Investigation of electro-osmotic micro-pumps using electrical field gradient and asymmetric micro-electrodes: numerical modeling and experimental validation

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ABSTRACT

In present study, in order to fabricate AC electroosmotic micropumps, the improvement of geometrical parameters of 3D electrode, such as width, height and location of 3D steps on the base electrodes in one pair, the base electrodes size (symmetric or asymmetric), electrodes gap, and also electrical characteristics including voltage and frequency have been investigated. Also, the fluid flow (KCl) in channel was analized. The governing equations of fluid flow and electrical domain have been solved using finite element method to investigate the effect of electrode geometry on slip velocity, which affects the fluid flow. In order to validate our numerical simulation, this chip is fabricated by photolithography method such as deposition of platinum electrodes, creating 3D steps on the base electrodes using a polymer and fabrication a microchannel. Finally, Our results indicate that an optimal design results in a pump with the width (50 µm) and steps height (5 µm) of each electrode and their displacement (30 µm) is capable of generating a high velocity, flow rate and pressure around 1.77 mm/s, 14.9 ml/min and 74.6 Pa, respectively at a given voltage (2.5 V) and frequency (1 kHz), which qualitatively matches the trend observed in experiment. This design provides an improvement in electroosmotic pumping.

KEYWORDS

Microfluidic, electroosmotic micropump, electrode geometry improvement, microfabrication, numerical modeling.

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1. Introduction

Microfluidics is a field of study that is limited in the control volume of fluids in microchannels. The term microfluidics is generalized to the study of the motion of colloids, micro-, and nanoparticles. Because the motion of fluids and particles are closely related and interact with each other [1]. These miniaturized devices are called lab-on-a-chip [2]. In the last decade, microfabrication technology has led to the use of polymers as a base material for the construction of microfluidic devices in a relatively simple way, such as injection molding, soft lithography, and so on.

Micropumps are one of the main types of microfluidic devices that can be generally divided into two main categories: mechanical micropumps and dynamic micropumps [3]. Among these mechanisms, the electroosmotic pump is an example of a dynamic pump, which provides fluid flow through driving ions in the electric double layer (EDL), along the interface between the electrolyte and the solid surface (channel wall or electrode). Electroosmotic micropumps are divided into two categories of alternating and direct current. AC electroosmotic (ACEO) pump compared to DC electroosmotic (DCEO) pump, has a low voltage and also less electrolysis, which this study also focused on this type of micropump.

Ajdri first theoretically predicted that the asymmetry of the electrode array (the width of the electrodes in a pair and the distance between them should be different) could be used to direct the fluid in a specific direction for pumping [4]. An electric field close to the distance between the adjacent electrodes acts on suspended charges near the surface of the electrode. This force creates vortices at the edges of the electrodes, and the size of these vortices depends on the width of the electrodes. A larger vortex is created on the wide electrode, and the wide electrode dominates the overall flow direction. Using the standard model of micropumps with planar electrodes, Gao et al. theoretically proposed arrays of asymmetric ring electrode pairs in three-dimensional cylindrical microchannels that could improve the flow rate [5]. There are many designs in which the asymmetry of the electrodes induces fluid flow, including asymmetric planar electrodes, orthogonal electrodes [6], planar asymmetric electrode arrays with pillar electrodes with high aspect ratio [7] and three-dimensional electrodes [8] with maximum fluid velocities have been reported.

In the present study, using numerical modeling, first two different micropumps including symmetrical planar electrode arrays and asymmetric planar electrode arrays have been designed. Then, in order to achieve efficient pumping with maximum velocity, flow rate and pressure, the effect of steps on each of the base electrodes (symmetrical and asymmetric in each design) is investigated. For this purpose (see Figure 1), the width (L_1, L_2) and height (h_1, h_2) of the steps, and their location (S_1, S_2) on the base electrodes have been improved, which can be considered as one of the innovations of this research. To validate the numerical simulation, the improved chip was fabricated using photolithography, including coating the platinum electrode on the glass substrate, creating steps on the electrode using polymer, and fabricating a PDMS microchannel (26 mm long and 2 mm deep) in the laboratory. In addition, the size of each electrode in a pair, in order to symmetry or asymmetry of the electrode pair, the gap between each electrode in a pair (G_1) and the gap between each pair of electrodes (G_2), as well as electrical characteristics including voltage and frequency are also investigated.

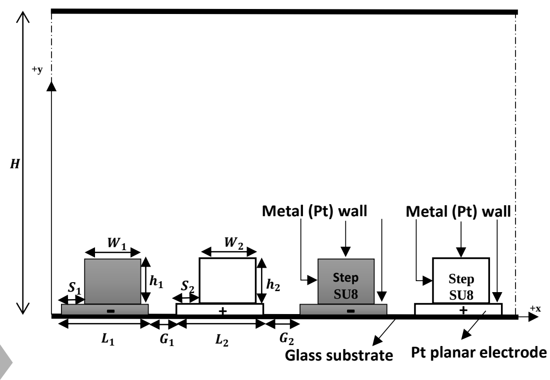

Figure 1. Schematic of improving the geometry of the electrodes in the microchannel

