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Electro Hydrodynamic Pumping of Liquids in Microchannels

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Abstract. This paper describes the concept of Electrohydrodynamic (EHD) pumping in microchannels and the study of EHD pumps in IntelliSuite's Microfluidic simulation module. The EHD pump study focuses on the factors influencing the velocity of fluid flow such as the conductivity of the fluid, the frequency of the driving AC voltage, the phase of the driving signal, the dimensions of the electrode, the gap between the electrodes and the number of driving electrodes. The results from the simulation will be used to characterize the presented design of the EHD pump. The presented design for the study of the EHD pump has a microchannel with a length of 0.2mm, width of 0.08mm and a thickness of 0.08mm. The width of the driving electrodes present at the bottom of the channel is 0.01mm and the gap between the electrodes is 0.04mm.

1. Introduction

EHD pumping finds applications in microfluidic cooling circuits and in micro-pumps to pump liquids through a channel. The typical velocities of the pumped fluids range from 10 µm/sec to 1000 µm/sec for driving frequencies ranging from 10 Hz to 100 KHz [1, 2]. The phenomenon behind EHD pumping is AC electroosmosis. When a potential is applied to the electrode, the field causes charges to accumulate on the electrode surface. This accumulation of charge on the surface changes the charge density near the surface and forms an electric double layer (EDL). The electrode is polarized and the EDL interacts with the tangential component of the electric field. This interaction causes a net force to be generated on the double layer and causes fluid motion. When an AC field is applied on the electrodes, the sign of the charges in the EDL and the direction of the tangential component of the electric field change with the applied AC signal and thus the direction of the resultant force on the fluid remains the same even as the polarity changes.

2. Theory

IntelliSuite's multiblock finite volume microfluidic solver with transient analysis options, electroosmotic boundaries and loads was used for characterization of the EHD pump. In IntelliSuite's finite volume solver, the electric field is computed using the Poisson's equation

$$\nabla^2 \phi = -\left(\frac{\rho_e}{\varepsilon_r}\right)$$

where ϕ is the electric potential, ρ_e is the net charge and ε_r is the effective relative permeability. The whole fluid is assumed to be electro-neutral and the electric potential is calculated by the laplacian

$$\nabla^2\phi=0$$

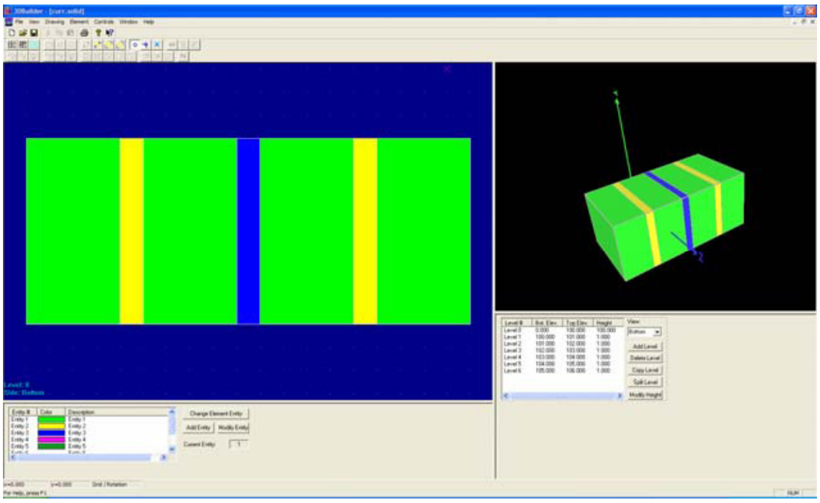
The electro-osmotic velocity is given by,

$$V_{eom} = -\frac{\varepsilon_r \varsigma}{\mu}\vec{\mathrm{E}}$$

where ς is the zeta potential at the wall and μ is the dynamic viscosity [3]. The electric potential is solved first and other transport equations solved subsequently. In IntelliSuite's finite volume solver for electroosmotic flow, the zeta potential at the walls can be prescribed according to sign convention.

