EFFECTS OF MICROCHANNEL CROSS-SECTION AND APPLIED ELECTRIC FIELD ON ELECTROOSMOTIC MOBILITY

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Abstract: In this work we report on the numerical and experimental investigation of the effects of channel cross-section and applied electric field on electroosmotic flow (EOF) mobility in poly-dimethylsiloxane (PDMS)/glass hybrid microchannels. The experimental results are used to calibrate and validate the simulation model to solve the Navier-Stokes equation for fluid flow and Poisson equation to resolve the external electric field. According to the Helmholtz Smoluchowski equation the electroosmotic mobility (μ_{EO}) is independent of channel cross-section and applied electric field. Contrary to the above relationship, the results presented in this work indicate that μ_{EO} is not constant but changes with channel cross-section as well as the applied electric field. The results of this work will be useful in determining the optimum channel dimensions for a desired electroosmotic velocity at a given applied electric field.

Keywords: EOF, electroosmotic velocity, electroosmotic mobility, wetted perimeter, zeta potential

1. INTRODUCTION

Electroosmotic flow (EOF) is used for transporting and mixing reagents in many biological and chemical lab-on-a-chip (LOC) systems. EOF occurs when the electric double layer in a solid-liquid interface is imparted a momentum by an external electric field [1], offering a number of advantages over conventional pressure driven microflows. In EOF, the velocity of the liquid normal to the cross-section is uniform all across the channel width producing plug flows. This reduces any possibility of sample dispersion as compared to pressure-driven flows, which are characterized by parabolic velocity profiles. EOF is influenced by the applied electric field across the microchannel, just as fluid velocity is influenced by pressure gradient in a pressure driven system.

Recent investigations suggest that electroosmotic mobility (μ_{EO}) is dependent on both microchannel cross-section as well as electric field, contrary to the Helmholtz Smoluchowski equation. Fujiwara *et al.* [2] investigated the relationship between electroosmotic mobility and applied electric field, and showed that as the electric field strength increases, so does μ_{EO}. The effects of microchannel hydraulic diameter and aspect ratio on μ_{EO} were recently studied by Karimi *et al.* [3]. It was found that as the channel hydraulic diameter is increased, it takes a longer period for the flow to become steady.

In this work we investigate the effects of microchannel wetted perimeter on μ_{EO} and hence electroosmotic velocity using both experimental and numerical methods. Experiments to study the influence of applied electric field on electroosmotic mobility were also performed. The experimental results were in good agreement with numerical simulations, and were compared with theoretical predictions based on the well accepted Helmholtz Smoluchowski equation.

2. METHODS

2.1 Simulation Methodology

Numerical simulations were performed using commercial finite element methods using an implicit 3D scheme. Microchannels of rectangular cross-section, filled with a buffer, as shown in Figure 1, were considered.

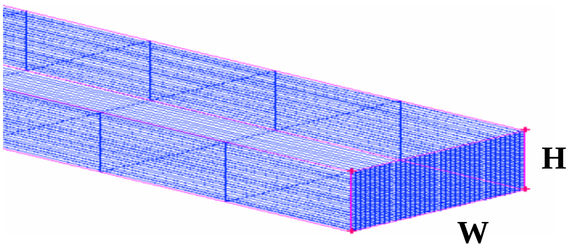

Figure 1. The computational grid for solving the electroosmotic flow in straight channels.

The height of the channels was fixed at 70 µm and the width was varied from 10 µm to 200 µm. At the inlet and outlet, applied voltage was specified as boundary conditions. Calculations were performed for buffer with density 1000 kg m^{-3}, dynamic viscosity of 0.001 Nsm^{-2} and relative permittivity of 80. In all theoretical calculations the zeta potential was determined to be 0.056 V. This was calculated from Spehar *et al.* [4], for electroosmotic flow in PDMS/glass microchannel filled with a 20 mM phosphate buffer.

For 20 mM phosphate buffer, the Debye layer (λ_D) was calculated as 2.15 nm thick, which is extremely thin compared to channel dimensions (λ_D */W (10µm)* = 2.15 × 10^{-4}). Thus, a slip boundary condition was implemented at the wall due to the wall charge. The slip velocity at the wall was calculated from the Helmholtz Smoluchowski equation [1].

$$U_{eo} = \zeta \varepsilon E / \mu \qquad (1)$$

where U_{eo} is the electroosmotic velocity, ε is electric permittivity of the buffer, ζ is zeta potential, and μ is dynamic viscosity of the buffer. The zeta potential for all numerical calculations, used as an input parameter to the model, was calculated from experimental data. The fluid was electrically neutral, with zero net bulk charge, thus eliminating any electrophoretic flow phenomenon. The governing equations for electroosmotic fluid flow are conservation equations for mass (continuity equation, Eq. 2) and momentum (Navier – Stokes equation, Eq. 3)

$$\nabla \cdot \boldsymbol{u} = 0 \qquad (2)$$

$$\rho_m (du/dt + (u \cdot \nabla)u) = \mu \nabla^2 u - \nabla p + f_e \qquad (3)$$

