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MODELING AND ANALYSIS OF LOW VOLTAGE ELECTRO-OSMOTIC MICROPUMP

Jayan Ozhikandathil[1*], Muthukumaran Packirisamy[2], Ion Stiharu[3]

[1,2]Optical Bio-Microsystems Laboratory
[3]CONCAVE
Dept of Mechanical and Industrial Engineering
CONCORDIA UNIVERSITY
Montreal, Quebec, CANADA
*Email: j_ozhik@encs.concordia.ca

ABSTRACT

Scaling down the biochemical analytical system has been an important topic of research recently. Minimizing the energy requirement for the microfluidic transportation is essential for the realization of a Lab-on-a-chip (LOC) that can perform the Point-of-Care Testing (POCT). In this work, modeling and analysis of a low voltage Electro-osmotic (EO) micropump applicable for the Bio-Microfluidic systems using COMSOL Multiphysics software package is presented. In the previously reported low voltage EO micropump (3), position of electrodes makes the fabrication process a tedious task. Here, we investigate the effects of placing the electrodes tangential to the microchannel since such designs can be easily fabricated using PDMS/glass fabrication process, and also comparing the effect of different electrode configurations on the pump performance. In addition, the effects of geometrical parameters of micropump on volumetric flow rate and velocity profiles are investigated.

INTRODUCTION

Miniaturization of biofluidic systems has been highly demanding due to the reduced analysis time, point of care inspection achieved by the portability of device, and reduced reagent cost (1). Though numerous silicon based microfluidic systems for the biochemical applications have already been developed (2), they suffer disadvantages including high fabrication and raw material cost. Polydimethylsiloxane (PDMS) has been an alternative to the silicon for the fabrication of optical Bio-Microfluidic systems because of its low cost fabrication process, bio-compatibility and good optical properties (1, 4).

Application areas of micropumps are numerous including microelectronics cooling systems, Lab-on-a-chips and drug delivery systems (2). Miniaturized optical bio-analysis systems require the processes such as transportation of bio-liquids to a microreactor through a microchannel. The main hindrance of miniaturization of traditional pressure driven flow is the dominance of viscous stress in the micro domain. However, microfluidics transportation can be achieved either by a displacement type pump in which a periodic flow pressure is generated by movable parts incorporated in the system, or by a dynamic type which will add the energy to the fluid without any moving parts in order to maintain a continuous flow through the channel (2). Electro-osmotic pumps fall under dynamic type. The main advantage of Electro-osmotic (EO) micropump is the absence of any moving parts in the device making the miniaturization an easy process. EO has been successfully employed in many micropumping applications (3, 6, 13, 15).

EO flow may be explained as follows; upon introducing a polar liquid (electrolyte) on the surface of a dielectric material, due to chemical reaction, ionization or ion absorption, spontaneous accumulation of charges on surface is observed (6). This leads to a redistribution of ions in electrolyte by attracting the counter ions to the dielectric surface and repelling away the co-ions. If we establish an electric field tangential to the surface, a body force can be produced on the liquid leading to a flow pressure. Normally, a high voltage supply is required to create the flow in the microchannel. Such high voltage pumps are not suitable for the development of portable Bio-Microsystems. Y Takamura *et.al* (3) reported a new technique to reduce the voltage, and theoretical validation of their work has been reported by A. Brask *et al.* (8). The main disadvantage of the design reported in (3) was complexities of electrodes. In this work, we model low voltage Electro-osmotic micropump suitable for the PDMS/glass based fabrication process. The proposed design is greatly simplifying the fabrication process by placing the electrodes tangential to the channel wall rather than vertical to the channel ends. Figure.1 illustrates the basic electrode position and electric field distribution when the COMSOL Multiphysics simulation is carried out in simple rectangular channel geometry with the electrodes are kept tangential to the channel wall.

