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# DESIGN OF NOVEL MICRO-PUMPS FOR MECHATRONIC APPLICATIONS

*Hamid Asadi Dereshgi
Faculty of Technology, Department of Mechatronics Engineering Sakarya University, Turkey

## Abstract

Due to the rapid development and increasing usage of micro fluid instruments in recent years, their fabrication has attracted a lot of attention recently. Micro-pumps are one of the sub branches of electro-mechanics along with the non-return valves or nozzle/ diffuser elements. Because of the problems arising with non-return valves such as blocking, erosion, failure of moving parts and etc., researchers incline towards the micro-pumps with nozzle/diffuser elements which are more reliable due to the simplicity and maintenance free characteristics. The main target in this paper is to modify the design of micro-pumps in such a way to increase the net flow rates while decreasing the fabrication cost. There are mainly three micro-pumps considered. One of them is the reference micro-pump which has a single chamber, an actuated by piezoelectric, an inlet (Nozzle) and outlet (Diffuser) elements. The second one is designed by modifying the internal space of the chamber by combining the rectangular and elliptical shapes together, which is hereby, named arched chamber Micro-pump. The third one is modelled in which two reference chambers are in parallel with a single piezo-electric actuator located at the interface. In the simulation carried out, the basic elements of reference, arched chamber, and parallel micro-pumps are modelled in equivalent conditions for easy comparing. The result shows a major improvement in arched micro-pump with respect to net flow rates, by decreasing back pressure value and eddy currents.

**Key words:** Nozzle/diffuser elements, piezoelectric actuation, COMSOL Multiphysics

## 1. Introduction

Due to the rapid development and increasing usage of micro fluid instruments in recent years, new researches are started in related areas of mechanics. Especially, when various problems arising with non-return valves such as blocking, erosion, failure of moving parts and etc., are frequently encountered in real world applications, the reliability of micro-pumps is seriously questioned. Therefore, these circumstances push researchers towards to work on micro-pumps with nozzle/diffuser elements, which are more reliable due to the simplicity and maintenance free characteristics [1-5].
Micro-pump are used to delivery accurate and small volume of liquid in chemical, biological or medical systems as one of the main components for delivery of liquid and samples in micro processing system. Properties such as high performance, low energy consumption and fabrication cost, simplicity in design and easy accessibility are the main requisitions of micro-pumps. Micro-

*Corresponding author: Address: Faculty of Technology, Department of Mechatronics Engineering Sakarya University, Turkey

pumps are mostly researched in 2D printers, drug delivery systems and other related areas in mechatronics [6-8]. Basic micro-pump components are piezoelectric crystal, membrane, chamber, nozzle / diffuser or non-return flap type valve. Schematic of a micro-pump is simply shown in Figure 1. In the figure it can be seen that by connecting piezoelectric crystal to an AC source, the crystal starts vibrating at the same frequency as the electric source. With the range proportional to the voltage of the source, it causes the membrane to vibrate accordingly, at the same time, results to fluid movement due to the presence of nozzle/ diffuser.

The structure of nozzle/ diffuser pair is designed such a way that a diffuser acts as an outlet valve while nozzle acts as an inlet valve. The different types of micro-pumps actuators can be used such as thermos-elastic, electro-static, electromagnetic, bimetallic, shape memory alloy and thermos-plastic [9]. Important parameters for improving a micro-pump performance are; thickness of piezoelectric actuator, wall thickness on membrane, shape of chamber, length of the nozzle/ diffuser and angle of opening on nozzle/ diffuser [10].

Piezoelectric actuator demonstrates good efficiency in medium pressure and consumes low energy for medical usages. Because of these properties, it is widely used in many areas [11-12]. Piezoelectric actuator works parallel with membrane. When an electric power is applied, piezoelectric actuator generates vibrations in vertical axis of the membrane (membrane is supposed by a silicon layer that isolates the chamber from piezoelectric). Because of the vibrations, the volume of chamber changes accordingly. When the membrane moves down, it generates a positive pressure in the fluid.

Hence the liquid moves out of chamber [13]. It is essential to choose the material of membrane in accordance with type and method of usage. The expense of membrane should be scrutinized; it should be of an appropriate material to resist against the wear and erosion. Silicon, Aluminum and Copper are among the membrane materials widely used in piezoelectric actuators [14-19].

