# DESIGN, FABRICATION AND FINITE ELEMENT ANALYSIS OF THERMO-PNEUMATIC MICRO PUMP FOR BIOMEDICAL APPLICATIONS

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**Abstract:** A thermo-pneumatic micropump has been designed with desired specifications and Finite Element Analysis has been studied using COMSOL Multiphysics. The micropump consists of a heating chamber, a diffuser, reservoir, inlet and outlet. The diffuser has been designed with the opening angle of 12º to prevent leakage from the reservoir. The micropump works on the principle by which the enclosed air inside the chamber expands to draw the liquid from reservoir to outlet. The numerical simulation suggests that the temperature of the heating chamber falls from 52ºC to the room temperature before the reservoir itself. At the start of the reservoir, the temperature was around 30ºC. The study also suggests that the temperature of the heating chamber will not affect the drug to be used in the reservoir. This study is very important because if the temperature of the chamber affects the reservoir then there will be chance of chemical reaction to be taken place inside the drug. In numerical simulation, pressure distribution profile suggests that the pressure falls from the maximum level at the chamber to minimum at the outlet. PDMS material has been chosen for the micropump because of its biocompatibility. The micropump structure has been fabricated with some easy fabrication steps and the flow has been tested without using any heaters. The device pumps out 1µL for a single stroke. If this device is implemented with heaters embedded underneath it, the flow will be controlled by applying different voltages to the heater.

**Keywords:** COMSOL, micropump, PDMS and buzzer.

## 1. INTRODUCTION

MEMS is a fast growing field which enables the manufacture of small devices using micro fabrication techniques relative to the ones that are used to create integrated circuits. In the recent years, MEMS technologies have been applied to the requirements of biomedical industry which gives rise to a new field called Microfluidics. It deals with the design and development of micro devices which can sense, pump, mix, monitor and control small volumes of fluids. The development of microfluidic systems has been rapidly expanded to a wide variety of fields. The main applications of microfluidic systems are drug delivery, chemical analysis, biological and chemical sensing, DNA analysis, amplification, synthesis of nucleic acids and environmental monitoring. Microfluidics is also an important part of precision control systems for machine tool, aerospace and automotive industries.

The use of MEMS in biological purposes (BioMEMS) has attracted the attention of many designers. There is a growing demand to design micro drug delivery systems with the newly well-developed fabrication technologies and are increasingly being used in medical fields. MEMS based microfluidic devices in general include micro needles, micro reservoirs, biodegradable MEMS devices, osmosis based devices, micropumps, and transdermal devices.

Microfluidic systems have proved highly successful in biomedical applications by minimizing the size of electrophoresis chips, drug delivery systems, microfluidic mixers, pumps and valves, devices for cell or protein patterning, and microfluidic switches. Specifically a PDMS pump is a device that is optimized for rapid prototyping and has proven to be a good material for microfluidic pump devices. PDMS stands for Polydimethylsiloxane and is most widely used as a silicon-based organic polymer. It is known for its unusual flow characteristics (rheological properties). The material is usually clear, inert, non-toxic, and non-flammable. The chemical formula for PDMS is: (H3C)[SiO(CH3)2]nSi(CH3)3, where n is the number of repeating monomer [SiO(CH3)2].

According to the definition of "MEMS", miniaturized pumping devices fabricated by micromachining technologies are called micropumps. In general, micropumps can be classified as either mechanical or non-mechanical micropumps. The micropumps that have moving mechanical parts such as pumping diaphragm and check valves are referred to as mechanical micropumps where as those involving no mechanical moving parts are referred to as non-mechanical micropumps. Thermo-pneumatic micropump falls under mechanical micropump because it consists of mechanical parts. But in recent years thermo-pneumatic micropumps have been developed without using any mechanical parts. It works on the principle of Charles law which states that volume of ideal air is directly proportional to the absolute temperature given that the pressure is held constant.

### 1.1 OBJECTIVE

The main objective of this project is to design a micropump based on thermo-pneumatic actuation and Finite Element Analysis has been analyzed using COMSOL Multiphysics. Then the proposed model is fabricated using some simple fabrication steps and the model has been tested with the flow of liquid in it. The liquid inside the reservoir of the micropump has been pumped out depending upon the supply of heat to the heating chamber. The flow rate changes depending upon the temperature has been studied.