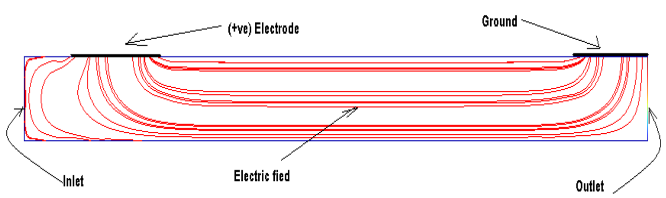


Fig 1 Electro-osmotic pump configuration with electrodes tangential to the channel wall. Electric field distribution is simulated by COMSOL Multiphysics.

The proposed design can be fabricated by using PDMS and glass wafer. The microchannel geometry can be easily fabricated on PDMS using the soft lithography as described in (4). The electrodes for the EO flow can be patterned by using metallization, lithography and metal etching on the glass wafer. The direct contact of electrodes with electrolyte will result in gas bubble formation in the channel due to the electrolysis (13), and this can be a serious issue in the pump performance. In order to eliminate this issue, a thin dielectric coating must be deposited on the electrode. The glass wafer with the electrodes and PDMS layer with microchannel can be bonded to realize the EO pump with the help of oxygen plasma treatment (17, 18) or any other bonding techniques (19).

ELECTRO-OSMOTIC FLOW (EOF)

Transportation of polarized liquid by the application of electric filed parallel to the flow path on a charged surface is often termed as Electro-osmotic flow(7).

For example, a glass surface can be charged by introducing an aqueous electrolyte onto it. This is due to the deprotonation of surface silanol groups (SiOH). Formation of a charge layer at the liquid solid interface is observed due to the interaction of charged species. The variation of electrical potential across the liquid solid interface is termed as Electrical double layer (EDL).

Schematic representation of EDL is shown in Figure 2. EDL is divided into two layers namely Stern layer and Gouy-Chapman layer. Stern layer is attached to the surface due the Columbic force of attraction and it is immobile, thickness of this layer is of the order of radius of hydrogen ion (14), where as Gouy-Chapman layer is above the Stern layer and contains both charges with majority of positive charges. Gouy-Chapman layer can freely diffuse into the bulk liquid due the weaker columbic force of attraction. The boundary separating Stern layer and Gouy-Chapman layer is known as shear plane. The electric potential at the shear plane is called zeta (ζ) potential.

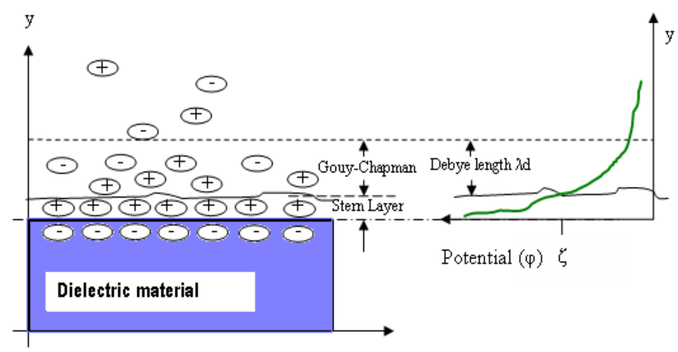


Fig 2 Schematic representation of EDL (7)

For the polymeric materials including the PDMS, measurements of electrokinetics is complex because of the hydrophobic nature of the surfaces, and theoretical modeling is found to be difficult due to the ambiguities in defining the physics of interfacial phenomena and space of applicable input parameters (10). However, in practice, hydrophobic polymers exhibit the electrokinetics potential same as that of hydrophilic surface such as glass. PDMS surface can be made hydrophilic by using oxygen plasma treatment. Electro-osmotic mobility of plasma oxidized PDMS is reported as same as that of glass (13). The origin of charges on PDMS surface in the presence of electrolyte is due to the silica fillers introduced by the manufactures (10).

