Analysis of Fluid Pumping with a Throttle Type Piezoelectric Micro Pump

Dejan Križaj[2], Borut Pečar[1*], Danilo Vrtačnik[1,3], Drago Resnik[1,3], Matej Možek[1,3], Uroš Aljančič[1,3], Tine Dolžan[1], Slavko Amon[1,3]
[1]University of Ljubljana, Faculty of Electrical Engineering, Laboratory of Microsensor Structures and Electronics, Tržaška 25, SI-1000 Ljubljana, Slovenia
[2]University of Ljubljana, Faculty of Electrical Engineering, Laboratory for Bioelectromagnetics, Tržaška 25, SI-1000 Ljubljana, Slovenia
[3]Centre of Excellence Namaste, Jamova 39, SI-1000 Ljubljana, Slovenia
*Corresponding author: Dejan Križaj, Tržaška 25, 100 Ljubljana, Slovenia, dejan.krizaj@fe.uni-lj.si

Abstract:
Operation of a modified type microthrottle (MT) pump is analyzed by numerical simulation. Conventional MT pumps have disk type piezoelectric membranes while the analyzed type has a membrane of a rectangular shape. This could be advantageous in case the pump is stacked into an array for parallel pumping. A complete electro–fluid–solid mechanics coupling model for numerical simulation of strip type piezoelectric micro pump has been developed using finite element analysis software. Numerical simulations revealed that although during one period of sinusoidal excitation period the liquid volume is flowing in both directions the net pumped fluid volume at the outlet after one period is non-zero (positive), indicating successful fluid pumping.

Keywords: strip-type microthrottle (MT) pump, fully coupled 3D model, electro–fluid–solid mechanics coupling

1. Introduction

Micropumps are becoming an essential part of many microfluidic devices e.g. micro TAS (total analysis systems) also called labs on chip [1, 2]. Among a variety of micropumps, microthrottle (MT) pumps are becoming increasingly interesting for biomedical applications due to their operation principle in which the valves do not totally close during operation but close only partially, depending on the deformation of a piezoelectricity actuated membrane. For this reason this type of valves are named throttles and the operation principle throttling. This type of pumps has first been described by Johnson et al. in 2004 [3] and further improved by simplifications of device geometry [4, 5] and by an inclusion of a ring from a polymer photoresist to enhance displacement in an elastomeric substrate [6]. In the proposed investigation, we analyzed a modification of currently known MT pumps by changing the geometry of the actuator (piezoelectric), the membrane and the cavity. In particular, instead of using a disk-type (round) actuator, the geometry of the analyzed actuator is rectangular; for this reason we will call this type of MT pumps strip-type micropumps. One of the advantages of this approach is possibility of stacking the micropumps in parallel which would make this type of pumps appropriate for complex lab on chip devices, requiring simultaneous and separate pumping of several liquids.

In order to verify adequacy of these modifications and for design support we used numerical device simulation software to develop a complete three dimensional model of the proposed pump. Operation of the proposed device has been simulated by solving a complete set of equations describing electro-fluid-solid mechanics coupling. Numerical simulation software, based on finite elements analysis Comsol Multiphysics (ver. 4.2a) was used for this purpose [7]. Due to the coupled physical phenomena and 3D modeling, this type of modeling requires careful design and solution strategies that will be discussed in the following chapters.

2. Structure design used in numerical simulation

Figure Figure 1 presents a 3D model of a strip-type MT pump (STMT) with a cross-section presented in Figure 2. The proposed new structure of a micropump consists of a PDMS substrate (Polydimethylsiloxane – silicon based organic polymer frequently used in MEMS microfluidics fabrication using soft litohraphy) bonded on a supporting bottom glass. PDMS channel walls and two throttles are extruded on the top of the substrate. On channel wall periphery, a thick glass membrane is bonded. Micropump is driven by a PZT actuator (lead zirconate titanate – and inorganic compound with marked piezoelectric effect) that is glued on top of the membrane.