Olsson (1998), used finite elements method (FEM) to analyze performance of a single chamber micro-pump and dual serial chamber micro-pumps in his Ph.D. thesis. The simulation results showed the higher performance of dual serial chamber micro-pumps to others [20]. In another essay, nozzle/ diffuser element is studied in order to decrease the eddy currents in the fluid path. The simulation achieves that when the sharp edges rounded in diffuser and deflected inward in nozzle [21].

B. Fan (2005) from university of Houston researched on the effects of voltage and frequency vibration on pumping speed (flow rate) and the results show that pumping performance depends on the frequency and voltage applied to the piezoelectric. Since the voltage causes the amount of curvature on the membrane and the frequency results the number of vibrations per second on diaphragm. It is observed that increasing both voltage and frequency properly (proportionally) improves the efficiency of flow rate. But in the case of constant voltage, increasing the frequency decreases the efficiency of pump due to the decrease in peak displacement during vibrations [22].

Qifeng et al. from Shanghai University introduce a non-valve dual chamber piezoelectric actuated micro-pump in which performance of micro-pump depends on the membrane vibration and characteristics of current in nozzle/ diffuser. Structure of micro-pump consists of three layers. Glass, silicon and piezoelectric crystal are attached together. It has three nozzle/ diffusers, two chambers and two piezoelectric elements.

The three elements of nozzle/ diffuser have the same dimensions and are used as entry and exit for different chambers of micro-pump. Two chambers of the micro-pumps are connected together with a medium diffuser element. While the micro-pump is in operation, piezoelectric crystal causes deflection of the membrane. When the diaphragm on chamber is vibrating upward, it moves in opposite direction in the other chamber (vibrating downward) [23].

Azarbadegan (2010) uses two single chamber micro-pumps in parallel in which inlet line and outlet line of two parallel micro-pumps are connected together in order to decrease the back pressure and hence increase the net flow rate. The results show an improvement of 10% to 15%, compare to the results of Olsson's [24].

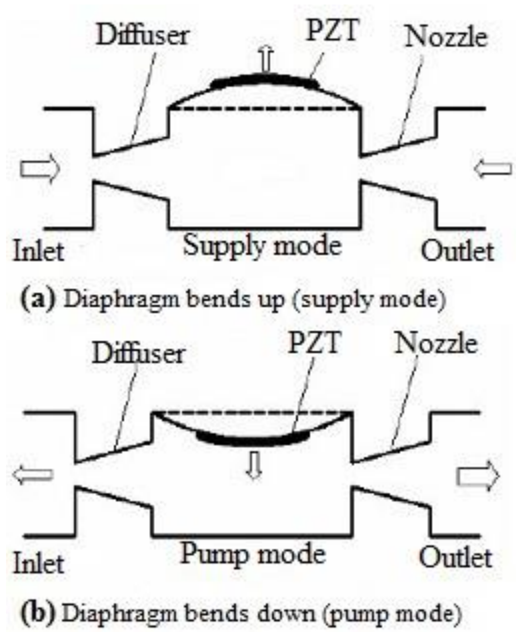


**Figure 1.** The working principle of a piezo electrically actuated valveless micro-pump [9]

The main goal in this paper is to modify the design of micro-pumps in such a way to increase the net flow rate while decreasing the fabrication cost. Meantime, the simulation of a reference single chamber micro-pump is also carried out, enabling to compare the results / output with the modified/ designed micro-pump. The simulated reference micro-pump is a single chamber, actuated by a piezoelectric crystal and has inlet and outlet nozzle/ diffuser elements. By modifying the internal space of the chamber by means of combining the rectangular and elliptical shapes together, a new type of micro-pump is designed and named as "arched chamber micro-pump". In the simulations carried out, the basic elements of reference micro-pump and arched chamber micro-pump are designed in such a way that the results can be compared.