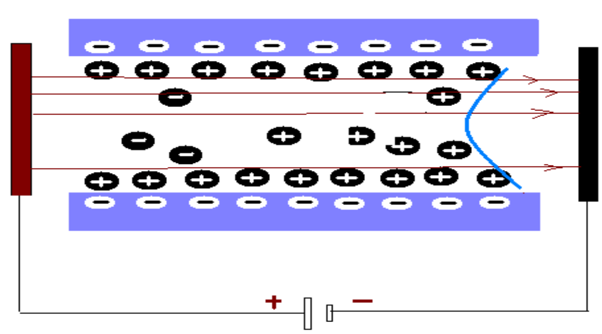


Fig 3 Basic Electro-osmotic pump configuration

Basic configuration of Electro-osmotic pump is shown in Figure. 3. An electric field is established tangential to the charged surface by a battery. Electric filed can exert a net columbic force of repulsion to the positive charges of the Gouy-Chapman layer and hence the bulk liquid can move towards negative electrode through viscous interaction (6). The steady state flow velocity profile due the Electro-osmotic is uniform across the channel cross-section, but due to the pressure difference between the inlet and outlet of the channel, a reverse flow is also possible, therefore the net velocity profile in the Electro-osmotic pump is found to be slightly parabolic as depicted in the Figure 3.

MATHEMATICAL FORMULATION OF ELECTRO-OSMOTIC FLOW IN A MICROCHANNEL

Electro-osmotic flow in a microchannel can be quantitatively analyzed by modeling Electrical double layer and flow field by using two-dimensional Poisson-Boltzmann equation and two-dimensional Navier-Stokes equation (7, 9) respectively. Figure 4 shows the channel geometry used for the simulation of Electro-osmotic micropump and simulated pump.

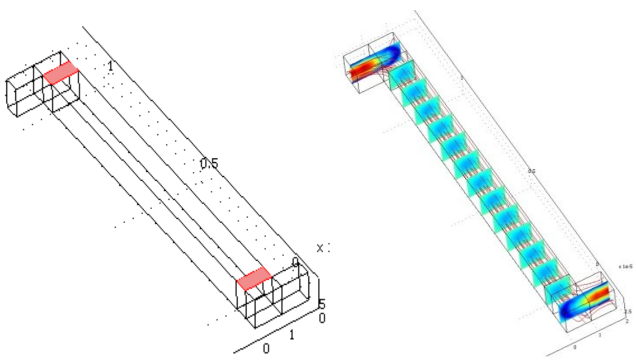


Fig 4 Rectangular channel used for the simulation of Electro-osmotic pump with electrodes on top of the channel

The ionic distribution per unit volume of the electrolyte is approximated by Boltzmann distribution:

$$C_i(r) = C_b \exp\{\frac{-z_i q\varphi(r)}{k_b T}\} \tag{1}$$

Where C_b is the bulk ionic concentration, z is the valance number of ion, q is electric charge, $\varphi(r)$ is the electrical potential, k_b is the Boltzmann constant 1.38×10^{-23} J/k and T temperature.

The net volume charge density ρ_e can be expressed as:

$$\rho_e = \sum C_i(r) z_i q \tag{2}$$

$$\rho_e = q\sum z_i C_b \exp\{\frac{-z_i q\varphi(r)}{k_b T}\} \tag{3}$$

Equation (3) can be rearranged for a symmetrical electrolyte (z: z=1:1) as:

$$\rho_e = -2qC_b Sinh(\frac{q\varphi}{k_b T}) \tag{4}$$

2D Poisson equation establishes the relation between the electrical potential and volume charge densities at any point in the channel:

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial^2 y} = -\frac{\rho_e}{\varepsilon\varepsilon_0} \tag{5}$$

Where ε is relative dielectric constant of liquid and ε_0 is the permittivity of vacuum (8.854×10^{-12} F/m). The equation (5) can be rewritten as nonlinear Boltzmann equation by substituting equation (4):

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial^2 y} = \frac{2\ q}{\varepsilon\varepsilon_0} C_b Sinh(\frac{q\varphi}{k_b T}) \tag{6}$$