3. Device Description

The presented EHD pump has 3 driving electrodes at the bottom of the channel with a width of 10 µm and a spacing of 40 µm. The 3D model was built in IntelliSuite's 3D Builder which is a 3D mesh generator. Figure 1 shows the model as built in IntelliSuite's 3D Builder module. For the microfluidic modeling, the complete fluid was drawn as a 3D representation and the regions of the fluid in contact with the driving electrodes were defined as different entities. Figure 1 shows the 2D drawing area on the left side of the figure and the corresponding 3D representation of the 2D structure on the right side of the figure. The entities and the thickness were defined as shown in the figure. The green, blue and the yellow entities represent the fluid. The blue and the yellow entities represent the fluid driven at a different frequency/phase. The 3D mesh was then exported to IntelliSuite's microfluidic module for Electroosmotic flow analysis. The simulation settings were defined to Fluid flow with Electroosmotic Boundary conditions. The various properties of the liquid such as density, viscosity and conductivity were specified in the simulation module. Electroosmotic inflow boundary was defined at the pump inlet and the ambient pressure outflow boundary was defined at the pump outlet. The density of the fluid was defined as 1000 Kg/m^3, the viscosity of the fluid was defined as 1e-3 N-s/m^2 and the dielectric constant of the fluid was 7. The conductivity of the fluid was varied from 2 mS/m to 8.4 mS/m. The electroosmotic inflow voltage was defined as -0.1V and the zeta potential at the bottom walls of the microchannel was defined as 0.1V (+/-). The sign conventions of the zeta potential depend on the phase of the applied AC signal. The driving voltage ranged from 10V to 50V and the frequency was varied from 10 Hz to 100 KHz. The driving voltages applied on the adjacent electrodes were 90 to 180 deg. out of phase.



Level #	Bot. Elev.	Top Elev.	Height
Level 0	0.000	100.000	100.000
Level 1	100.000	101.000	1.000
Level 2	101.000	102.000	1.000
Level 3	102.000	103.000	1.000
Level 4	103.000	104.000	1.000
Level 5	104.000	105.000	1.000
Level 6	105.000	106.000	1.000

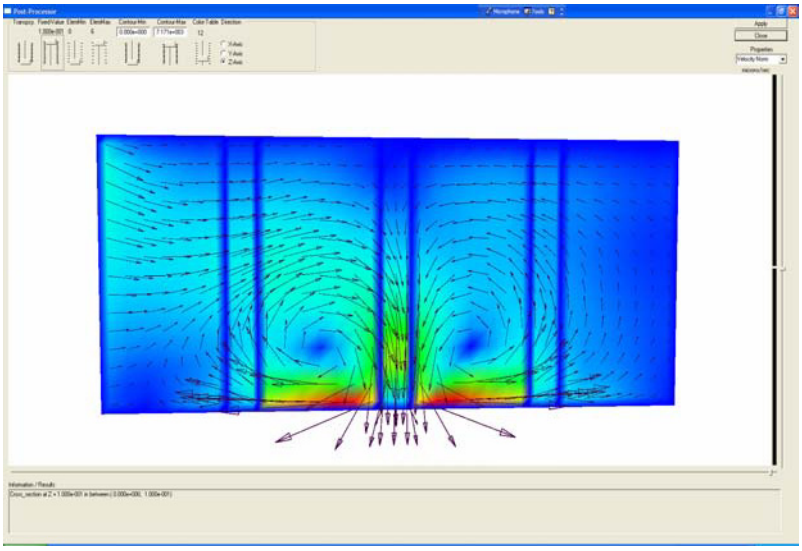
Entity #	Color	Description
Entity 1	🟩	Entity 1
Entity 2	🟨	Entity 2
Entity 3	🟦	Entity 3
Entity 4	🟪	Entity 4
Entity 5	🟩	Entity 5

Current Entity: 1

Figure 1: The 3D representation of the fluid as drawn in IntelliSuite's 3D Builder.

4. Results and Discussion

Theoretical and experimental observations [1, 2] conclude that maximum AC electroosmotic velocities can be achieved at low frequencies (10Hz to 1KHz) with conductivities of the fluid medium in the range of 2.1mS/m .For very high frequency operation, in the range of 100 KHz, the conductivity of the medium should be in the range of 84mS/m and the electroosmotic velocity is reduced to half of that obtained at low frequencies. This data from experiments and theory was used in the simulation to compare the electroosmotic velocities for various values of conductivities and frequencies. Figure 2 and Figure 3 show the velocity vectors progressing in the microchannel with the applied AC driving signal.



Transparency	FixedValue	ElemMin	ElemMax	ContourMin	ContourMax	Color Table	Direction
	1.000e-001	0	6	0.000e+000	7.171e+003	12	Z-Axis

Cross_section at Z = 1.000e-001 is between (0.000e+000, 1.000e-001)

Figure 2. Velocity vector at the center of the microchannel with three driving electrodes