The mentioned simulations show major improvements in net flow rate, by decreasing back pressure value and eddy currents. In addition to above mentioned types, another type of a micro-pump that consists of two reference chambers in parallel with a single piezoelectric actuator in between is designed and simulated. In the design, while the piezoelectric moves in positive direction, insert pressure on the fluid inside the chamber pumps the fluid out. At the same time, the resultant vacuum in the lower chamber causes suction and vice versa while the piezoelectric moves in negative direction .The advantage of above mentioned design is, that both suction and discharge occur at the same time/ stroke simultaneously and result uniform flow instead of pulsing flow that is produced by a single chamber micro-pump.

## 2. Materials and Method

### *2.1. Geometry of the micropumps*

Simulated all micro-pump's dimensions, materials and the simulator voltage are selected according to the available technology on the market. Geometries of the micro-pumps are shown in Figure 2. The main components of this micro-pumps equally selected and listed in Table 1.

In the simulations, the objective is to obtain maximum net flow. For this reason, the design is optimized to eliminate areas that have no high density. Therefore the diffuser's opening attached to the micro-pump's body is considered approximately near to micro-pump's chamber height. Whenever, the height of chamber is small enough, the net flow rate becomes high. So, when the diaphragm in the second period moves downward and if the chamber's height is small, the more pressure affects the fluid. Other important parameters in the designing of a micro-pump include; length of nozzle/ diffuser (the longer the better), angle of opening on nozzle/ diffuser (the smaller angle means better performance), higher thickness of piezoelectric crystal compare to membrane, piezoelectric voltage and frequency [10].

The simple shape (reference) micro-pump's chamber is considered to have a cylindrical or rectangular shape for improving micro-pump performance. The fluid in the corners of chamber is considered as dead space (unnecessary) and to investigate this issue in the simulated micro-pumps, two lower corners of the left and right portions of the lower chamber, are removed. The chamber is combined by an ellipse and a rectangle, so that the small radius of the ellipse 100 $\mu m$ and large diameter 6000 $\mu m$ are used.

In other words, the arched chamber micro-pump is simulated by changing the geometry of the reference micro-pump. The structure of double-chamber micro-pump is so that two cylindrical or rectangular chambers are in parallel mode, and piezoelectric is between the two chambers, and used as an actuator for both chambers. A membrane is used for the piezoelectric to separate it from fluid environment. Each chamber has its own nozzle/diffuser element, or in other words the micro-pump has two inputs and two outputs. The volume of fluid chambers in all micro-pumps is same.

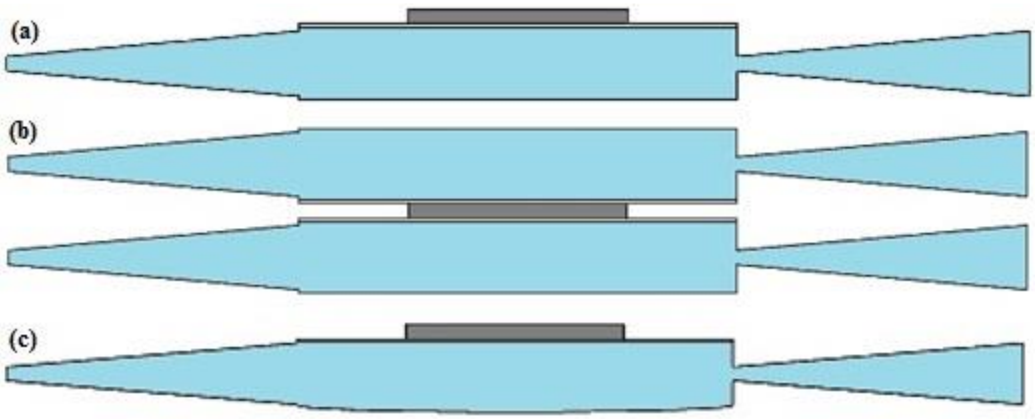


**Figure 2.** Geometric view of micro-pumps (a: Reference micro-pump, b: Double chamber micro-pump with parallel mode, c: Arc-chamber micro-pump)