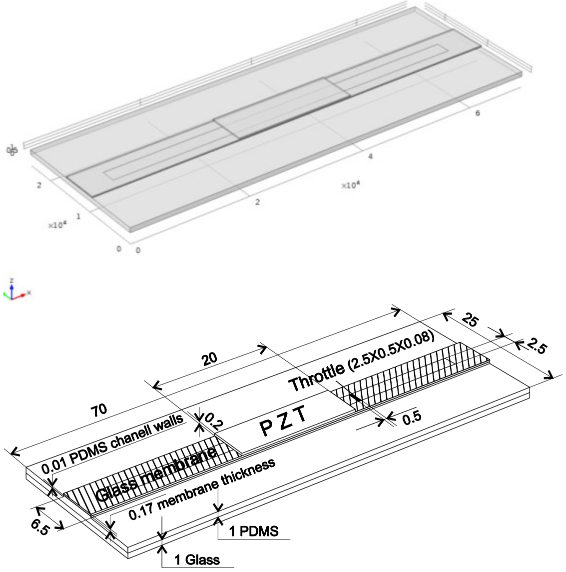

Figure 1. Top: 3D model of a strip type microthrottle pump. Bottom: dimension details.

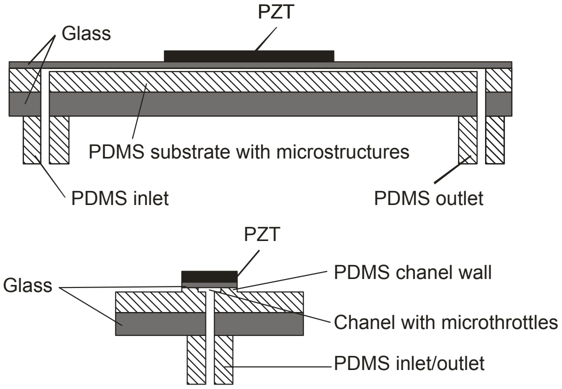

Figure 2. Cross-section of the proposed structure (dimensions are not to scale).

3. Use of COMSOL Multiphysics

3.1 Equations, materials and boundary conditions

As a support for the micropump design and fabrication, a complete electro–fluid–solid mechanics coupling model for numerical simulation of piezoelectric micropumps has been developed using finite element analysis software COMSOL Multiphysics (COMSOL, Inc.). Fluid flow is modeled using Navier-Stokes equation which is simplified due to low Reynolds number, resulting in a model of creeping flow that does not take into account fluid inertion. Piezoelectric actuator deformation by applied excitation signal is modeled by a coupled electro-structural mechanics model in which a coupling matrix takes into account deformation dependence on the direction of the electric field. A full 3D modeling was required due to complex design geometries.

3.2 Meshing and solving strategy

Fluid flow-rate at micropump outlet is determined as a surface integral of the fluid velocity. To obtain micropump volume flow, the fluid flow-rate is integrated once again but now over the time period. Possible fluid velocity computational errors are therefore enhanced during integration process which severely worsens the accuracy of the computed volume flow. For this reason proper meshing and solving strategy is essential for accuracy of simulation results.

In particular we found optimization of mesh density crucial for reliable simulation results. The main trade-off is between large number of mesh points where higher accuracy of solution is expected, limitations of computer RAM and solution time. We were limited to usage of 16 GB of RAM which was in our case a serious limitation due to complex device geometry in particular due to a large geometry with small (70000:20 μm) but crucial details such as regions around the throttles. For this reason we optimized the parameter *Resolution of Narrow Regions* that enabled generation of increased mesh density near the throttles (RNR up to 0.6). The final mesh for fluidics is composed of 57486 tetrahedrals, pyramids and prisms. Figure 3 presents a result of local meshing around the throttle region.

