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Modeling of Micropump Performance and Optimization of Diaphragm Geometry

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ABSTRACT

A SIMULINK model for the simulation of the valveless micropump is developed. In this model the operating parameters namely voltage, diaphragm diameter and thickness are considered for simulation. To optimize the pump performance, three commonly used materials are considered for diaphragm and their performance for different diameters and thickness's is studied. Results obtained through the developed model compare well with earlier results. The volumetric discharge versus pressure difference is used for characterizing the pump performance.

General Terms

Modeling and Simulation.

Keywords

Valveless micropump, SIMULINK model, optimization

1. INTRODUCTION

Micropumps are being used in the field of space exploration, cooling of micro devices, drug delivery where small and accurate flow control is essential. For instance in the injection of insulin to diabetic patients or chemotherapy given to cancer patients[1] or in space explorations[2] and more recently in the cooling of lab-on chips[1] micropumps are used. In all these applications where we require minimal usage of space and power consumption and at the same time require high precision and accuracy, the use of piezoelectric actuated micropumps is generally preffered.

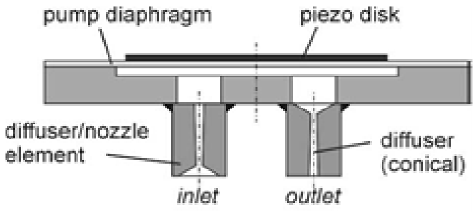
Micropumps can be classified as dynamic pumps and displacement pumps. Dynamic pumps are based on the principle that force due to electrostatic and magnetic fields can be used to displace the fluid such as electro hydrodynamic [3] and magneto hydrodynamic pumps [4]. The displacement micropumps on the other hand have diaphragms which are actuated by piezoelectricity. Several actuating principles have been used to develop micropumps, they are electromagnetic [5-6], piezoelectric [7-9], shape memory alloy [10], electrostatic [11], and thermo-pneumatic [12] devices. The advantage of using piezoelectric actuation is that it is a simple structure and consumes less power. When a voltage is applied to the piezoelectric film, it deflects thereby deflecting the diaphragm attached to it. Displacement micropumps are based on the principle that change in volume of the pump chamber, due to the deflection of the diaphragm, exerts pressure on the fluid to displace it from the inlet to the outlet side using moving mechanical parts such as valves.

Micropumps conventionally have active valves for closing and opening during the pumping and delivery cycles [13]. Unfortunately these pumps are fragile and costly due to cumbersome fabrication process for valves. Moreover wear and fatigue can be a critical issue and there is also a risk of valve blocking by small particles which instantly degrade the pumping performance. Hence the need for a pump with no moving parts arises. An alternative to active valves was proposed by Stemme et al. [7] where valves are replaced by diffuser/nozzle elements which have flow directing properties to pump fluid.

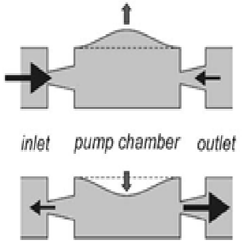
Over the past decade valveless micropumps have been extensively studied by various researchers. Almost all the research literature available on valveless micropumps deals with improving the pump performance by varying the diffuser/nozzle parameters ([14], [15]), by having more than one pumping chamber actuated in phase or out of phase[16,17] or by experimenting with different actuation principles. In this present study , a SIMULINK model is proposed based on the mathematical model for micropumps developed by Ullmann [18]. Using this model the design and operating parameters of the micropump is optimized.

2. PRINCIPLE OF VALVELESS OPERATION IN MICROPUMP

A schematic configuration of a piezoelectric actuated valveless micropump is shown in Figure 1(a).The pump consists of two diffuser elements which are connected to a pump chamber at the inlet port and the outlet port of the micropump with a piezoelectric disc attached to a diaphragm. The diffuser/nozzle element offer direction dependent flow resistance. A diffuser is a channel for which the cross section diverges in the flow direction and a nozzle is a channel whose cross section decreases in the flow direction.



