Effect of Conductivity and Viscosity in the Velocity Characteristics of a Fluid Flow Induced by Non-uniform AC Electric Field in Electrolytes on Microelectrodes

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Abstract:

We study the electroosmotic velocity of electrolyte in coplanar parallel electrodes. The velocity of the electrolyte measured at a certain point above the electrode shows a maximum as the frequency of the applied potential varies from ~1 Hz to 10 kHz which is within the approximation of a planar structure for electric double layer. We study an extended the range of applied frequency as it is plausible that interplay of various forces as well as the finite size of the ions would lead to a deviation from the simplification adopted in most theoretical models. In view of this, in the present study, the frequency range was extended to 80 kHz and a second maximum, albeit smaller by an order of magnitude, was also found, consistent with our apprehension. Moreover the variation of the velocity spectrum with respect to different viscosity and the conductivity of the materials have also been studied.

Keywords:

AC Electro osmosis, Navier Stokes equation.

1. Introduction

Electro kinetic transport of fluids has been investigated both experimentally and numerically [1-3] due to its various applications in micro fluidic devices. Interestingly these devices, at macro and nano levels, offer the advantage of transporting fluids or particles to specific locations without the aid of mechanical components like pumps and valves. The study with devices by Pribyl et al showed that the Poisson-Nernst-Planck-Navier-Stokes non-equilibrium model was applicable. Pham et al [2] used a modified Poisson-Boltzmann for electro kinetic studies of symmetric geometry of coplanar parallel electrodes (CPE). It is indeed true that a widely studied geometry for AC electroosmotic flows is that of CPE with respect to both symmetric and asymmetric geometries. In this context it is worth mentioning the device by Green's et al which consisted of a symmetric arrangement of CPE subjected to an AC potential.

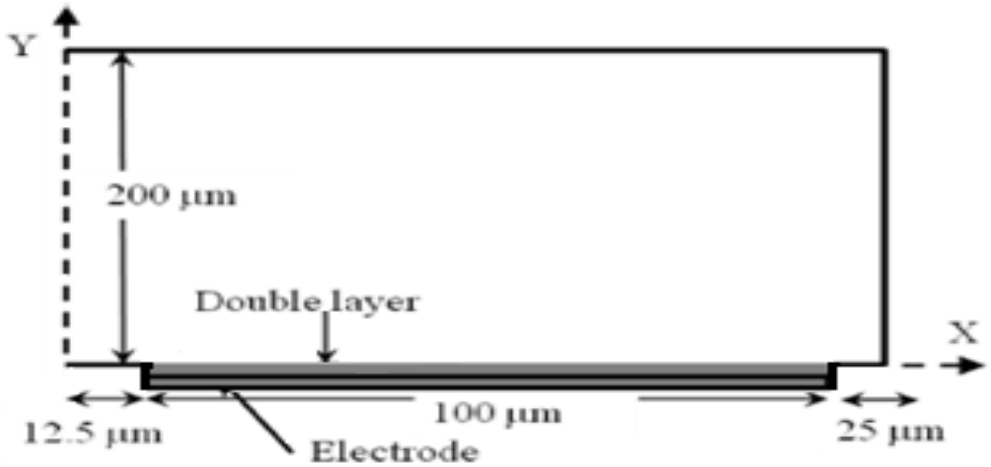

Figure 1: Schematic of the geometry of one half of the system. The Y-axis is the plane of mirror symmetry of the system.

2. Theory:

Application of an AC electric field across a system of coplanar parallel electrodes immersed in a liquid medium leads to capacitive charging induced polarization of the electrodes. Ions of opposite charges from the bulk solution form a thin mobile layer of ions on the surface known as the double layer. The force due to high electric fields in micrometer sized gaps acting on the mobile ion layer causes movement of the ions in a regular symmetric pattern , the phenomenon known as AC electro osmosis.

3. Numerical Model

Micrometer-sized electrodes are used in the device simulations. The schematic of the geometry of one half of the system is shown in Figure 1.

The electrolyte (KCl) was taken to have a conductivity $\sigma = 2.1 \times 10^{-3}$ S/m and viscosity η = .001 Pa s. In Green et al's [7] work the frequency of the applied sinusoidal potential ranges from about 10 Hz to 10 kHz. We study an extended range of the frequencies to 100 kHz.

The model was solved using the Electric Currents interface for the Electric field and Electric Potential which was coupled with the Creeping Flow interface to solve for the electro osmotic velocity. The double layer was modeled as a capacitive boundary condition. The time dependent Navier Stokes equation was used to solve for the fluid flow. Owing to the symmetry of the fluid flow pattern, only one half of the system was simulated.