**Table 1.** The same geometrical characteristics of micro-pumps

| Micro-pumps component | |
|---|---|
| Chamber length | 6000 $\mu m$ |
| Chamber area | $6 \times 10^{-6}$ $m^2$ |
| Nozzle / diffuser angle | 10° |
| Nozzle / diffuser length | 4000 $\mu m$ |
| Membrane width | 6000 $\mu m$ |
| Membrane thickness | 50 $\mu m$ |
| Piezoelectric width | 3000 $\mu m$ |
| Piezoelectric thickness | 200 $\mu m$ |
| Piezoelectric material | Lead Zicronate Titanate (PZT-2) |
| Membrane material | Silicone |
| Fluid | Water |

### 2.2. Diaphragm in the micropumps

The sinusoidal voltage $200\times\sin\,(2\pi\ \times 10t)$ of all diaphragms is considered in which its amplitude is 200V and natural frequency is 10 Hz. By clamping the two corners of diaphragm, only vertical motion is allowed. In the first half period, diaphragm vibrates upwards, and in the second half period moves downward.

The maximum vertical displacements of diaphragms (along with y axis) can be seen in Figure 3 in which the displacement corresponds the center of diaphragm because, always the maximum value of the displacement occurs in the center, and minimum displacement are related to the corners of the diaphragm. Displacements in reference chamber and arched micro-pumps are equal, and insignificant differences are due to the arched shape geometry.

Because, in the second half period, diaphragm bends inward in chamber and is similar to arched chamber floor, diaphragm can easily to be bent downward. In the double-chamber micro-pump the fluid pressure is in two directions (from top and bottom), so resistance against diaphragm vibration is high. Diaphragm's displacement causes pressure change in the pump's chamber, and Figure 4 shows pressure distributions in the arc-chamber micro-pump, double chamber micro-pump with parallel mode and reference micro-pump.