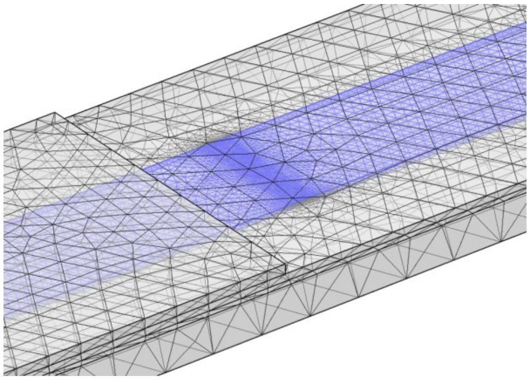

Figure 3. A detail of meshing at the edge of a PZT and around the right throttle.

Final solution accuracy depends also on the settings of the solver, however, from our experiences, much less that proper meshing of the structure. This was evident in the phase of optimization of some geometrical parameters where in case of not appropriate meshing the final results were inconsistent.

The complete mesh is constructed from 116487 tetrahedral elements. Usage of less elements resulted in non-exact solutions for the fluid flow at outlet. A sinusoidal voltage signal of 400 V was applied to the PZT with frequency of 1 Hz. Time simulations were performed for 1 s with a 0.01 s time step. A time dependent simulation with DIRECT MUMPS linear solver and scaled absolute tolerance of 0.001 was chosen. It was found that fluid inlet/outlet (creeping flow module) non-zero pressure boundary condition was crucial for DIRECT solver to obtain a solution. Furthermore, appropriate setting of this parameter greatly improves the solution time.

4. Results

Figure 4 presents typical simulation result of a deformation of a piezoelectric actuator and a membrane at 400 V and -400 V excitation signal. Maximal positive displacement occurs at the middle of the PZT while a negative displacement is observed some distance away from the edge of the PZT. Knowledge of exact deformation of a PZT with a glass membrane is required for proper positioning of the throttles. A detailed view of membrane displacement for variations of the applied voltage signal is shown in Figure 5 for a longitudinal cross-section. The membrane oscillates around six nodes. Two inner nodes are found in the PZT region close to the edge while other are found outside the PZT region. Largest deformation occurs in the middle of the PZT while another peak of deformation occurs outside but near the PZT. This deformation is of opposite direction to the main deformation. This is stressed in Figure 5 by marking one deformation plot with a thicker line. From Figure 5 we can deduce possible positions of the two throttles. One is positioned below the maximum of the negative peak while the other should be placed in the region of a positive peak below the PZT region.

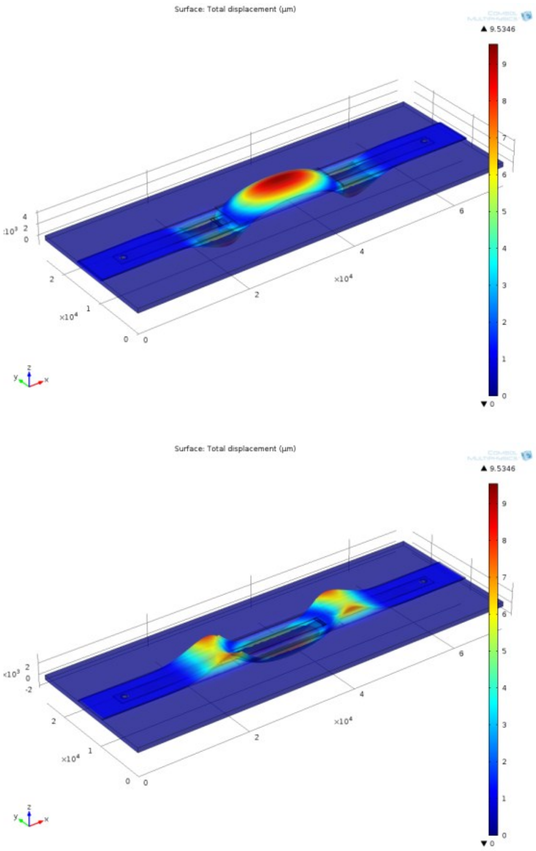

Figure 4. 3D view of deformation of a piezoelectric actuator and a membrane with a color scale representing displacement at current excitation of 400 V (top) and -400 V (bottom).