where u is the velocity vector (m/s), ρ_m is the density of the buffer (kg/m^3), ∇ is the gradient operator (m^{-1}), μ is the dynamic viscosity (Ns m^{-2}) of the electrolyte solution. The last term, f_e, is the coulomb force due to application of an external electric field on wall charges. It is given by

$$f_e = \rho_e E \qquad (4)$$

where ρ_e is the charge density (C/m^3), E is the electric field (V/m). Hence the Coulomb force term is zero. The governing equation for resolving the electric field is the Gauss law equation given by:

$$\nabla \cdot (\varepsilon \nabla \phi) = -\rho_e \qquad (5)$$

where ρ_e is the charge density. Since net charge in the buffer is zero, $\rho_e = 0$, Eq. 5 becomes

$$\nabla^2 \phi = 0 \qquad (6)$$

At the inlet and outlet of the microchannel applied voltage is specified.

2.2 Experimental Methodology

The microchannels were fabricated in PDMS using SU-8 masters (Figure 2). Initially, 3" Si wafers were coated with a negative photoresist, SU-8 2075 (MicroChem Corp., MA) to define the 70 µm high microchannels. Next the wafers were transferred onto a leveled surface for 10 min to allow the photoresist to relax. The pre-bake was then performed on a temperature controlled level hot plate at 65 °C for 10 min and 95 °C for 45 min. The wafers were then gradually cooled to room temperature by turning off the heater on the hot plate and leaving the wafers on the hotplate for 15 min. The resist was then exposed for 35 s at 5 mW/cm^2 using an I-line (365 nm) high pass filter. Glycerin was used during exposure to reduce any diffraction effects that may arise due to surface roughness. Post exposure bake was then carried out on a level hotplate at 65 °C for 5 min and 95 °C for 15 min.

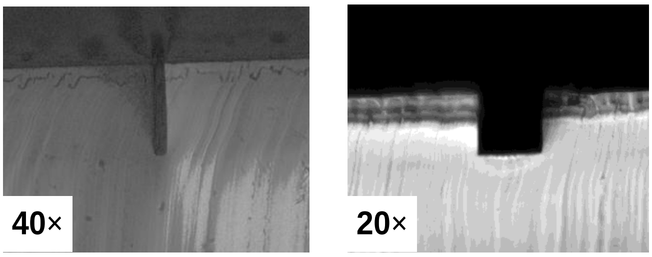

Figure 2. Cross-section images of the channels fabricated in PDMS. (left) 10 µm × 70 µm (W × H), and (right) 100 µm × 70 µm (W × H) channels.

The wafers were then developed in the SU-8developer (MicroChem Corp., MA). To confirm development the wafers were rinsed with isopropyl alcohol. Following development, wafers were rinsed with DI water, blown dry using N_2 and descummed in O_2 plasma (20 sccm, 13.56 MHz) for 2 min at 300 W to clean the wafer off any residual photoresist.

To complete the channels, microscopic glass slides (1" × 3") are then bonded to the PDMS molds using O_2 plasma [5]. Following fabrication the μ_{EO} of channels having varying cross-sections was measured using the conventional current-time relationship using a 20 mM phosphate buffer (pH 8). The experimental setup to measure the μ_{EO} consists of the fabricated microchannels with inlet and outlet reservoirs, platinum electrodes powered using a high voltage power supply, and data acquisition system driven

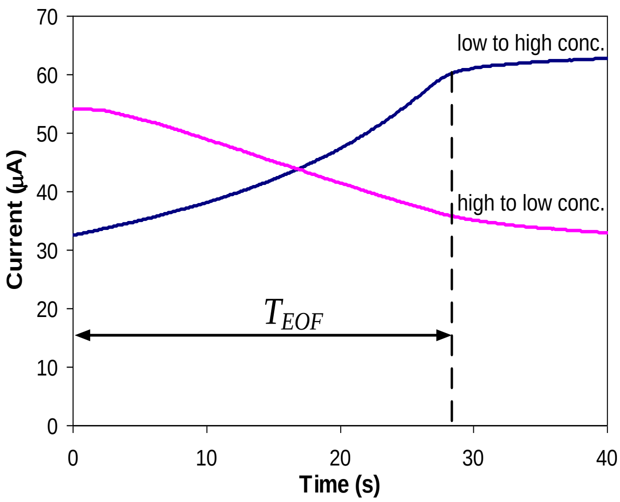

Figure 3. Current versus time for 10 mM phosphate buffer solution (pH 8) in PDMS/glass channels under an applied voltage of 500 V over the 2 cm length of the channel.

by LabVIEW program. Figure 3 shows a typical current-time profile acquired using LabVIEW.

From the plot, the time, T_{EOF}, required for the 10 mM buffer to replace the 20 mM buffer (and vice versa) was recorded. The μ_{EO} is then given by

$$\mu_{EO} = \frac{L}{E \times T_{EOF}} \text{ cm}^2/\text{V-s} \qquad (7)$$

where, L (cm) is the length of the microchannel and T_{EOF} (s) is the time required for one buffer to displace the other.