### 1.2 PROPOSED DESIGN

A micropump consists of a heating chamber, diffuser, outlet and inlet has been designed with the following specifications: Overall dimension of the micropump structure is 22mm x 7mm x 4mm.Dimensions of heating chamber are 4mm x 5mm x 0.5mm.Diameter of the reservoir is 5mm and diameter of outlet area is 2.5mm.Both the inlet and the outlet holes are of 1mm diameter. Length of the micro channel is 4mm with the thickness of 0.5mm. The diffuser design is very important in these kinds of micro pumps because there is no membrane deflection to initiate fluid flow. The diffuser has been designed with the opening angle of 12° to prevent the fluid leakage from the reservoir to the heating chamber.

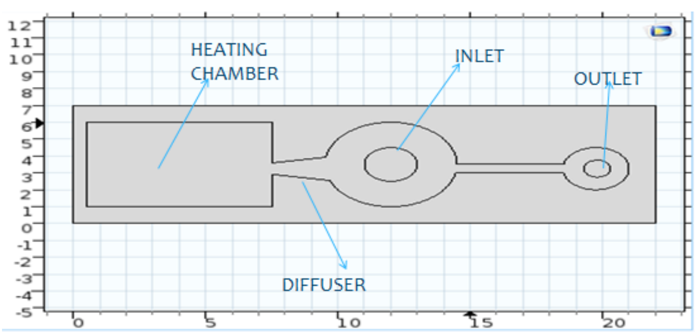


Figure 1.1 Design of proposed micropump

### 2. NUMERICAL SIMULATION

### 2.1 3D-Design

A 3D model has been created with the dimensions 22mm x 7mm x 4mm made of PDMS biocompatible material which is divided into three domains namely fluid,top-bottom and heating chamber. The following figure shows the 3D design model of the micropump. The model consists of a block in which the pump layer has been modeled in 2D using workplane that has been extruded after designing it. Inlet and outlet were also modeled in the same way but extruded till top of the pump. Use the node under Materials to add predefined or user defined materials to specify material properties using model inputs, values, functions and expressions as needed, or to create a custom material library.

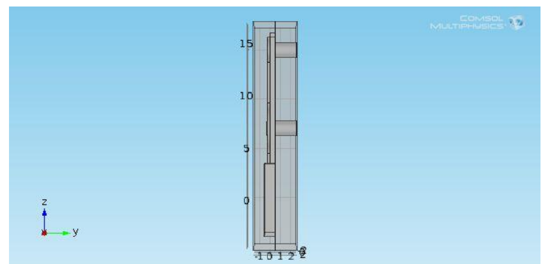

Figure 2.1 3D Model in COMSOL

Material Overview section provides an overview of the materials in the component node and where they are used. The Material column lists the current materials in the component using the materials' node labels from the model tree according to the settings.

The micropump is made of PDMS bio compatible material which can be selected under MEMS → Polymers→PDMS.

The heating chamber comprised of air which can be selected from Built in →Air. Then the domain fluid has been selected with water which can be chosen from Built in → Water. Material properties are as follows:

### 2.2 Conjugate Heat Transfer

Conjugate heat transfer profile deals with the combination of heat transfer in solids and heat transfer in fluids. In solids, mostly conduction takes place whereas in liquids it will be convection. This is observed in many occasions.Heat transfer in solids due to conduction is described by Fourier's law for conductive heat flux, q, directly proportional to the temperature gradient:

$$q = -k\nabla T$$

The temperature field changes for a time dependent problem as represented by the following equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k\nabla T) + Q$$

Heat transfer in fluid includes three extra terms which contributes for convection, viscosity and density of fluids. These terms changes the heat equation as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u}\cdot\nabla T = \alpha_p T\left(\frac{\partial p_A}{\partial t} + \mathbf{u}\cdot\nabla p_A\right) + \tau : S + \nabla\cdot(k\nabla T) + Q$$

Convection happens due to flow of fluid and also due to the thermal properties of the fluid. Fluid heating arises depending upon the viscosity of the fluid. Compression of air produces heat which contributes to the heat equation.

### 2.2 Meshing

Two different meshing has been made for the different domains of the design. Built in fine meshing has been done for the fluid domain and coarse meshing has been done for the bottom layer of the system. Free tetrahedral meshing has been done for the remaining domain.

