A Comparative Study of AC Electroosmotic Micropumps by Computational Modeling of Non-Equilibrium Electrokinetics

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AC electroosmosis is an electrokinetic phenomenon based on the interaction between an externally applied alternating electric field and mobile electric charge in an electrolyte, and it is originated at the electrolyte-electrode interface. AC electroosmostic micropumps (ACEOM) take advantage of this phenomenon to induce a net fluid flow in a microchannel through a set of electrodes located at the microchannel walls or inside the microchannel and an AC voltage signal applied to them. The main characteristic of AC electroosmotic micropumps is the possibility of driving fluids without the need of moving parts within the device, thus some advantages are offered such as low cost and ease of fabrication, possibility of integration with other structures, the reduction of unwanted electrochemical reactions due to a negligible Joule effect, and the ability to drive high programmable flows at low voltages varying the voltage signal characteristics [1]. AC electroosmotic micropumps are capable of reaching fluid flows in the range of commercially available micropumps for microfluidic/nanofluidic applications.

In this work, a non-equilibrium approach was applied to the three most common electrode geometries for AC electroosmotic micropumps: the asymmetric co-planar array, the traveling wave array with a set of four symmetric electrodes, and the 3D or non co-planar array. The implemented models were solved using *COMSOL Multiphysics*® to calculate the average fluid flow rate. This approach comprises the Poisson equation to describe the distribution of the electric field strength, the Nernst-Planck equation to denote the sum of the diffusive and electro-migration flux intensities of the ionic components, the Navier-Stokes equation to define the velocity of the fluid, and the continuity equation to determine the pressure field [2,3].

For a matter of simplicity, the system was defined as an isothermal system and gravity effects were neglected; the fluid was defined as an incompressible Newtonian fluid with constant relative permittivity, viscosity, density, and ionic diffusivities.

For a precise comparison on the performance of the micropumps, the microchannel dimensions were standardized to a transversal section of 30 um by 10 um, and variations were only made on the electrode array. Inside the microchannel, the electrode set for the three different cases had a total length of 15 um, which was distributed in the two inner quarters of the channel width.

For the asymmetric co-planar array, a pair of asymmetric electrodes was used to generate different size eddies above the electrodes by means of applying sinusoidal signals with a phase shift difference of 180^{o} to each electrode; thus inducing a net fluid flow. The large electrode had a width of 12 um and the short electrode had a width of 2 um. The gap between the electrodes was 1.5 um.

The second array is the traveling wave array, where a set of four symmetric electrodes was used to induce a net fluid flow by means of applying a sinusoidal electric potential to each electrode with a

phase shift of 90^o between two adjacent electrodes. In this case, all the electrodes had a width of 3 um and the gap between each pair of electrodes was 0.75 um.

Finally, a 3D array of electrodes was implemented using a set of symmetric, non co-planar electrodes. In this case, half width of each electrode was inside the microchannel and half size was at the boundary of the microchannel, emulating an L-shape. The inner section of the electrode is 3.25 um width and 1 um height. The section at the boundary of the microchannel is 3.25 um.

The structure of each micropump was modeled as a bi-dimensional geometry. The non-equilibrium approach was implemented using three branches: the *Electric Currents* branch for the definition of the electric field distribution, the *Transport of Diluted Species* branch to solve the Nernst-Planck equation and the *Creeping Flow* branch for the Navier-Stokes equations solution. Pertinent boundary conditions were established at liquid-solid interfaces and open boundaries were defined at the fluid inlet/outlet boundaries.

For the three cases of electrode arrays, a 1V amplitude and 1kHz frequency voltage signal was applied; phase shifts depended upon the case for the analyzed electrode array.

For the case of the asymmetric co-planar array, the applied signal to the large electrode was $\varphi_L = A\sin(2\pi ft)$, and the applied signal to the right electrode was $\varphi_R = A\sin(2\pi ft + \pi)$, thus an alternating electric field was induced into the bulk fluid. The generated electric field causes ion movement towards the opposite charge on the electrodes, and by means of viscous forces, a fluid flow is obtained in the bulk fluid. With this induced fluid flow, vortexes are observed near the electrodes edges, which have different sizes due to the difference in the width of the electrodes: large vortexes above the large electrode and small ones above the small electrode; thus a net flow is induced in the direction going from the narrow electrode to the wide electrode. The maximum instant fluid velocity obtained is 90 um/s, while the average fluid velocity is around 40 um/s.

For the traveling wave array of electrodes, the signals applied were $\varphi_1 = A\sin(2\pi ft)$, $\varphi_2 = A\sin\left(2\pi ft + \frac{\pi}{2}\right)$, $\varphi_3 = A\sin(2\pi ft + \pi)$, and $\varphi_4 = A\sin\left(2\pi ft + \frac{3\pi}{2}\right)$ to their respective electrodes. The fluid flows towards the 0^o shift phase electrode; in this case, in the direction of the first electrode. The maximum instant fluid velocity obtained was 370 um/s, which is higher in one order of magnitude in comparison to the asymmetric co-planar electrode array. The average fluid velocity was around 180 um/s.

Identical voltage signals to the asymmetric co-planar electrode array were applied to the 3D electrode array and the electric field distribution varies near the electrodes surface but it becomes similar as the distance away from the electrodes increases. The purpose of the 3D electrodes is to reduce vortexes in the opposite direction of the net fluid flow.

For the three cases, it was noticed a stronger electric field magnitude at the electrodes' edges, hence the greatest concentration of ions around those areas.

For the same voltage signal in amplitude and frequency and the same fluid conditions, the asymmetric co-planar array showed the lowest fluid velocity of the three micropumps. The average fluid velocity obtained with this array was 45 um/s. With the traveling wave array, an average fluid velocity of 200 um/s was obtained, and the 3D array showed an average fluid velocity of 5000 um/s, which is considerably higher than the traveling wave array and the asymmetric co-planar array. All the three devices showed a similar parabolic velocity profile, but only the traveling wave showed a negligible

back-flow, while the asymmetric co-planar array and the 3D array showed a back-flow around 11% and 13%, respectively.

The presented work describes the three most commonly studied AC electroosmotic micropumps through the non-equilibrium approach implemented in a finite-element modeling software. The three micropumps showed an acceptable performance. The lowest fluid velocity is achieved by the asymmetric co-planar electrode array; the traveling wave electrode array achieves one order of magnitude higher that the asymmetric co-planar array, and the 3D electrode array is the configuration with the highest fluid flow. Both, the asymmetric co-planar array and the 3D array of electrodes generate a small back-flow that reduces the overall performance of the micropump, while the traveling wave array of electrodes preserve a positive flow along all the applied signal cycles. An important parameter that was not included in this study is the microchannel dimensions since the bigger the microchannel dimensions, the lower the fluid velocity for the same voltage amplitude and frequency for any of the presented cases, neither the fabrication process was considered for the modeling of the devices, where are involved the electrodes and microchannel materials and minimum resolution in the manufacturing process.

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