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Electro-osmotic Pumping Flow Model in a Microchannel with Squeezing Walls

Yasser Aboelkassem

College of Innovation and Technology, University of Michigan-Flint, USA
Michigan Institute for Computational Discovery and Engineering, University of Michigan, USA

Abstract

An electroosmotic pumping flow model of aqueous electrolytes confined in a microchannel with squeezing walls is developed in this study. The mathematical model is derived based on using a strong coupling between the nonlinear Poisson–Boltzmann equation and the flow lubrication theory. The model aims to study electrolyte creeping flow transport in a microchannel and to describe the distribution of the electric potential across the electric double layer. The effects of wall zeta potential on the fluid axial velocity profiles and time-averaged net flow rate are presented. The results show that the electrokinetics parameters can be used to alter the net flow directionality without any additional mechanical valves and this system can work as a micropump.

Keywords: electroosmotic flow, lubrication theory, squeezing walls, micropumps, microfluidics.

1 Introduction

Flow transport at the microscale regime is dominated by viscous effects and lower inertial forces. For this reason, the classical approach of using active pressure drop technique to pumping micro/picoliters amount of fluid within microfluid devices is not an attractive approach. Other external methods are indeed can be used such as electroosmotic pumping. Generally speaking, electrokinetics phenomena can be used to induce an external body force that is capable of manipulating the motions of a small amount of fluid in several biomedical microdevices, [1–3].

Active means such as applying an external electric potential (using electric source) to ionized solutions (electrolytes) confined in a microchannel can be used to induce electroosmotic flow motion. Once the electric source is powered on, an electric field is generated and moves the excess counter ions located in the electrical double layer (EDL) [4]. These motions act on the surrounding fluid molecules, generating a bulk flow motion. The flow velocities induced by electroosmotic effects are typically independent of conduit size, as long as the EDL is much smaller than the characteristic length scale of the channel. Therefore, electroosmotic flow pumping is most important when microchannels are used [5–7].

Flow pumping models that are based on the peristaltic theory are widely used to investigate flow transport in many biological systems [8, 9]. In addition to peristalsis, the flow transport by membrane wall contraction has attracted considerable attention in recent years [10, 11]. For example, the rhythmic wall contraction found in the insect trachea system has been well investigated and has led to novel bioinspired micropumps [12–17].

This study offers a theoretical electroosmotic pumping flow model in a microchannel with squeezing walls. The mathematical analysis focuses on the electroosmotic-driven aqueous electrolytes flow transport phenomena by the motion of the squeezing wall. The flow lubrication theory coupled with the nonlinear Poisson–Boltzmann equation is used to model the unsteady creeping flow motion in a microchannel with moving walls. The model also has the capability to describe the distribution of the electric potential across the electric double layer. The analytical solution is obtained without the classical Debye–Hückel linearization technique. The effects of several electrokinetic parameters including the zeta potential, electric field and the Debye length on the pumping net flow rate are investigated in details.

2 Methods

Consider an electrolyte aqueous flow medium within a microchannel of height H and length L with $H << L$ under the coupled influences of (i) squeezing upper wall of the channel $H_2(x,t)$ and (ii) electroosmotic body force applied at lower wall H_1 as shown in Fig. 1. The lower wall was kept stationary at all simulation times. The flow conservation equations of an incompressible Newtonian fluid with electrokinetic body force takes the form

$$\nabla \cdot \mathbf{V} = 0, \tag{1a}$$

$$\rho\Big(\frac{\partial}{\partial t} + \mathbf{V}\cdot\nabla\Big)\mathbf{V} = -\nabla p + \mu\nabla^2\mathbf{V} + \mathbf{F}, \tag{1b}$$