(a)



(b)

Figure1:The valveless micropump (a)Schematic diagram (b)Pumping principle [19]

The working principle of the valveless micropump is shown in Figure 1(b).The valveless micropump works in two modes i.e. the suction mode and the discharge mode. In the suction mode, as the volume of the pumping chamber increases, more fluid enters the pump chamber through the input port which acts as a diffuser than that through the output port which acts as a nozzle. In the discharge mode, the volume of the pumping chamber decreases so more fluid goes out of the output port which now acts as a diffuser than the input port which acts as a nozzle. Hence, net fluid transport is achieved in the pumping chamber from the input port to the output port.

3. PUMP PERFORMANCE MODEL IN SIMULINK

An analytic model to predict the maximum flow (at zero pump pressure) and the maximum pump pressure (at zero pump flow) was presented by Stemme and co-workers [7] and [15]. The model is based on the continuity consideration and requires an input of the nozzle parameters, frequency and volumetric displacement. The analysis using the continuity equation was extended (Ullmann [18]) to predict the pressure variations and output flow rate during a single cycle of pumping. The output flow rate obtained is integrated over time period of the pump. The values of the output flow rate is calculated for various pump pressures. The plot of output flow rate versus pressure difference is obtained to study the characteristics of the micropump. Based on the earlier work it can be reasoned out that the performance of the pump can be attributed to its ability to have high flow rate and output pressure over a cycle. The performance of the micropump is governed by various parameters as shown in Figure 2.

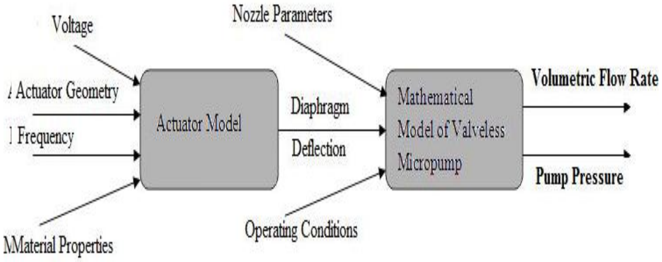


Figure 2: Mathematical model of the valveless micropump

The parameters; voltage, actuator geometry, frequency of actuation and material properties are inputs to the actuator model to calculate the deflection of the diaphragm. Based on the earlier work [18] following equations are used to develop the SIMULINK model. The Equations (1-2) are used for the calculation of the diaphragm displacement and volumetric displacement respectively.

$$X = \frac{0.55R^2}{EL_D{}^3}F \qquad (1)$$

Where R is the radius of the diaphragm, L_D is the thickness of the diaphragm, and E is the Young's Modulus of the diaphragm. F is the force acting on the diaphragm due to piezoelectric actuation. Force acting on the diaphragm is directly proportional to the actuation voltage and inversely proportional to the stress constant of the piezoelectric material. The volumetric deflection is calculated by using Equation (2)

$$V_o = \frac{\pi}{4} * d^2 * X * K_v \qquad (2)$$

Where d is the diameter of the diaphragm and K_V is an additional correction factor since X is the maximum central deflection, the volumetric displacement is less than A_D*X, where A_D is the area of the diaphragm.

The volumetric displacement, nozzle parameters and operating conditions of the micropump i.e. pressure at the inlet and the outlet pipes are inputs to the model of the valveless micropump to calculate volumetric flow rate and pressure variations within the micropump chamber for one complete pump cycle.

The time dependent volume displacement of the pump is given by

$$V = V_0 \;[1 - \cos(\omega t)] \qquad (3)$$

Where ω is the angular frequency, t is the time, Vo is the maximum volumetric amplitude and V is the instantaneous volumetric amplitude. Pressure difference in the nozzle can be equated to flow-rate as:

$$Q_1 = C_h\sqrt{P_{in} - P} \text{ for } P_{in} - P > 0 \qquad (4)$$

$$Q_1 = -C_l\sqrt{P - P_{in}} \text{ for } P_{in} - P < 0 \qquad (5)$$

$$Q_2 = C_h\sqrt{P - P_{out}} \text{ for } P_{out} - P < 0 \qquad (6)$$

$$Q_2 = -C_l\sqrt{P_{out} - P} \text{ for } P - P_{out} > 0 \qquad (7)$$

Where C_h and C_l are the conductivity coefficients of the micropump. Differentiating above equations and equating to the corresponding Q_2- Q_1 yields the governing equation of the pump. The equation is solved in three different regions and three equations for three different cases are obtained: Case 1: $P>P_{out}>P_{in}$, Case 2: $P<P_{in}<P_{out}$, Case 3: $P_{in}<P<P_{out}$ .Using Equations(2)-(7) the mathematical model of the pump is developed in SIMULINK to obtain volumetric discharge and pressure.