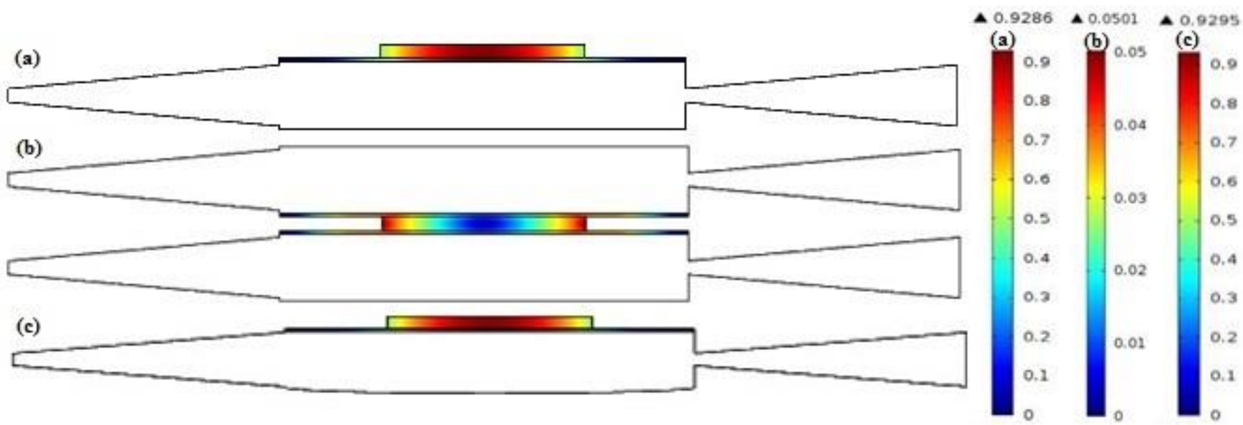


**Figure 3.** Deformation of diaphragm in the Micro-pumps

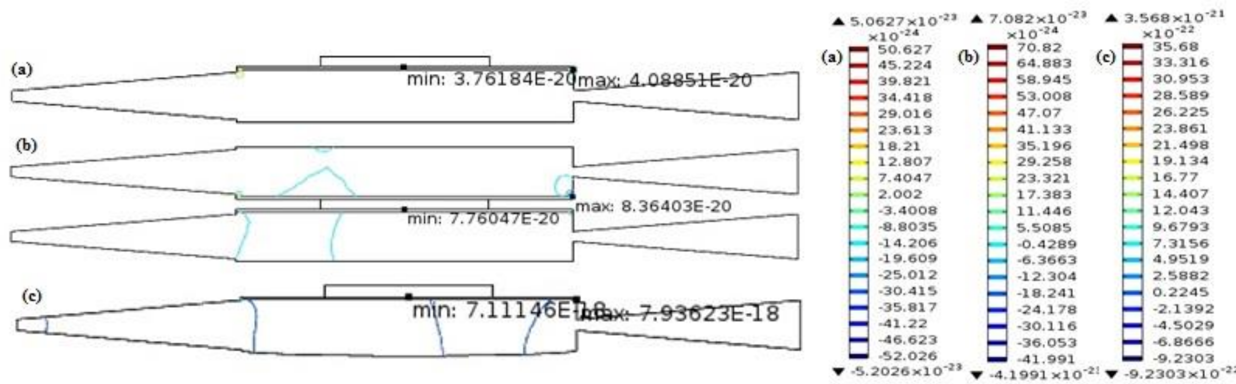


**Figure 4.** Pressure distribution in the different parts of the micro-pumps

### *2.3. The effect of voltage on the displacement of the diaphragms*

Voltage causes a curvature on vibrating diaphragm, and the frequency determines the times of vibration. If the applied frequency was high, the diaphragm can't reach the maximum displacement. If the excitation frequency will be constant, increasing in the voltage rate increases the spatial variability of the diaphragm. As a result, the net flow rate and applied pressure on the micro-pump increase also. Displacements of diaphragm for micro-pumps other than 200V in 100V and 300V are calculated and are given in Table 2.

**Table 2.** The displacement (μm) of the micro-pump's diaphragm in different voltages

| | 100V | 200V | 300V |
|---|---|---|---|
| Reference micro-pump | 0.4626 | 0.9286 | 1.3978 |
| Arc-chamber micro-pump | 0.4638 | 0.9295 | 1.3998 |
| Double chamber micro-pump | 0.0251 | 0.0501 | 0.0752 |

### *2.4. Net flow in the micro-pumps*

Micro-pumps simulations are modeled and carried out in two dimensions. Thus, the obtained net flow rate is in square meter unit. In the second half of period, because of the applied sinusoidal current, diaphragm moves down and increases pressure in the chamber. As a result, the fluid is transported out of the chamber, and in this position, because the resistance of the fluid passing through the nozzle is more than the resistance passing through the diffuser.

Obviously, passing flow through nozzle is less than the passing through the diffuser. In the nozzle/diffuser element, the amount of pressure loss, at input and output is high [25]. It's clear that in the designing of arched shape chamber, due to turbulence and eddy currents and also catalyzing of current, the speed and the flow increase. While the low amplitude of diaphragm's vibration reduces the maximum pressure in the double-chamber micro-pump, the existence of two chambers makes the flow rate increase. The results of flow are shown in Figure 5.