4. Governing Equations

The typical thickness of a double layer is given by the Debye length:

$$\lambda_D = \sqrt{\frac{\square K_b T}{N_A q_1 q_2 2C}}$$

In the bulk electrolyte the electric field is governed by Ohm's Law:

$$\mathbf{J} = \sigma \mathbf{E}$$

The fluid flow is governed by the Navier Stokes equations:

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} = \mu \nabla^2 \boldsymbol{u} + \nabla . \boldsymbol{p} \qquad ; \qquad \nabla . \boldsymbol{u} = 0$$

The electro osmotic velocity is given by the Helmhotlz Smoluchowski formula:

$$\boldsymbol{u} = -\frac{\boldsymbol{\varepsilon \zeta}}{\boldsymbol{\mu}} \boldsymbol{E_x}$$

Where,

λ_D = Debye length

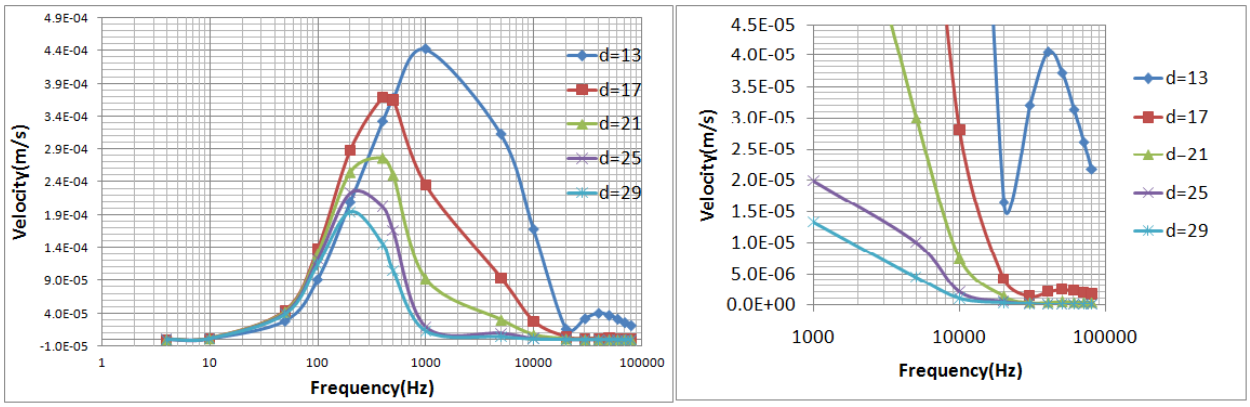

Figure. 2 Plot of the velocity spectrum of the electrolyte. (d is in units of μm)
Left panel: The velocities are taken at distances d=13, 17, 21, 25 and 29 μm (curves from top to bottom) from the plane of symmetry.
Right panel: The log plot of the velocity spectrum in the high frequency range clearly shows a second peak .

ε = Permittivity of medium

k_b = Boltzmann constant(1.23×10^{23}J/K)

T = Ambient Temperature (298K)

N_A = Avagadro Number

q_1, q_2= Charges on the ion

C= Concentration of ion

J = Current density

σ = electrical conductivity

E =Electric field

ρ = Density of electrolyte

μ = Dynamic viscosity of the electrolyte

u = Electro osmotic velocity

p = Pressure

$\boldsymbol{E_x}$= Tangential electric field

ζ = Zeta potential

5. Results and Discussions:

The plot of the velocity magnitude as a function of frequency of the applied potential at different distances across the electrode surface is shown in Figure. 2(left panel). The prominent peak (first peak) in the graph is in agreement with the experimental results by Green et. al [6]. Along with the first peak, a second peak in the velocity spectrum at higher frequencies is clearly visible in Figure. 2 (right panel) at different distances on electrode surface. Although the peaks persist at higher frequencies, the velocities go down almost by an order of magnitude compared to the first peak occurring at lower frequencies. It is also to be noted that the frequency dependence of the peak velocity at the two peaks at increasing distances from the electrode edge is opposite in nature. While the first peak moves to lower frequencies as the distance on the electrode increases, the second peak moves to higher frequencies. Figure.3a shows the plot of electro osmotic velocity for three different values of viscosity keeping conductivity fixed at 0.0021 S/m. The values of velocities at different distances increase as the viscosity decreases in agreement with experiments by Green et. al [8]. At a fixed value of viscosity we examine the dependence of velocity on conductivity at three different values of conductivity as shown in Figure.3b. As conductivity increases, the peak frequency increases. Interestingly, the patterns remain the same as these parameters are varied, indicating linear behavior of the system in the chosen frequency range. Both the peaks persist at different conductivity and viscosity values.