The SIMULINK model for the actuator is shown in Figure 3.The simulation parameters considered are diaphragm thickness and diameter ,diaphragm material and actuation voltage. The parameters of the piezoelectric disc used for actuation are inputs for estimating the diaphragm deflection.

The SIMULINK model of the valveless micropump is shown in Figure 4. The deflection of the diaphragm is input to the model for the valveless micropump for estimating volumetric discharge and pressure. The parameters of the pump and the operating conditions such as; the pressure loss coefficients K_h and K_l, the liquid density ρ, outlet pressure P_{out}, frequency f and inlet pressure P_{in}, are inputs to the model of the valveless micropump in SIMULINK.

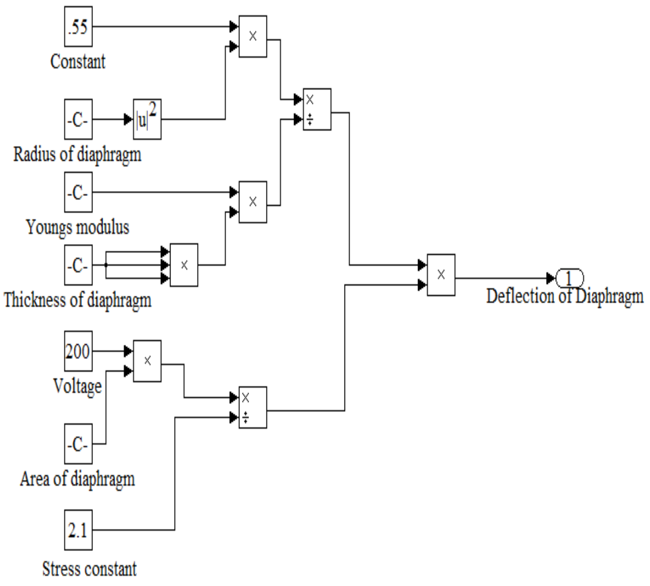


Figure 3: SIMULINK model for the actuator

The pump parameters used for the simulation are shown in Table 1. The simulation is carried out for three materials Aluminium, Copper and Silicon. These materials are commonly used for making the diaphragm and have Young's Modulus of 69 GPa, 110 GPa and 180 GPa respectively. The pumping liquid chosen is water and the pressure difference across the inlet and the outlet is chosen to be zero for the sake of simplicity. The simulation time is chosen and the block is simulated to obtain pressure variation and volumetric discharge for a single pump cycle. Average performance of the pump is then determined from the above.

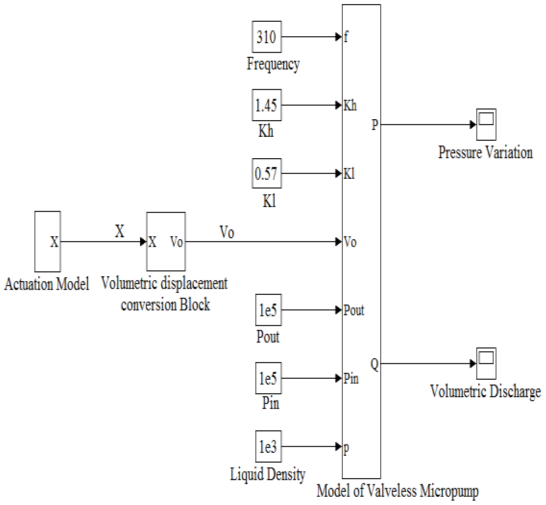


Figure 4: SIMULINK model of the valveless micropump with integrated actuator model

Table 1:Pump Parameters

Disc membrane material	-Aluminium , Silicon, Copper
Disc density for Aluminium	-2700 kg/m³
Disc density for Silicon	-2329 kg/m³
Disc density for Copper	-8940kg/m³
Piezoelectric device diameter(PZT BM- 400)	-10 mm
Liquid Density	-1000 kg/m³
D_n	-0.53 mm
K_h	-1.45
K_l	-0.57
P_{in}	-1 bar
P_{out}	-1 bar
f	-310 Hz
g_{33}	-0.03 (Vm/N)

4. RESULTS AND DISCUSSION

The variation of pressure within the pump chamber and volumetric discharge for a single pump cycle is shown in Figure 5a and Figure 5b respectively. The pressure and volumetric discharge for Aluminium is highest as its Young's modulus is lowest and the pressure and volumetric discharge for Silicon is lowest as its Young's modulus is highest, among the selected materials.