Motion of aqueous electrolyte can be represented by Navier-Stokes equation:

$$\rho\{\frac{\partial u}{\partial t} + u.\nabla u\} = -\nabla P + \mu\nabla^2 u + E\rho_e \tag{9}$$

Where u is velocity, μ is viscosity of the electrolyte, ρ is density of fluid, and E electrical field strength applied to the channel ρ_e is the local electric charge density. For a fully developed two dimensional steady flow, velocity is expressed as $u = u(x, y)$, then the inertial term $u.\nabla u = 0$ and $\frac{\partial u}{\partial t} = 0$ on the left hand side of the equation (9) and also assuming the pressure at both ends of the channel is same, so $\nabla P = 0$. There for the equation (9) can be modified as:

$$\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}=-\frac{1}{\mu}(E\rho_e) \qquad (10)$$

Also by substituting the expression for the ρ_e from (4) we have:

$$\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}=-\frac{1}{\mu}(2qE\sinh(\frac{q\varphi}{k_b T})) \qquad (11)$$

The volumetric flow rate in the channel can be estimated as:

$$Q=\int_0^H\int_0^W u(x,y)dxdy \qquad (12)$$

Where H is height and W is width of the channel. For relatively low electrostatic potential (i.e, -1< φ <+1), the hyperbolic sin function ($\sinh(\varphi)$) in the governing equations can be approximated to φ and this approximation is called Debye-Hückel approximation. The flow velocity at the surface that is the Electro-osmotic velocity u_{eo} is given by the Smoulchowski Expression (9):

$$u_{eo}=\mu_{eo}\frac{E}{L} \qquad (13)$$

Where, μ_{eo} is Electro-osmotic mobility and L is the length of the channel.

The flow rate Q for Electro-osmotic flow for uniform velocity distribution across the channel is given by:

$$Q = u_{eo}\mathrm{A} \qquad (14)$$

Where A is the sectional area of the channel
Q can be written using (13) as:

$$Q=\mu_{eo}\frac{E}{L}A\frac{R_{hyd}}{R_{hyd}}$$

$$\equiv\frac{\Delta p_{eo}}{R_{hyd}}$$

Where R_{hyd} is the hydraulic resistance and Δp_{eo} is defined as:

$$\Delta p_{eo}=\mu_{eo}ER_{hyd}\frac{A}{L}$$

Δp_{eo} may be defined as the hydraulic back pressure required to balance flow due to the Electro-osmotic pressure, there for the total flow is equal to the sum of Electro-osmotic flow and pressure driven flow.

Table 1
Parameters used for the numerical simulation

No.	Parameter	Value
1	Electrical conductivity of DI water(pumping solution)	0.01(S/m)
2	Dynamic viscosity of DI water	$1x10^{-3}$ Pa.s
3	Relative permittivity of water	78.5
4	Electro-Osmotic mobility	$0.06mm^2/V.s$
5	Density of DI water	$1x10^3Kg/m^3$
6	Voltage applied	10V
7	Inlet and outlet pressure	0 Pa

RESULTS AND DISCUSSION

In order to analyze the Electro-osmotic flow behavior though microchannel, numerical solution of governing differential equations is possible by commercially available software packages. The COMSOL Multiphysics (20) solves the problem using the Finite Element Method (FEM). The effects of position of the electrodes and geometrical characteristics of the Electro-osmotic micropump on the volumetric flow rate and velocity profile were analyzed and the results were given in the following discussions.

Effect of position of electrodes in Electro-osmotic micropump

The channel geometry used for COMSOL Multiphysics simulations is shown in Figure.5. Different electrode configurations used in the simulations are illustrated in Figure 6. All COMSOL simulations were carried out with the parameters given in Table.1.

Figure 7 shows the variation of flow rate when the height(H) of the channel was inceared from 5 to 50μm with TOP electrode, END electode and TOP, BOTTOM and END electode together. The length of the channel (L) was kept at 250μm and TOP and BOTTOM electode width, *We* is 5μm in this simulation. The width of the channel (W) was 10μm. It was found that the flow rate is same for all the electode configuration upto the channel height of around 15μm.