3. RESULTS AND DISCUSSION

The effect of channel width on μ_{EO} is shown in Figure 4, and compares numerical and experimental results. It was found that as the wetted perimeter decreases the μ_{EO} increases. However, a substantial increase in μ_{EO} was observed for channels having widths smaller than 50 µm (height = 70 µm).

This phenomenon can be explained by the fact that as the microchannel width increases, a consequent increase in liquid volume results in inertial forces dominating over electric body

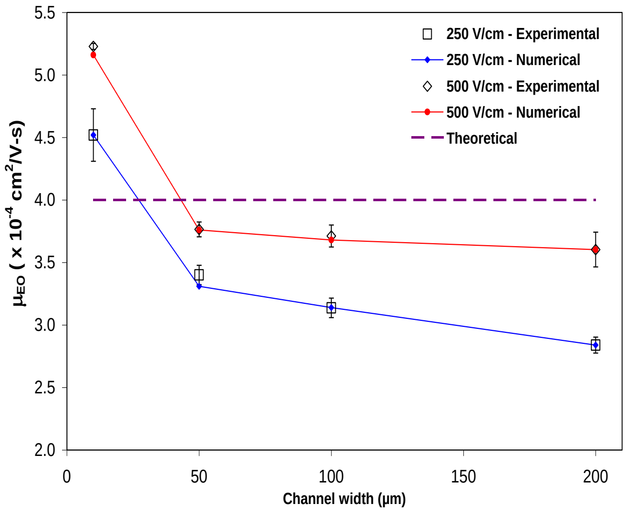

Figure 4. Numerical and experimental results showing the effect of channel width on electroosmotic mobility for 250 V/cm and 500 V/cm electric fields. The height of the channels is fixed at 70 µm. The dashed line indicates the μ_{EO} calculated using Helmholtz Smoluchowski equation.

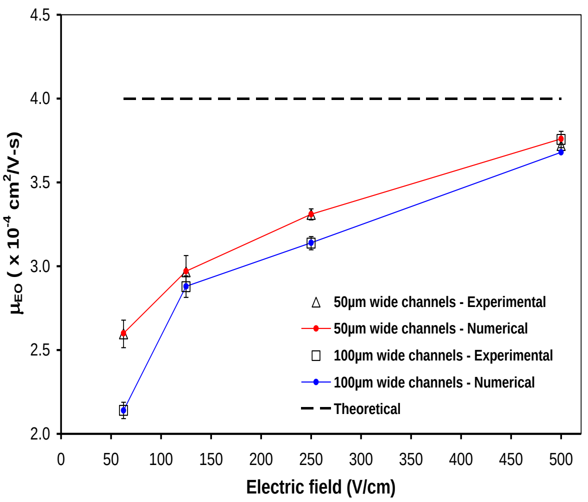

Figure 5. Numerical and experimental results indicating the effect of electric field (E) on electroosmotic velocity (U_{eo}) for 50 µm and 100 µm wide channels (height = 70 µm). The dashed line indicates the μ_{EO} calculated using Helmholtz Smoluchowski equation.

forces. For 250 V/cm input, experimental μ_{EO} varies from 3.84 % to 40.8 % from theoretical predictions as the microchannel width increases from 10 µm to 200 µm. Similarly for a 500 V/cm input, the error between experimental and theoretical predictions was between 6.38 % to 23.5 %. This implies that the electric field also has an influence on μ_{EO}.

The effect of applied electric field on μ_{EO} is shown in Figure 5 for channels with 50 µm and 100 µm widths. For the same conditions, we observed varying μ_{EO} for varying electric fields. Similar to the study by Fujiwara *et al.* [2], we initially believed that Joule heating could explain this discrepancy, since Joule heating could lower the viscosity of the buffer and raise the electroosmotic mobility. However, the maximum temperature rise was calculated to be 3.5 ^{o}C based on the work by Ramos *et al.* [6]. Therefore to explain this effect we must consider the possibility that zeta potential varying with applied electric field as supported by Fujiwara *et al.* [2].

For 50 µm wide channels, μ_{EO} varied from theoretical predictions by 6.38 % to 53.8 % for increasing electric fields. Similarly for 100 µm wide channels, 8.1 % to 86.5 % variations from theoretical values was observed. These results imply that as the electric field increases for a given microchannel width, the experimental μ_{EO} complies well with the Helmholtz Smoluchowski predictions. It was found that the experimental and numerical results were in good agreement (< 2 % error).

4. CONCLUSIONS

Our results show that the μ_{EO} is dependent on both microchannel cross-section and electric field. As the microchannel width increases, the μ_{EO} decreases for a given electric field. Similarly, for a given microchannel cross-section, μ_{EO} increases with increasing electric field. With the recent trend of reducing channel dimensions, towards nanofluidics, we believe that the results reported in this work will be critical in designing EOF-based microfluidic LOC systems.

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