits the integration of many actuators on one wafer if the actuators have to be placed in the micro fluidic channels. In order to provide real estate for other micro fluidic components in the micro channels, the large actuators have to be placed away from the main micro fluidic channels. [5]

There is a comparison between piezoelectric and other types of actuation that is shown in the table.2

Table1. Classification of micro valves

Categories			
Active	Mechanical	Magnetic	External magnetic fields
			Integrated magnetic inductors
		Electric	Electrostatic
			Electrokinetic
		Piezoelectric	
		Thermal	Bimetallic
			Thermopneumatic
			Shape memory alloy
		Bistable	
	Non-mechanical	Electrochemical	
		Phase change	Hydrogel
			Sol–gel
			Paraffin
		Rheological	Electro-rheological
			Ferrofluids
	External	Modular	Built-in
			Rotary
		Pneumatic	Membrane
			In-line
Passive	Mechanical	Check valve	Flap
			Membrane
			Ball
			In-line mobile structure
	Non-mechanical		Diffuser
		Capillary	Abrupt
			Liquid triggered
			Burst
			Hydrophobic valve

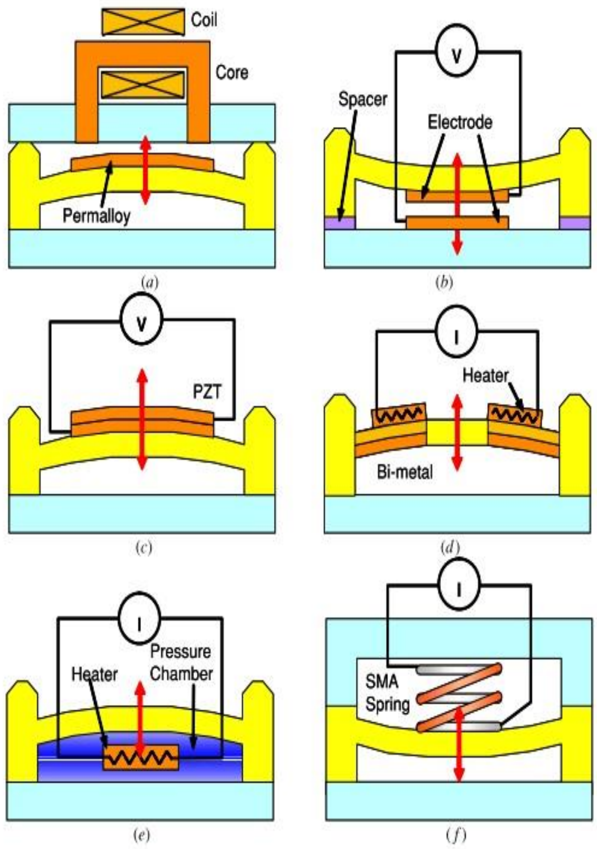

Fig .1. Illustrations of actuation principles of active micro valves with mechanical moving parts: (a) electromagnetic ;(b) electrostatic; (c) piezoelectric; (d) bimetallic; (e) thermo pneumatic and (d) shape memory alloy

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II. MATHEMATICAL MODELING OF PIEZOELECTRIC

The schematic and formulation of piezoelectric are as below:

Equation 1

$$\Delta l = d_{31}.V.\frac{l}{t}$$

$$\Delta w = d_{31}.V.\frac{w}{t}$$

$$\Delta t = d_{33}.V$$

Equation 2

$$\varepsilon_k = d_{ik}E_i + s_{kl}^E\sigma_1$$

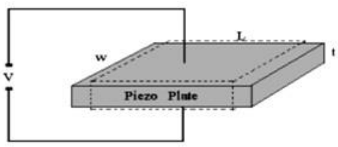
where $\varepsilon_k =$ strain

$d_{ik} =$ piezoelectric constant (m/V)

$E_i =$ electric field

$s_{kl}^E =$ the compliance at constant field

$\sigma_1 =$ stress



Equation 3

$$D_i = d_{ik}\sigma_k + e(d)_{ik}^{\sigma}E_i$$

where $D_i =$ charge displacement

$d_{ik} =$ piezoelectric constant (C/N)