Flow rate is found to be decreasing after the height of 15μm for the case of TOP electrode configuation. This analysis confirms that the TOP electode configuration is suitable for the pumps having lower aspect ratio. The effect of different electrode configurations is further investigated on the length of the channel. Figure 8 shows the variation of flow rate when length of the channel was increased from 5 to 500μm.

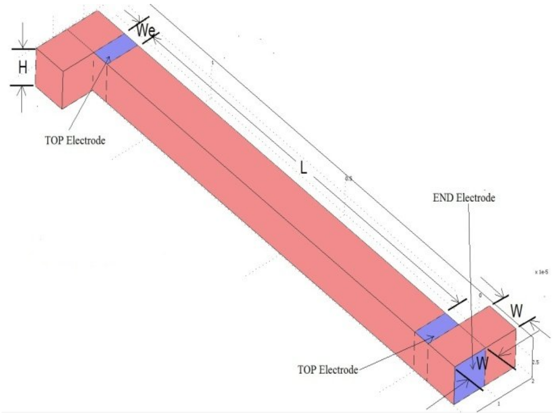
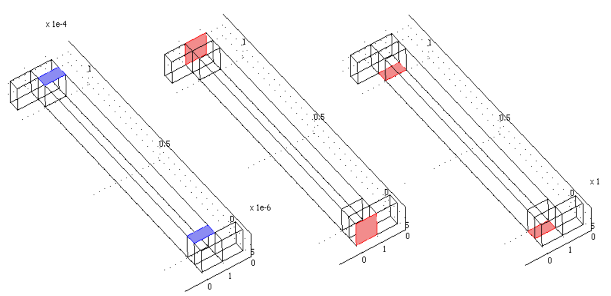


Fig 5 Electro-osmotic pump geometry used for the COMSOL modeling *H* –Height, *W*-Width, and *L* length of the channel *We* -Width of the TOP electrode



(a)TOP electrode *(b) END electrode* *(c) BOTTOM electrode*

Fig 6 Electro-osmotic micropump geometry with different possible electrode configurations