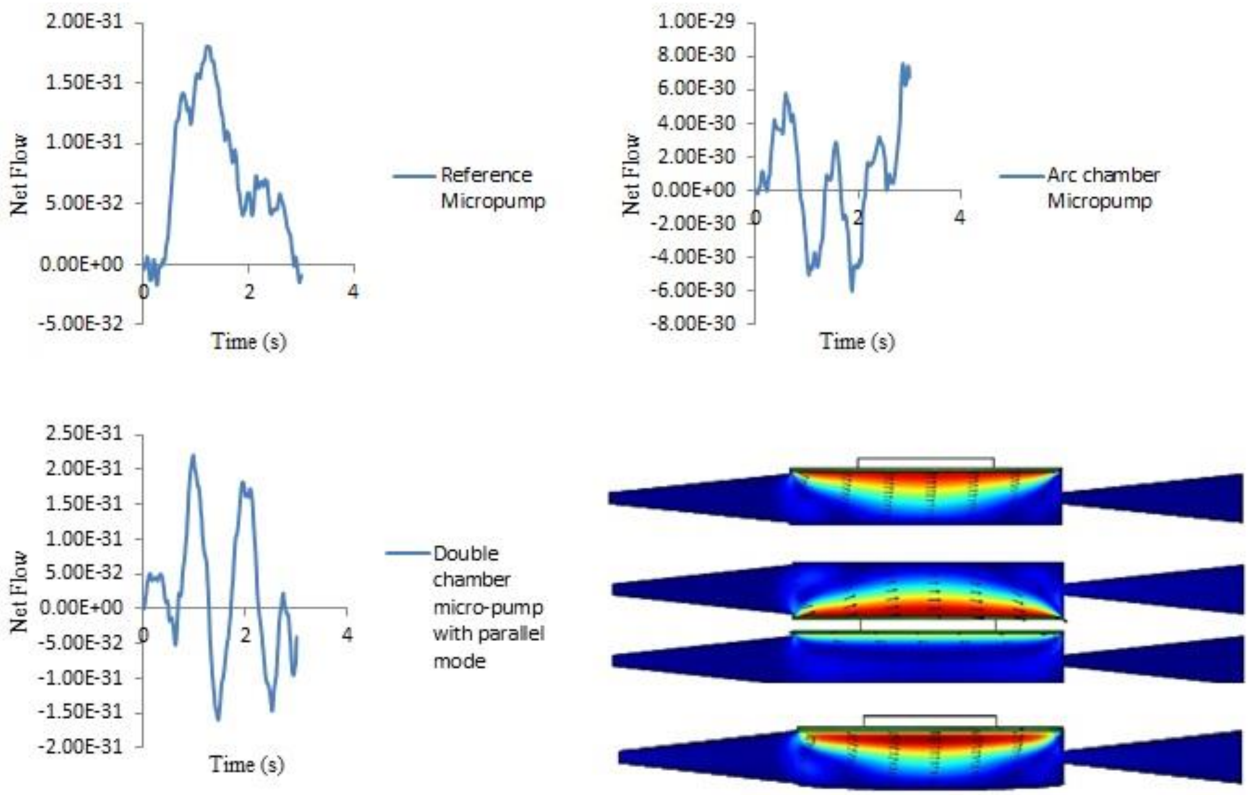


**Figure 5.** The values of net flow of micro-pumps in the three-time performance

### *2.5. Micro-pump simulations*

COMSOL software is a powerful interactive environment for modeling and analysis of a variety of scientific and engineering problems. The software can be easily used to analyze the conventional model in one kind of physics or to span multiple physical models or coupled physical phenomena simultaneously.

Many applications in real world include a system of coupled partial derivative differential equations. A micro-pump simulation is one of these. A unique feature in the COMSOL software is to develop multiple-physical simulations. The use of variable defined coupled throughout the simulation connects PDE models in different geometries.

This is a step towards modeling at the system level. Another unique feature of COMSOL is the ability for combining the areas in different spatial dimensions in the same problems. This flexibility not only simplifies the modeling, but also reduces the running time.

## 3. Results of simulations

After finishing all analyses of micro-pumps, results for each micro-pump are given in Table 3. In all cases, 200 voltages and 10 Hz frequency are applied to piezoelectric. The first column in Table 3 shows the displacement of diaphragm in which both single-chambers have little differences in piezoelectric vibration. Because both of the vibrating diaphragms are free from the upper wall and there is no obstacle in the first half period. The diaphragm condition in double chamber micro-pump is different from the other two models. Because the diaphragm is under pressure of chamber's fluid coming from the upper and lower walls. It can bear the weight of the fluid in the upper chamber when it vibrates upward. But the weight of upper chamber causes the vibrating diaphragm bent down toward the lower chamber more than its inherent structure to bend, and thereby spatial changes of diaphragm are not equal with two chambers. Also the obtained flows of two chambers too.

Vibrating diaphragm of arched shape micro-pump shows the best of operations of two other diaphragms in which the maximum displacement of 0.9295μm is achieved. Because the fluid moving path inside this chamber is channelized, the lower corners of the chamber are removed from inside the reference micro-pump that caused whirling and back pressure. And it will be like an arch in the lower wall of the chamber and the same shape of the piezoelectric that bend toward down results in the increase of the amount of the diaphragm's positioning changes.