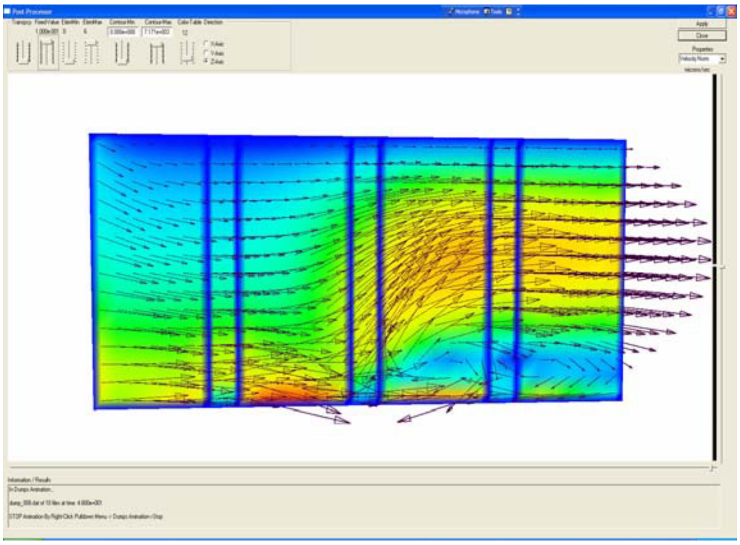


Figure 3. The direction of the velocity vectors during a transient simulation of the EHD pumping principle.

Since the driving AC signals were out of phase, it resulted in concentric "roll" formations at the tip of the electrodes. The rolls at the bottom of the channel drive the flow. Figure 4 shows the formation of rolls at the tip of the electrodes in the bottom of the channel. Figure 5 shows the electroosmotic velocities for various frequencies ranging from 100HZ to 3 KHz. The conductivities of the fluid medium used were 8.4 mS/m and 5.2 mS/m respectively. The maximum velocity for a conductivity of 5.2mS/m was achieved at an operating frequency of 600Hz whereas for a conductivity of 8.4mS/m, the maximum velocity occurs at 1 KHz. The signals were 90 deg out of phase.

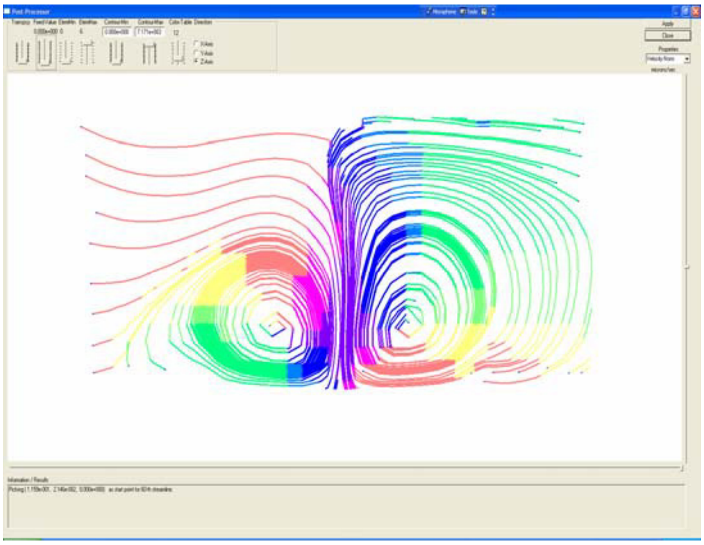


Figure 4. Streamlines in the channel indicate the formation of rolls at the tip of the electrodes.

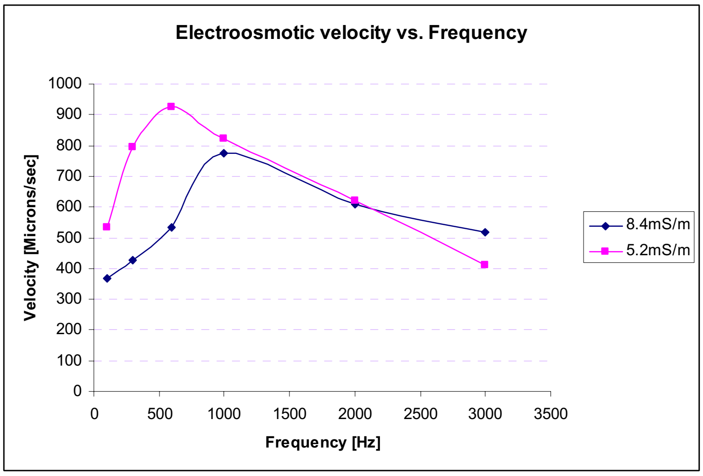


Figure 5 Comparison of AC electroosmotic velocity vs. frequency for a fluid with a conductivity of 8.4mS/m and 5.2 mS/m

5. Conclusion

The phenomenon of EHD pumping was successfully modelled in IntelliSuite's Microfluidic module and the effect of driving frequency and the conductivity of the liquid on the Electroosmotic velocity were successfully characterized using the simulation tool.

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[2] N.G. Green,A.Ramos,A. Gonzalez, H. Morgan and A. Castellanos "Fluid Flow Induced by Nonuniform AC Electric Fields in Electrolytes and Microelectrodes II", Physical Review E, pp. 1-8, vol. 66, 2002

[3] IntelliSuite Technical Reference, Copyright 2006 IntelliSense Corporation.