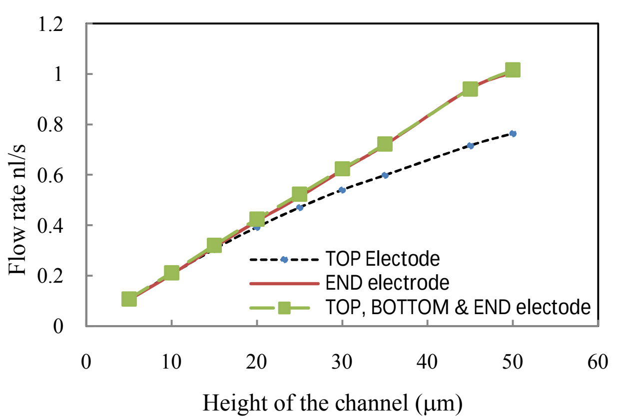


Fig 7 Effect of position of the electrode in the volumetric flowrate

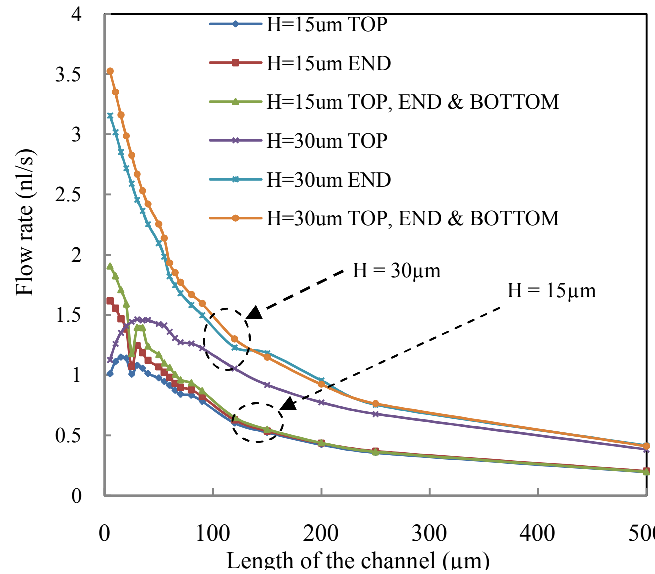


Fig 8 Effect of electrode position on the length of the channel

Simulations with varying lengths were performed for two different channel heights such as 15µm and 30µm. From the Figure 8, we can see that, for the height of 15µm, the flow rate is becoming independent of electrode configurations after around 100µm and decrement in flow rate is insignificant with respect to the length. For the pumps having height of 30µm with END electrodes and all the three electrodes, a significant increment in flow rate is observed when length of channel was decreased below the100µm. The flow rate of channels with length of 100µm or more is found to be less dependent on the electrode configurations. This concludes that the flow rates of longer pumps have less influence on the electrode configuration, and can be operated with easily fabricable TOP electrode configuration without much performance degradations. We investigate the pump performance with only TOP electrode configurations in the forthcoming sections. The Electro-osmotic micropump simulated with TOP electrode is shown in Figure 9.

Effect of length of the pump on velocity profile and flow rate

Figure 10 shows the variation of velocity with respect to the channel length across the channel width of 10µm. The channel height was kept at 10µm in the simulation. The channel length was varied from 50 to 500µm. This analysis indicates that the decrease of channel length increases the flow velocity, but velocity distribution across the channel is becoming more and more nonuniform. In biochips, usually particle separation is an important requirement; this can be achieved by the uniform velocity profile of the Electro-osmotic flow. The basic principle of this task is that the particles with different masses encounter different drag force under uniform velocity (16). The non-uniformity in the velocity distribution introduced from decreasing the length of the channel is then a disadvantage. The velocity at the channel wall and at the center of the channel is separately shown in Figure 11. The Influence of length of the channel on the volumetric flow rate is shown in Figure 12. Flow rate is decreasing exponentially with respect to the length of the channel.

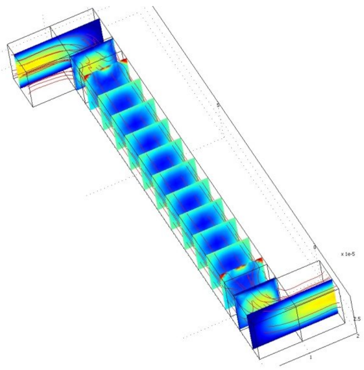


Fig 9 COMSOL simulation of EO micropump with stream line and velocity profile

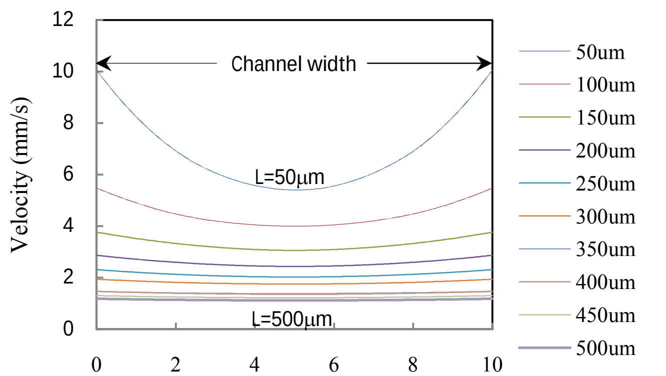


Fig 10 Variation of velocity profile across the channel width with length of the channel varried from 50 to 500um. Height H=10µm