To study the effect of voltage on the output flow rate different voltage should be selected as per the application voltages in steps of 100V are applied. It can be inferred from Figure 6. that a larger voltage produces a larger diaphragm deflection and hence higher volumetric flow rate . In practical applications we cannot keep on increasing the voltage as it would affect the material properties of the diaphragm, hence voltage should be selected as per the application.

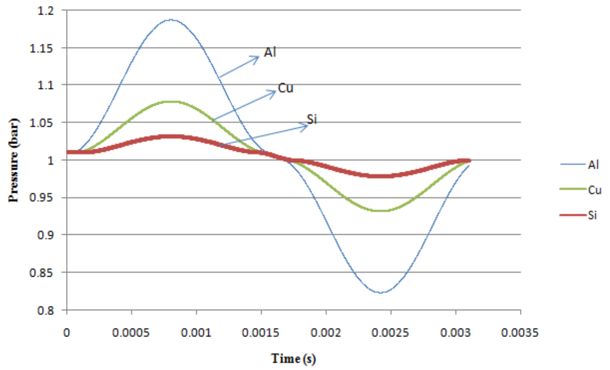


Figure 5a: Pressure variation with time for one cycle of pumping

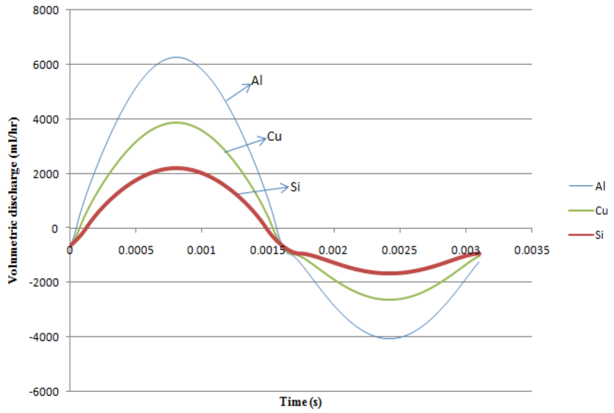


Figure 5b:Output flow rate variation with time for one cycle of pumping

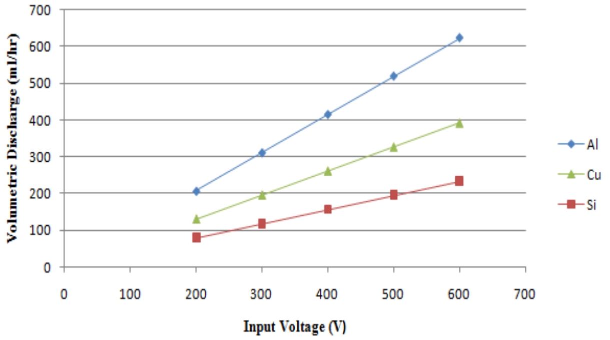


Figure 6:Variation of volumetric discharge with voltage applied

The variation of volumetric discharge of the pump with diaphragm thickness at an actuation voltage of 200V is shown in Figure 7. It can be observed that with increase in thickness, there is a considerable decrease in volumetric discharge for all the materials. Since the Young's Modulus for Aluminium is least the volumetric discharge is higher than the other two materials. The results obtained for this parameter optimization are in good agreement with the ANSYS simulation values obtained earlier [20]. We can infer from this parameter optimization that the material chosen for the diaphragm should have a low Modulus of Elasticity .