The maximum fluid velocity within the micro-pump's chamber is obtained equal to $2.7029\times10^{-18}$ for arched shape micro-pump. The applied geometric changes to the chamber cause regular and fast movements of fluid. Consequently, whirl and back pressure are reduced, and the resulting net flow compared to the reference form of this chamber with equal area has increased dramatically. But the most net flow amount related to double chamber micro-pump in parallel mode has not. The reason is quite obvious that the vibrating diaphragm in each half period of the sine pushes one of the chambers and the opposite of sinusoidal motion, a suction at that chamber takes place, and it is noteworthy that the discharge in the lower chamber and suction in the upper chamber happen best, that it is because of the applied weight power performed by the upper chamber to upper wall of the piezoelectric.

Total resulting flow of two chambers which together constitute the double chamber micro-pump is high. And the benefit of this micro-pump is that, if fluid outlet from both chambers connected with a tube which resulting fluid outlet of these micro-pumps, the result will be great because continuously in each cycle of diaphragm's motion, fluid output action in one of the chambers takes place and results a constant output. Then the problem of stopping fluid output in a half periods that suction action in arched shape micro-pumps and single chamber and other micro-pumps with the similar forms is resolved. And finally it is said that micro-pumps with arched shape chamber from the fluid motion aspect in the chamber and parallel double chamber micro-pump from the flow output aspect have unique characteristics.

The reason of that is found that when vibrating diaphragm pushes the fluid of chamber in resulting flows after reaching a peak the downside and the maximum spatial variations is in this regard, the highest rate of flow is achieved. Then diaphragm's state goes to balance state, namely, in the case that spatial variations will be zero. After that, this state moves upward until the suction action takes place and stops in the case of net flow output for a half period of diaphragm motion. Because of reasons that are related to physics of nozzle/diffuser elements, the amount of outputted flow from the chamber again comes back, but in contrast, to fluid entrance to chamber.

**Table 3.** Comparison table

| | Diaphragm displacement (μm) | Fluid velocity values in the micro-pump chamber (m/s) | Peak pressure value in the micro-pump chamber (Pa) | Maximum net flow value (Net flow in $m^2$) |
|---|---|---|---|---|
| Reference micro-pump | 0.9286 | $1.7628\times10^{-20}$ | $5.0627\times10^{-23}$ | $1.80\times10^{-31}$ |
| Arc-chamber micro-pump | 0.9295 | $2.7029\times10^{-18}$ | $3.568\times10^{-21}$ | $7.48\times10^{-30}$ |
| Double chamber micro-pump | 0.0501 | $1.7548\times10^{-20}$ | $7.082\times10^{-23}$ | $2.20\times10^{-31}$ |

## Conclusions

Research and development of micro-pumps are primarily by using the construction technology is started since the 1980s. Micro-pumps with the control valve (movable valve or one-way tap) and micro-pumps with nozzle/diffuser elements are two main classifications for mechanical micro-pumps with moving parts.

Micro-pumps with one-way taps have problems such as abrasion, fatigue, loss of fluid pressure during passages of taps and sometimes clogging of taps. Micro-pumps with nozzle/diffuser elements can solve this kind of problems. Hence this paper presents two-dimensional simulation models of micro-pumps with nozzle/diffuser elements using COMSOL software. COMSOL is software that uses the finite element method and engineering issues, especially issues that are combination of different physics and also analyzes them.

Micro-pump simulations are on the modes of simple single chamber (reference) micro-pump, micro-pump with arched shape chamber (that the changes are made only in the geometry of reference micro-pump's chamber shape and area of the chambers is equal), and double chamber parallel micro-pump (that actually two single-chamber micro-pump are located both in the form of parallel). The difference is that for all of them, a piezoelectric is used and the piezoelectric is located tangent to for two chambers.

Actually in the simulation of the micro-pumps, parameters such as the thickness and length of the piezoelectric, thickness and length of membrane, the length of micro-pump's chamber, length and angle of the elements of the nozzle/diffuser and the areas of the micro-pumps chamber are considered equally.

It is aimed to improve maximum amounts of spotted flow in the arched shape micro-pumps and micro-pumps with two parallel chambers to single-chamber micro-pumps. Results obtained from the performed simulations show that an improvement in the flow significantly takes place because of changes and also in the double chamber micro-pumps that have two separate chambers with a piezoelectric located between them can be realized without using two diaphragms, and therefore, the cost of production can be reduced.

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