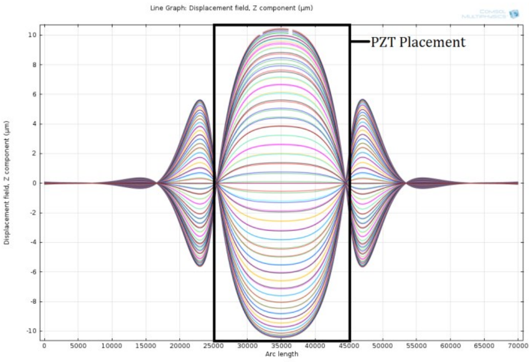

Figure 5. Deformations of a membrane in a central longitudinal cross-section for different applied voltages.

Some further simulation results are presented in Figure 6. Operation of the device can be studied from different perspectives either from differences in pressure that appear near the throttles (different flow resistance close to the throttles) or directly through the observations of the fluid flow rate (figure 6).

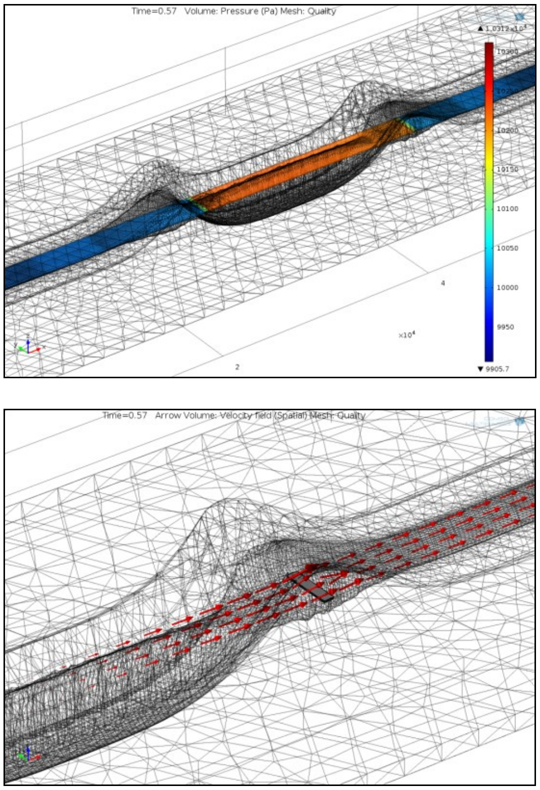

Figure 6. Pressure profile in the channel (top) and fluid flow rate (top) at the right throttle at 0.57s time.

Time dependent fluid flow at the channel outlet as a function of 1 Hz 400 V sinusoidal excitation signal is shown in Figure 7. As expected, the shape of the volume flow rate at outlet has a similar shape as the excitation signal (sinusoidal) indicating that the volume flow is not only directed towards the outlet but also in a negative direction, toward the inside of the pump. Nevertheless, by integrating the volume flow rate at the outlet in time we obtain the net pumped volume which is also shown in Figure 7 (broken line). In the first half of the period the net volume flow is even negative – pumping the fluid towards inside of the pump. However, during the second half of the period the pumping volume towards the outlet is positive and remains positive after one time period. This means that although during one time period the fluid flows in both directions – toward the inlet and the outlet – the final result is a “small” positive flow through the outlet.

Exact positioning of the throttles is crucial for proper device operation. Figure 8 presents results of determination of optimal position of the throttles. The right throttle was positioned below a region of maximal negative membrane deflection that can be seen in Figure 5. The optimal position of the left throttle can be determined from Figure 8 showing simulation results of net pumped fluid volumes at different positions of the throttle. Results show that for this particular structure the optimal position of the left throttle is close to the edge of the PZT, more precisely, 2.6 mm from the left edge of a PZT.