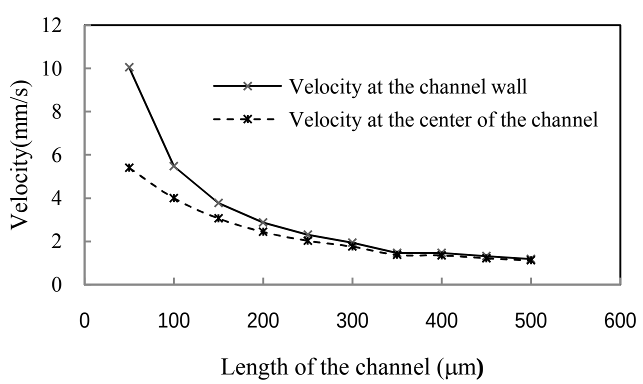


Fig 11 Variation of velocity at the center of the channel and at the channel wall when length of the channel is varied form 50 to 500µm

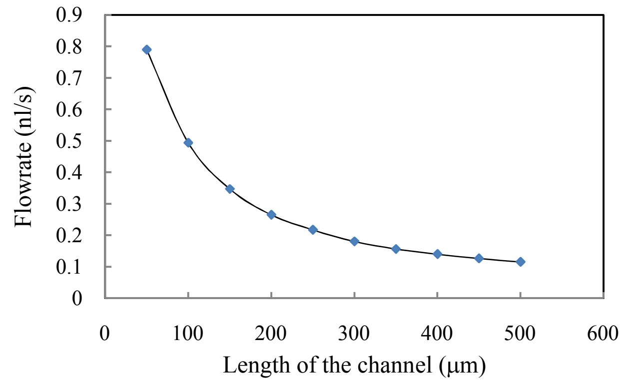


Fig 12 Folwrate vs Length of the channel, Height H=10µm Width W=10 µm

Effect of height and width of the pump on flow rate

In order to investigate the effect of height (H) and width (W) of the EO micropump, channel with a length (L) of 320µm is simulated. Figure 13 shows the variation of flow rate when height was increased from 5 to 10µm, and width was varied from 5 to 15µm. A linear relation between flow rate and height of the channel can be observed from the Figure 13. The slope of the curve is found to be increasing with the width of the channel.

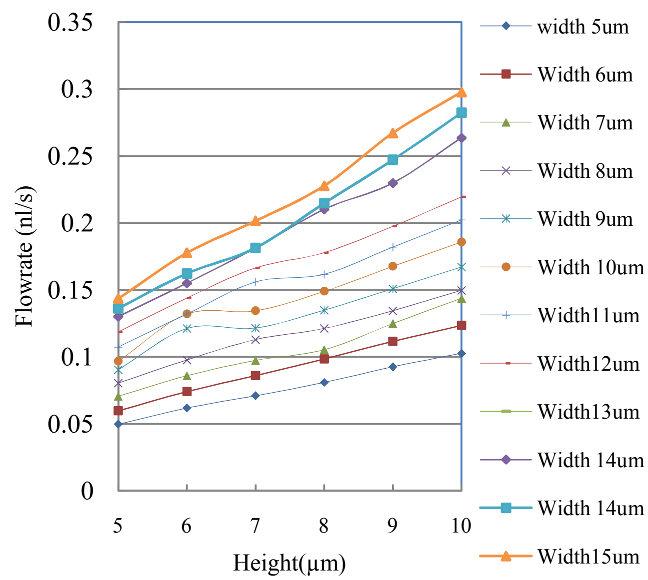


Fig 13. Effect of channel height and width on flow rate of micropump with length kept at 320µm. Simulated with TOP electrode configuration, We =5µm.

CONCLUSION

Modeling and analysis of low voltage Electro-osmotic micropump using COMSOL Multiphysics is carried out in this work. Three different possible positions of electrodes in the micropump are identified and their dependence on pump performance is investigated. Simulation results show that position of the electrodes have less dependence on flow rate for the longer pumps with length of 100µm or more. For the shorter pumps, significant increment in flow rate is noticed with END electrodes. Easily fabricable TOP electrode configuration is suitable for the longer pumps with lower aspect ratio (H/W). Studies on velocity profile measured across the width and middle of the channel shows that the velocity distribution is becoming more and more uniform when length of the channel was increased. In order to improve the flow rate, the proposed pump geometry can be cascaded parallelly and serially as described in (3, 8).

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