2. Methodology

The numerical model includes two sets of governing equations and boundary conditions related to each domain. The EDL is in quasi-equilibrium at low voltage and low frequencies. After that, the system requires a short time after each small change in the system to reach equilibrium. As a result, the properties of the system are considered constant. Finally, assuming a linear regime for the distribution of potential in the bulk of fluid, the electric charge density is zero. For small voltages, the concentration of the electrolyte (and conductivity) remains almost uniform, and the electric field is assumed to be uniform and the Laplace equation (Ohm's law) is established:

$$\nabla^2 \phi = 0 \qquad (1)$$

The boundary conditions at non-electrode surfaces:

$$n.\vec{\nabla}\phi = 0 \tag{2}$$

The boundary condition at the surface of the electrodes:

$$n.\vec{\nabla}\phi = \frac{i\omega C_{Dl}\Lambda}{\sigma}\left(\phi - V_{peak}\right) \tag{3}$$

$$C_{Dl} = \frac{\varepsilon}{\lambda_D} \tag{4}$$

Here σ is the electrical conductivity of the electrolyte, V_{peak} is the applied voltage, ε is the fluid permeability constant, λ_D the double layer thickness, and ω is the angular frequency. Also, the ratio of the diffuse layer potential and the total potential of the EDL is shown with a correction factor. The time-averaged velocity field at the electrodes is then calculated by the Helmholtz–Smoluchowski formula:

$$u_{ACEO} = -\frac{\varepsilon}{4\mu}\Lambda\frac{\partial}{\partial x}\left|\phi - V_{peak}\right|^2 \tag{5}$$

The incompressible Navier – Stokes equation will be used to analyze the fluid flow domain. In addition, Reynold's Number is very small in microchannel thus, the governing equation is:

$$\vec{\nabla}P = \eta\nabla^2\vec{V} \tag{6}$$

μ is the dynamic viscosity of the solution, *V* is the fluid velocity vector, and *P* is the pressure.

3. Discussion and Results

In order to design a step on the pair of asymmetric base electrodes, the size of the base electrodes in a pair, the distance of the step from the initial edge of the electrodes, the width of each step and also their height were considered different. As a result, non-uniform streamlines and asymmetric vortices were observed near the electrodes. These vortices interact with the electrode and generate significant reverse flow at the steps electrode, which weakens the pumping performance.

To improve the step height of the electrodes in a symmetric array, the constant parameters used in all design such as channel length, channel height, base electrodes, the gap between each electrode in a pair, and the gap between each pair of electrodes. In each case, there are 108 pairs of electrodes in the microchannel, the width of the step electrode and their start from the edge of the electrode is considered constant to show the effect of different step heights. The step height is from 1 to half the width of the base electrode (45 µm) and the specified frequency range (1 to 100 kHz) is considered. At step heights in the range of 1 to 5 µm, the velocity is dependent to the applied frequency. Although the step height is small, there is no flow reversal at low frequencies. Therefore, for very small steps according to the linear method, although the velocity is low, there is no reverse flow at low frequency. While at high frequencies, due to small step, significant flow reversal is observed. The electrodes with a step height of more than 5 µm are less sensitive to the applied frequency (above 4 kHz) and reverse flow does not occur at high frequencies (see Figure 2).

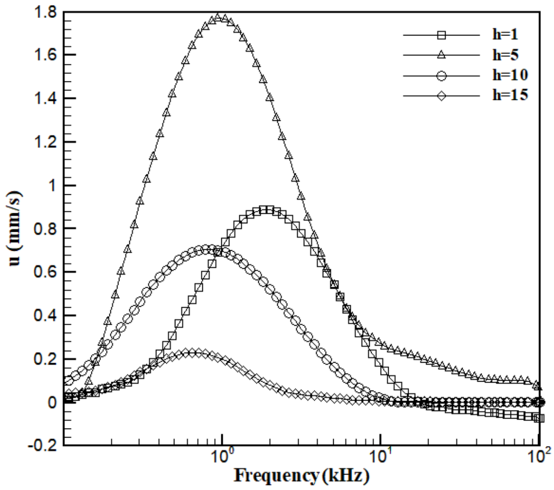

Figure 2. Comparison of pump velocity in numerical method at different step heights with $S_1 = S_2 = 50$ µm $W_1 = W_2 = 30$ µm

In order to prevent the faradic current that may occur at low frequencies, the frequency for experimental method is higher than 500 Hz using AC electric field [9]. Figure 3 the experimental results are compared with numerical simulations, which show a good agreement between the velocity and pressure.

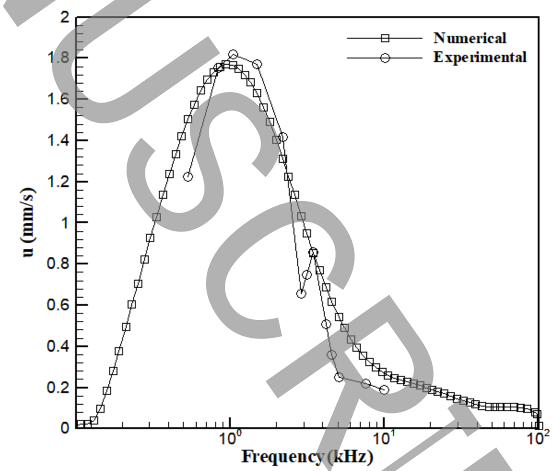

Figure 3. Comparison of flow velocity in numerical and experimental method at 2.5 V

4. Conclusion

In this study, by investigation the location of the step electrodes (50 µm), their width (30 µm) and their height (5 µm), a forward flow with high velocity can be generated. Numerical results for a voltage of 2.5 V and the frequency of about 1 kHz, the flow velocity, flow rate and pressure are 1.77 mm/s, 14.9 ml/min and 74.6 Pa, respectively. Experimental results and numerical simulations have a difference of 82 2.82% in terms of maximum velocity in 2.5 V. Also, in terms of maximum pressure at the same voltage, a difference of 2.95% has been observed. A good agreement between can be seen in the numerical and experimental results.

5. References

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