$e(d)_{ik}^{\sigma} =$ permitivity at constant stress

$E_i =$ electric field

Equation 4

$$\frac{Eh^3}{[12(1-\upsilon^2)]}\nabla^4 W_p + \rho_p h\frac{\partial^2 W_p}{\partial t^2} = f - P$$

where $W_p =$ transverse deflection of membrane

$E =$ Young's Modulus

$h =$ membrane thicknes

$\nu =$ Poisson ratio

$\rho_p =$ membrane density

$t =$ time

$f =$ piezoelectric actuating force

$P =$ dynamic pressure of fluid on membrane

Piezoelectric Applications

We can divide the applications of piezoelectric into two general parts. One of them is “converting mechanical to electrical forces” and the other one is vice-versa. For the first one there are Force, Pressure, and acceleration sensors, smart sensors for side impact diagnostic, high voltage-low current generators, yaw rate sensors and platform stabilization sensors. In electrical to mechanical category we have ultra sonic motors, small vibration shakers, and micro-actuators, Sonar arrays for collision avoidance and pumps for inkjet printers. In this study we focus on micro actuators.

III. MODELING THE ENVIRONMENT

Here an attempt has been made to design analysis and characterize a micro valve that is actuated with piezoelectric mechanism. The contribution of this work, is designing piezoelectric actuated micro valve that would be applicable for biomedical applications especially drug delivery systems.

1. Fluent modeling

The pressure and velocity profiles were individually considered by analytical solutions with solving the momentum equation. The problem was considered in two dimensional analyses, because of the ax symmetrical geometry found in top view of the micro valve package and to make the calculation steps shorter which was done by the FLUENT® code 6.3.26. The problem was solved in the laminar fluid flow and steady state fluid by passing time. For the boundary conditions, an inlet velocity for the system inlet (velocity inlet), a wall at the vicinity of the fluid, and also an exit boundary (outflow) have been introduced by the GAMBIT® software. After finishing the completed geometry with final meshing and identified boundaries, it was being exported into FLUENT® software, and by doing this, a default interior zone for inspecting the fluid flow has been introduced by the FLUENT® program itself. A liquid was considered to flow in the microvalve as water (H_2O) to make the analyses easier. Both continuity equation (conservation of mass), and momentum equation in X and Y directions were studied by the FLUENT® code. The pressure and velocity solver were coupled together to being analyzed simultaneously. The momentum equation was solved with the second order upwind manner rather than the first order to make better approximation for the solution. The surveys has run into the FLUENT® Code by the pressure based Navier-Stokes and in double precision mode within the FLUENT® Code.

2. Design and analysis of micro valve by ANSYS

For analysis the micro valve, SOLIDWORKS software is employed for modeling the micro valve. Then the designed micro valve is imported to ANSYS software for investigate some parameters which seems to be vital in designing and characterizing of micro valve systems such as stress, strain and displacement.

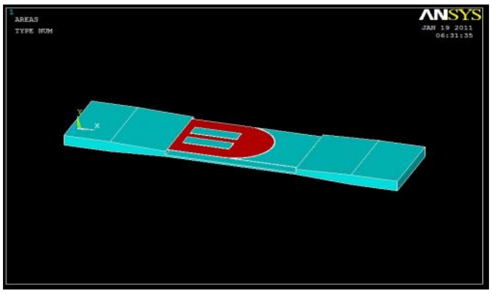


Fig .2. Schematic of microvalve designed by SOLIDWORKS software

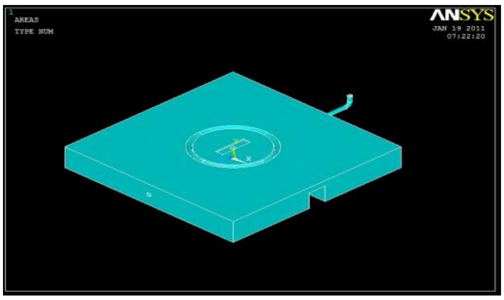


Fig .3. Schematic of completed model of microvalve system designed by SOLIDWORKS software

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In the preprocessor section for the diaphragm of micro valve SHELL93 is chosen as the element type. The other properties that must be determined before solving this problem are Young's modulus and Poisson's ratio that are convinced by using material properties table in MEMS course lectures. Meshing is the next step before solving and analyzing. Smart size is selected as an important option in meshing section. Smart size has the ability to produce fine meshes in critical regions.

For solution section Static analysis type is chosen. Then appropriate loads are applied. In the displacement section degree of freedom for the support of the cantilever beam must be bent.

IV. RESULTS AND DISCUSSION

1. FLUENT

Many models have been defined in the GAMBIT® software to investigate individually whether it would be an efficient one, or not for the flow which was passing by through the micro valve. Here, just two most important models are being introduced. First, a typical micro valve was introduced to the GAMBIT® software that a gooseneck joint was attached to the entrance boundary of the micro valve.