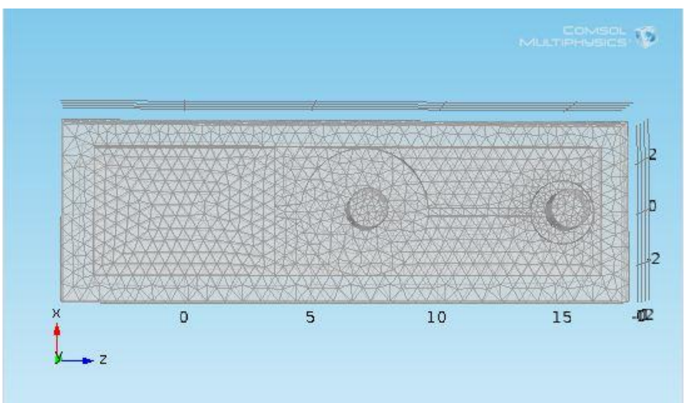

Figure 2.2 Meshing

Table 2.1 Material Properties

| MATERIAL | HEAT CAPACITY Cp [J/(KgK)] | DENSITY ρ [KG/M3] | THERMAL CONDUCTIVITY K[W/(mK)] | YOUNGS MODULUS [Pa] |
|---|---|---|---|---|
| PDMS | 1460 | 0.97 | 0.15 | 4.5 x 10^5 |
| AIR | 1.006 | 1.100 | 0.0280 | - |
| WATER | 4.183 | 987 | 648.2 | - |

### 2.3 Study

Stationary study has been carried out for the designed model. A cut line has been drawn from the chamber to the outlet to study the temperature distribution along the micropump.

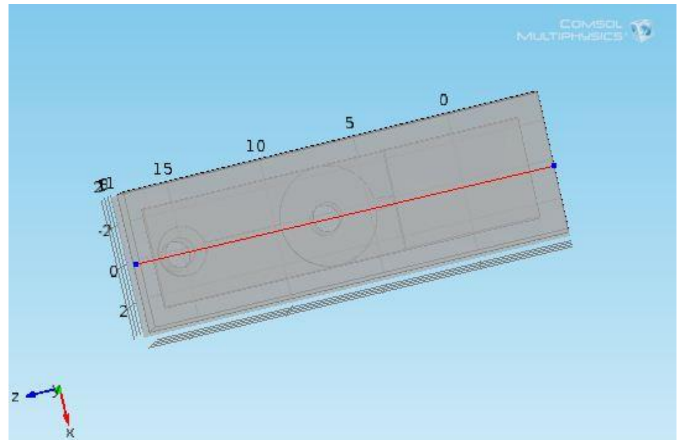

Figure 2.3 Cutline 3D

The following figure shows the flow direction from the outlet to the inlet and also the velocity field along the length of the channel.

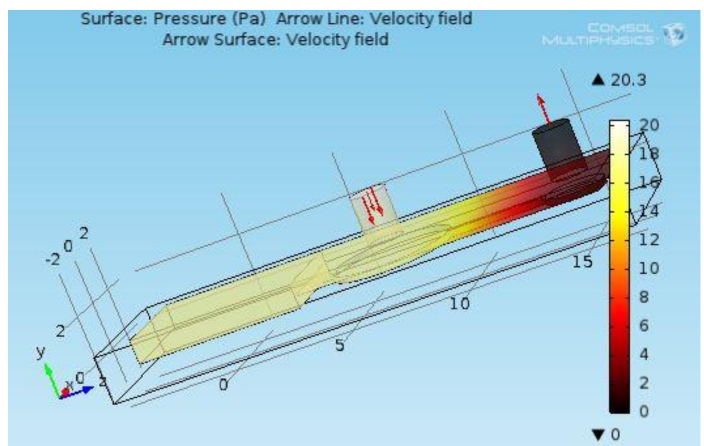


Figure 2.4 Velocity field

From the pressure distribution profile, the pressure changes from maximum value at the heating chamber to a minimum value at the outlet. The pressure was high at both the chamber and the reservoir due to the expansion of air inside the chamber. The pressure here acts as the force to draw the liquid from the reservoir to the outlet.