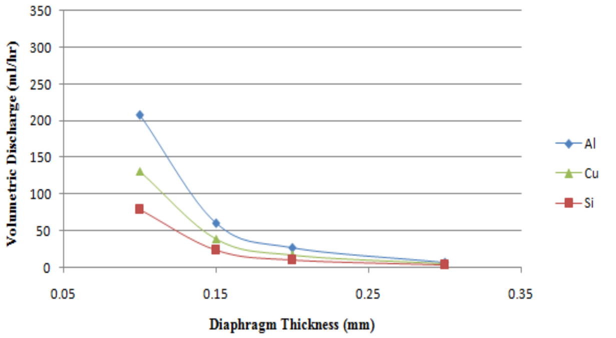


Figure 7: Variation of volumetric discharge with diaphragm thickness

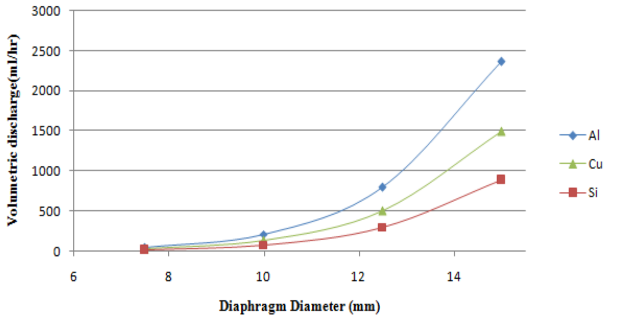


Figure 8: Variation of volumetric discharge with diaphragm diameter

To study the effect of diaphragm diameter on the output flow rate the diaphragm diameter was varied from 7.5 mm to 15mm in steps of 2.5 mm, at 100 micron thickness of diaphragm and 200 V. It was observed that there was a drastic increase in volumetric discharge for a small variation in diameter which can be seen in Figure 8.

The plot of volumetric discharge with pressure difference between inlet and outlet is plotted in Figure 9. The results are obtained via numerical simulation of Equations (3) – (7). The pressure was varied and the volumetric discharge for each pressure is obtained. The results show a straight line relation between discharge and pressure difference between inlet and outlet for all three materials. The thickness of the diaphragm is 0.1 mm, the diameter of the diaphragm is 15 mm and the actuation voltage and frequency chosen are 200V and 310 Hz respectively. It is observed that for Aluminium the maximum pressure and output flow rate is the highest among the three chosen materials. Since the graphs show a straight line relation between pump pressure and volumetric flow rate of the pump, it would therefore be easier to determine the pump pressure at zero flow and volumetric flow rate at zero pump pressure and obtain the characteristic curves for various parameters. The relation between discharge and pressure agree well with [7] and [18].

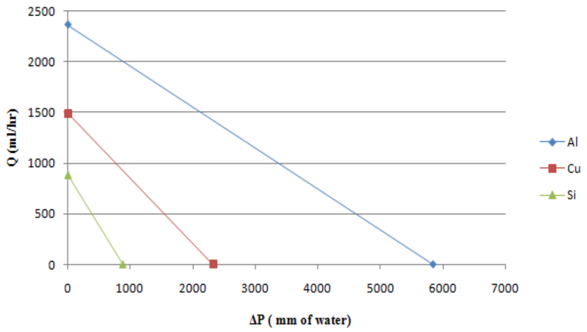


Figure 9: Variation of discharge with pressure difference

5. CONCLUSION

In this present work a SIMULINK model is developed for the optimization of parameters of the valveless micropump based on its mathematical model . The model is capable of predicting the performance of the micropump for a various geometries and actuating parameters.

It is found through simulation that increase in voltage increases the volumetric discharge linearly. The best material among the chosen materials is Aluminium as it shows highest volumetric discharge. With increase in diaphragm thickness the volumetric discharge decreases indicating that the diaphragm material should be as thin as possible. The volumetric discharge increases exponentially for small changes in diaphragm diameter, thereby showing that there is a tradeoff between the space constraints and the volumetric discharge needed for the required application.

The developed model is capable of predicting the performance characteristics of the micropump in the form of volumetric discharge versus pressure difference graphs. It is found that both the volumetric discharge at zero pressure and the maximum pressure for Aluminium is highest.

It is demonstrated here that despite the complexity involved in the physical behavior of the valveless micropump, the model presented here predicts the performance for various parameters and can be used as a design tool.

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