The incoming fluid streamed from the gooseneck joint at the velocity of 0.01 m/s, and the entrance of this joint was introduced as a velocity inlet boundary at the left bottom of the geometry. The outflow boundary was determined by the top edge within the geometry.

Then, the geometry was being exported to FLUENT® code. By analyzing some of the flow characteristics such as pressure contours and velocity profiles, we observed an op-posing pressure exactly in the region after the valve and a reverse flow before reaching to the valve. That was meant to a huge pressure drop by using the inlet gooseneck joint and resulted in an unsatisfactory efficiency. The main reason of this type of contrariness lies into the fact that the upstream of the flow directly influences on downstream current. So, the inlet condition might be changed in order to not to encounter with such these losses.

So, another model of the micro valve has been designed to investigate the follow inside channel. At first, the geometry has been constituted into the GAMBIT® environment with the lower limit as velocity inlet boundary layer and the upper one as outflow. By investigating the problem in the FLUENT® code, we observed the reverse flow again, but in the outflow of the microvalve (the upper limit region).

So, by changing the length of both the entrance and exit ducts in different characteristic lengths, a realistic decay was observed in the amount of reversed flow even in the exit line. The pressure changes in a reasonable manner and the values suggest this. As it is visible in Fig.4 the pressure changes in a reasonable manner and the values suggest this.

By referring to Fig.5, Velocity vectors are illustrated as maximum on the transition region between the below of the valve and the upper region.

The given data in the analysis also verify this procedure. Every other data needed to consider, could be obtained by the both analytical and numerical solving of the problem with the FLUENT® code.

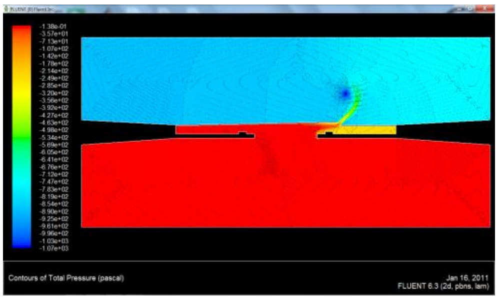

Fig. 4. Pressure contours of the optimized planning, shown in FLUENT Code

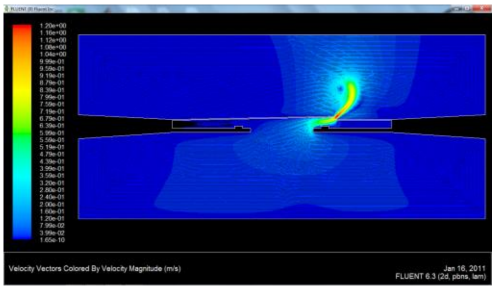

Fig. 5. Velocity vectors for optimized modling

2. ANSYS

After solving this case, in the post processing part, in the contour plot and nodal solutions, displacement vectors, stress vectors and also strain vectors will be obtained. The results of analysis are shown in the following Figures. Noting that, the pressure of value of water that is passing through the valve is: 20 µPa.Figure.6 demonstrates stress contour of valve. As it is obvious from this contour, maximum stress has occurred at the support of the beam as it was anticipated. Moreover stress at the tip of the beam shows the minimum value. Another contour is corresponded to the strain vector. As it is demonstrated in the Fig.7, maximum of strain is related to support of cantilever beam similar to the stress contour. Major parts of strain vector vary between 0.970E-06 and 0.113E-06. The next contour that is considered as one of results is displacement vector. The Fig.8 shows displacement contour. It is shown that at the tip of the beam as it was expected displacement is maximum and the value of the displacement is about 0.428E-03. Also and it is not unlikely that at the support of the beam displacement represents value of zero and it was anticipated that valve opens maximum at 15 degree from horizontal state. It seems that this value for opening of valve is logical. The last figure, figure.9 is given in this paper to show displacement vector. As it is indicated in the figure.9, red vectors have maximum values of displacement comparing to other vectors. It proves that at the tip of beam displacement would be higher than other regions of this beam.