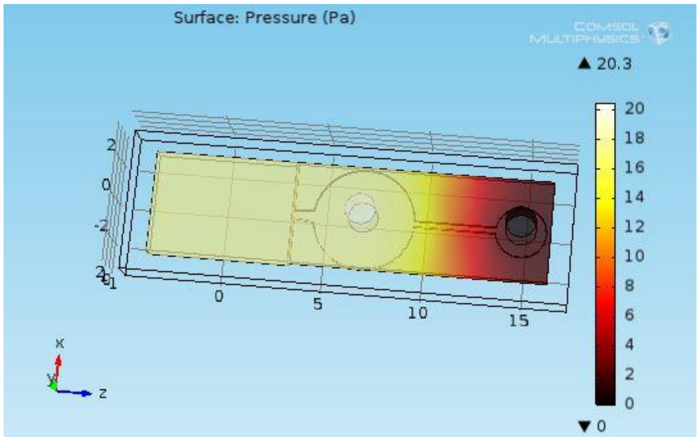


Figure 2.5 Pressure distribution

### 2.4 Simulation and analysis

#### 2.4.1 Temperature Distribution Profile

The temperature distribution profile of the model has been simulated and analysed which shows how the heat is distributed along the length of the micropump. The boundary conditions are set at the heating chamber along its four sides. The following figure shows the temperature distribution along the micropump.

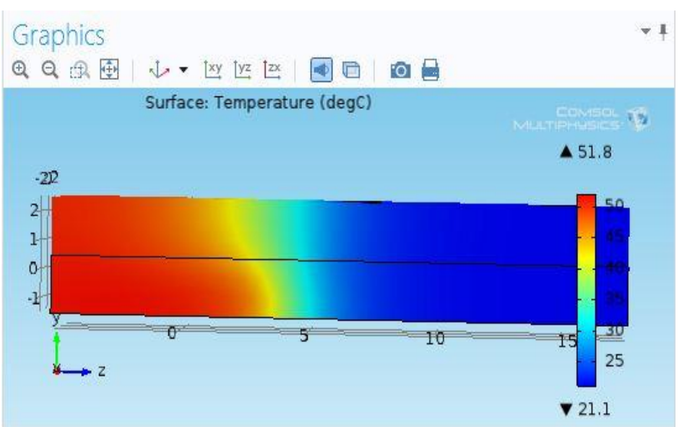


Figure 2.6 Temperature Profile

The graph obtained using the cut line along the length of the micropump shows the fall of temperature from heating chamber to the other end of the micropump. At the centre of the heating chamber the temperature is at the peak level of around 52 degC and then it falls apart.

## 3. Fabrication steps

### 3.1 Mould making

The following steps were followed during the process of mold making: The design of the micropump has been designed using Adobe Illustrator and then it was printed on the OHP sheet. The print on the OHP sheet has been used as a mask during the fabrication process of PCB. The same design has been printed on the printed circuit board which can be used as a master for the PDMS fabrication. The thickness of the copper layer on PCB is around 35µm. The printed circuit board with the design of pump structure on it has been pasted inside the Petridis as shown in the figure 3.1.

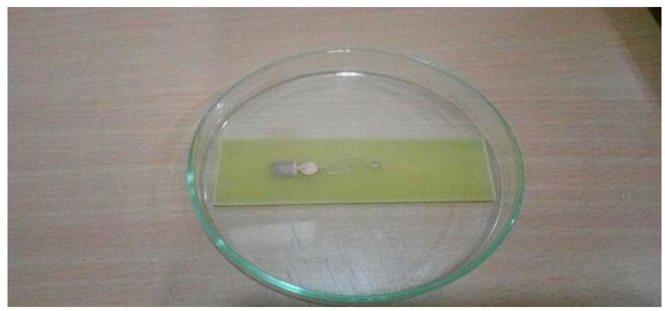

Figure 3.1 Mould

### 3.2 PDMS fabrication

PDMS is a biocompatible material which makes it widely used for biomedical applications. It can be fabricated using various methods. In this project, we have followed some easy fabrication steps as follows:

1. Chemical compounds of resin and hardener were mixed in the ratio of 10:1 thoroughly using a stirrer in a beaker.
2. The beaker was placed in the ultrasonic mixer for 30 minutes to remove bubbles in it.
3. Then the mixture was poured into the petridish in which the mold pasted inside it as shown in the figure 6.1.
4. After that the mixture was kept as like that for 20 hours for curing process.
5. The cured PDMS has been cut off from the petridish.