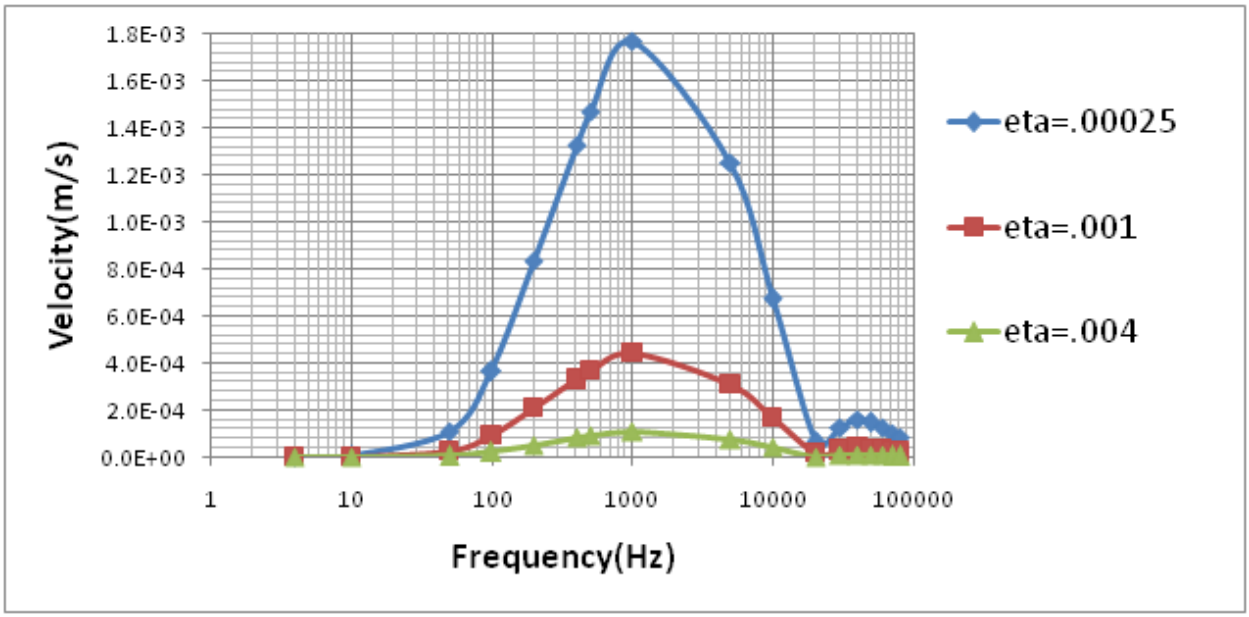

Figure 3a: Variation in electro osmotic velocity at different viscosities

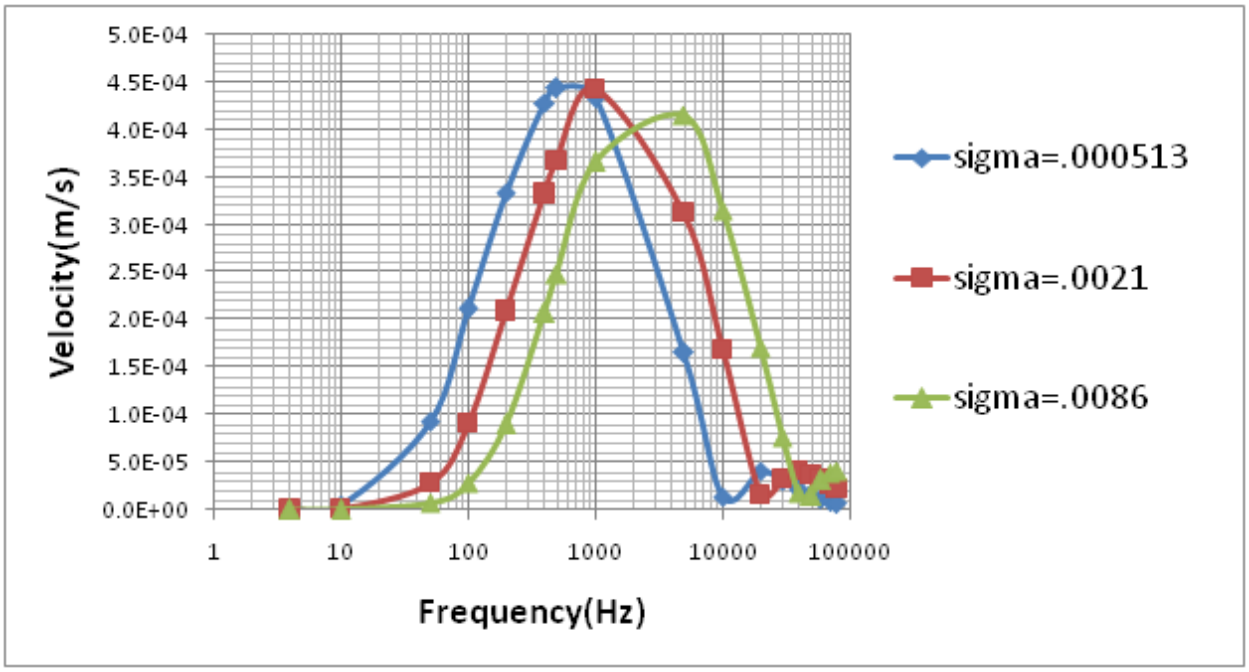

Figure 3b: Variation in electro osmotic velocity at different conductivities

6. Conclusion

A symmetric CPE geometry filled with an electrolyte was subjected to an alternating potential. A peak in the velocity spectrum is obtained which remained even when other parameters such as viscosity and the conductivities of the electrolyte were varied indicating linear behavior.

Acknowledgement: One of the authors (SB) would like to thank the Department of Atomic Energy, India for supporting this work.

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