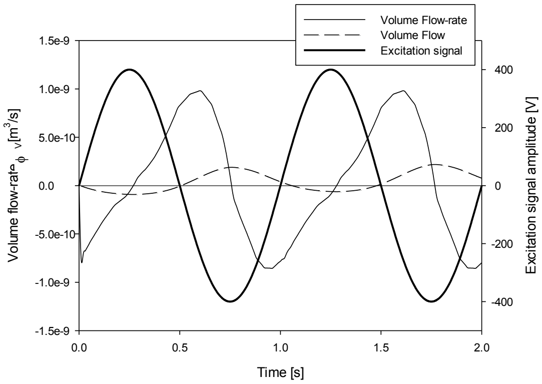

Figure 7. Time dependent fluid flow at the channel outlet, as a consequence of 1 Hz 400 V sinusoidal excitation signal.

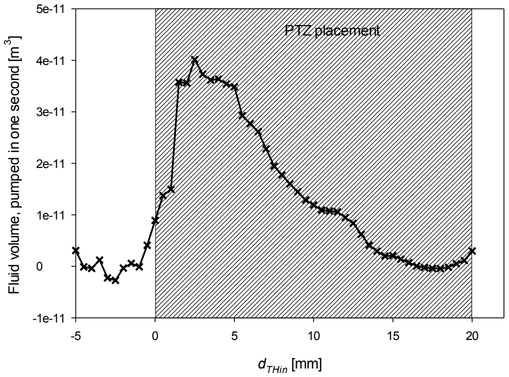

Figure 8. Fluid volume through the outlet depending on the position of the left throttle measured from the left edge of the PZT.

6. Conclusions

A strip-type microthrottle pump was analyzed by numerical simulation. Such pumps could enable compact parallel pumping of several separate liquids what is of great interest in various micro structures and so called Lab on Chip devices. Detailed operation of the proposed device was analyzed through numerical simulation by design of a full 3D model of a pump. A complete three dimensional time domain electro-mechanical-fluid flow numerical simulation was performed. In order to obtain accurate solutions the simulation mesh has been densified in the regions near the throttles. Simulations revealed that in this type of pumps fluid flow is largest at largest deflection rate of the piezoelectric actuator, which occurs when the driving sinusoidal voltage signal changes sign. Similar to excitation signal, also fluid volume rate approximately follows sinusoidal shape. However, due to different deformations of the membrane close to the throttles a positive total fluid volume flow is achieved. Optimal throttle positions have been determined: the right throttle is positioned directly at the place of the negative deformation peak while the position of the left throttle was determined to be few mm from the left edge of the PZT.

7. References

1. S.J. Lee and S.Y. Lee. Micro total analysis system (μ-TAS) in biotechnology. Applied Microbiology and Biotechnology. Volume 64, Number 3 (2004), 289-299.
2. Long Zhao, Zhenshan Wang, Sufang Fan, Qiang Meng, Bowei Li, Shujuan Shao and Qi Wang. Chemotherapy resistance research of lung cancer based on micro-fluidic chip system with flow medium. Biomedical Microdevices. Volume 12, Number 2 (2010), 325-332.
3. Johnston ID, Davis JB, Richter R, Herbert GI, T. M. (2004). Elastomer-glass micropumps employing active throttles. Analyst, 129, 829–834.
4. Johnston I D, Tracey M C, Davis J B and Tan C K L 2005. Microfuidic solid phase suspension transport with an elastomer-based, single piezo-actuator, micro throttle pump. Lab Chip 5 318–325
5. Johnston, I. D., Tracey, M. C., Davis, J. B., & Tan, C. K. L. (2005). Micro throttle pump employing displacement amplification in an elastomeric substrate. Journal of Micromechanics and Microengineering, 15(10), 1831–1839
6. Fujiwara, T., Johnston, I. D., Tracey, M. C., & Tan, C. K. L. (2010). Increasing pumping efficiency in a micro throttle pump by enhancing displacement amplification in an elastomeric substrate. Journal of Micromechanics and Microengineering, 20(6), 065018.
7. COMSOL Inc. (http://www.comsol.com/).