### 3.3 Plasma cleaning

Plasma cleaning has to be done for both the glass slide and the cured PDMS for changing the hydrophobic nature of the material to hydrophilic. Then only they both will get stick together to get the even flow through the channel. As we don't have any plasma reactor to clean, we have tried out with the simple method of creating plasma using grapes in microwave oven. The following steps have to be carried out during the process:

1. Both the glass slide and cured PDMS has been fixed to the bottom of a container like that the surface which has to be treated with the plasma.
2. A grape has been cut into two pieces and placed inside the oven.
3. Then the container was placed with the grapes inside it as shown in the figure.
4. Set the power of oven at 750W for 30 seconds.
5. Both the surfaces have been treated with the plasma for few seconds.

Bond oxidized PDMS surfaces and seal irreversibly to create leak-tight channels in microfluidic devices. Hydrophilic surfaces enhance fluid flow and wetting of channels in microfluidic devices. PDMS surface recovers hydrophobic properties after some time.

**4. Micro heater**

A micro heater with the dimension of 5mm x 4mm has been designed and developed using the PVD coating. A mask has been designed in the shape of the desired heater design for the PVD coating process. Aluminium material has been coated on the glass substrate and contacts were taken from that. When we connected the contacts with power supply, the heater didn't work because the PVD coating was not regular on the surface of the glass slide.

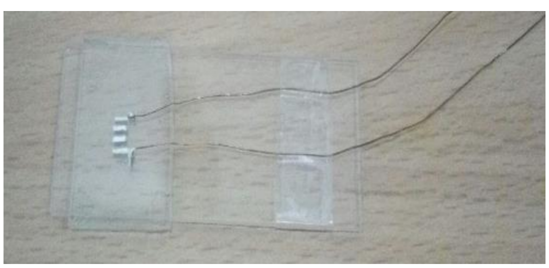

Figure 3.2 Microheater

**5. Device testing**

After treating with the plasma, both can be pasted together within a short period of time otherwise it will change back to hydrophobic. Sometimes they won't stick together after treating with plasma so many times. Then the flow has been tested by injecting the liquid into the reservoir. The flow was continuous with few air bubbles inside the microchannel.

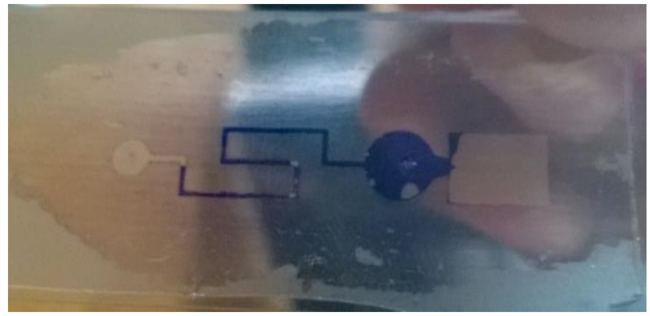

Figure 3.3 Device Testing

**6. Conclusion**

A thermo-pneumatic micropump has been designed with the desired specifications and the temperature distribution along the micropump has been studied using COMSOL Multiphysics. The diffuser design is very important in these kinds of micropumps because there is no membrane deflection to initiate fluid flow. The diffuser has been designed with the opening angle of 12° to prevent the fluid leakage from the reservoir to the heating chamber.

From the temperature profile of the micropump, the temperature changes from 51°C to 52°C at the center of the heating chamber and start falling exponentially to reach the room temperature at the reservoir. At the start of the reservoir, the temperature was around 30ºC. So this study suggests that the drug to be stored in the reservoir will not be getting affected due to the temperature of the heating chamber. This study is very important because if the temperature of the chamber affects the reservoir then there will be chance of chemical reaction to be taken place in the drug.

From the pressure distribution profile, the pressure changes from maximum value at the heating chamber to a minimum value at the outlet. The pressure was maximum at both the chamber and the reservoir due to the expansion of air inside the chamber. The pressure here acts as the force to draw the liquid from the reservoir to the outlet.

The micropump structure has been fabricated with the PDMS material by following some easy fabrication steps. The flow inside the pump has been tested by injecting fluid into the reservoir. Continuous flow of fluid in the pump has been achieved with very few bubbles in it without using heater.

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