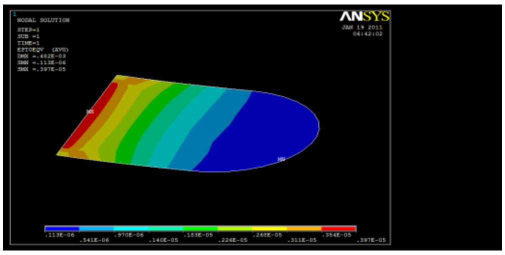

Fig. 6. Stress contour of microvalve

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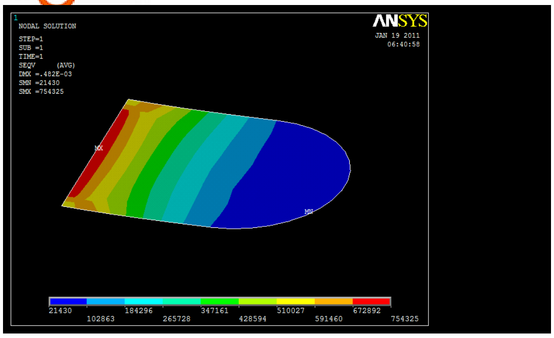

Fig . 7. Shows strain contour

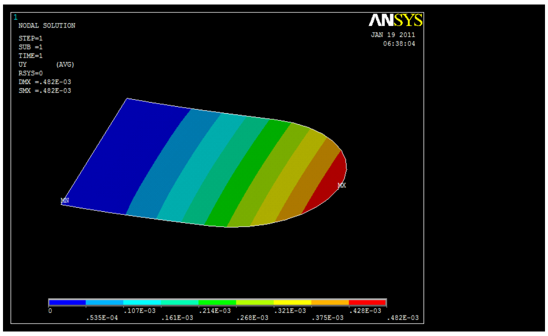

Fig . 8. Illustrates Displacement contour

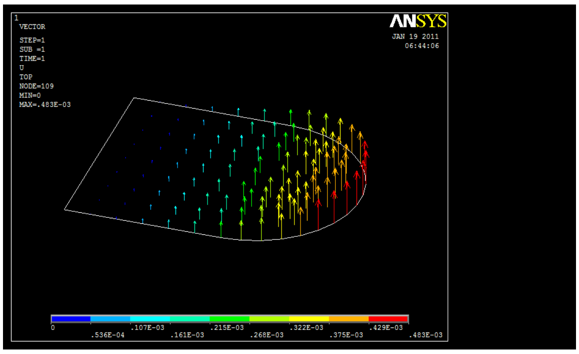

Fig . 9. Shows displacement vector

According to the below formula:

$$\varepsilon = d\,V$$

And by using table in the slides we can see that for the Quartz:

d =2.3E-12 m/volt

So by having strain we can easily find the generated voltage by piezoelectric. We should consider that in this formula V is in terms of volt/meter and since our piezo's length is 1 mm so we should divide the achieved voltage by 1E-3 and the results are as below:

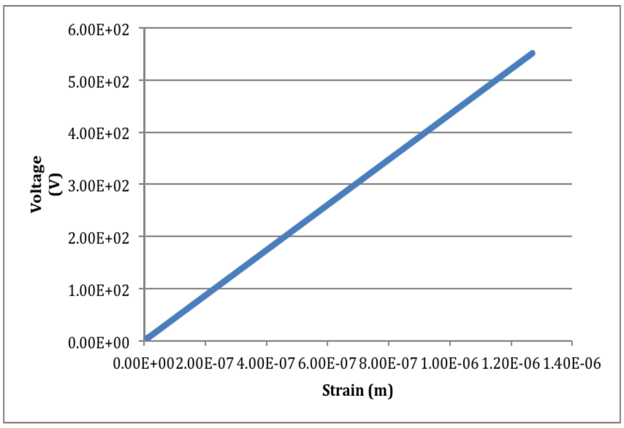

Figure . 10. Variations of strain versus voltage

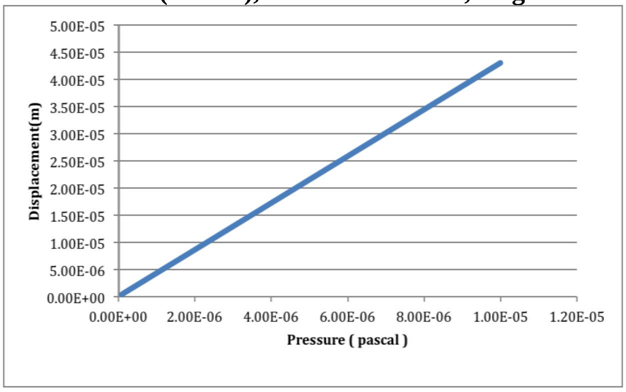

Fig . 11. Variations of pressure versus displacement

V. CONCLUSION

Here, just two most important models introduced. First, a typical micro valve was introduced to the GAMBIT® software that a gooseneck joint was attached to the entrance boundary of the micro valve. The incoming fluid streamed from the gooseneck joint at the velocity of 0.01 m/s, and the entrance of this joint was introduced as a velocity inlet boundary.

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