$$\mathbf{F} = \rho_e\mathbf{E}, \tag{1c}$$

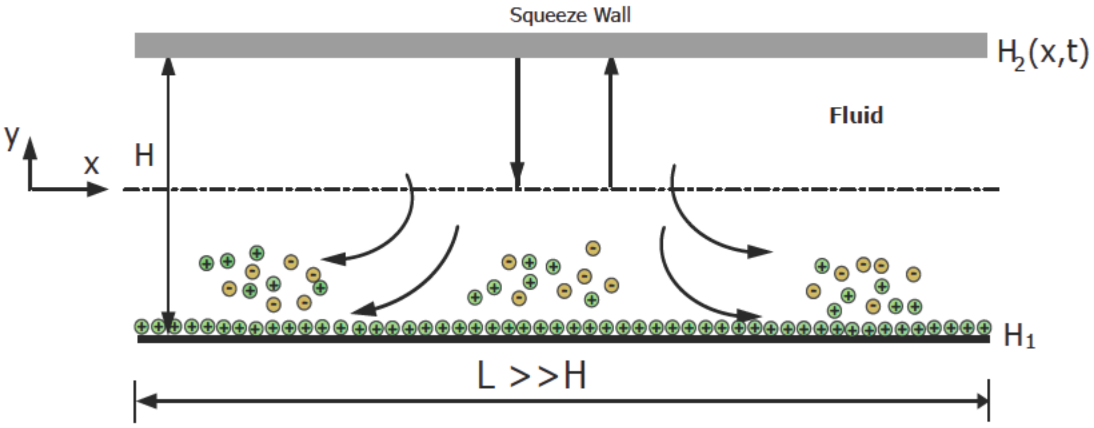

Figure 1: Electrokinetics pumping model based on a microchannel with a squeezing upper wall and a stationary lower wall patterned with a positive zeta potential.

In the above equations, ρ is the fluid density, $\mathbf{V} = (u,\ v,\ 0)$ is the flow velocity which is subject to the no-slip boundary conditions on the walls, p is the pressure, $\mathbf{F}$ is the electrokinetic body force per unit volume, $\mathbf{E}(= -\nabla\Phi)$ is the applied external electric field, ρ_e is the net charge density of the aqueous medium of permittivity ϵ, and Φ is the electric potential.

The electric potential Φ distribution inside the EDL can be governed by Poisson equation

$$\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial y^2} = -\frac{\rho_e}{\epsilon}. \tag{2}$$

Normally, all ions are assumed to be point charges and the permittivity of the fluid is treated as constant, the net electric-charge density in symmetric electrolyte solution, ρ_e, can be obtained by the Boltzmann distribution as

$$\rho_e = -2zen_0 \sinh\left(\frac{ze\Phi}{k_B T}\right), \tag{3}$$

where e is the fundamental charge, z is the valence of the ions, n_0 is the bulk concentration, k_B is the Boltzmann constant, and T is the absolute temperature. Combining equations (2) and (3) gives Poisson-Boltzmann equation:

$$\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial y^2} = \frac{2zen_0}{\epsilon} \sinh\left(\frac{ze\Phi}{k_B T}\right). \tag{4}$$

The flow conservation equations can be solved by using lubrication theory approximation. The viscous effect of a flow in the microscale regime is dominant, hence, the assumption of very low Reynolds number assumption is valid.

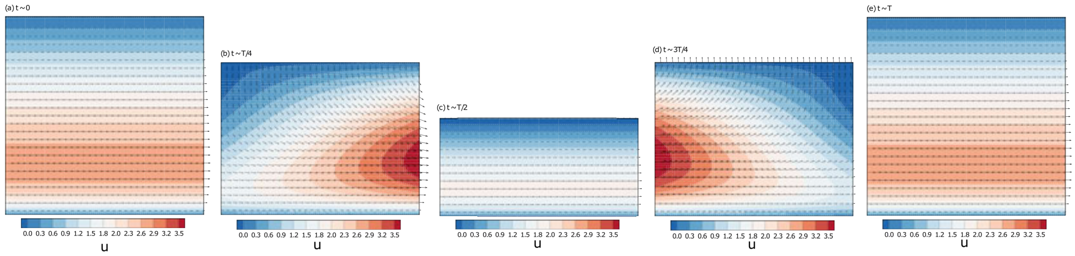

Figure 2: The axial velocity contour lines induced by both wall motion and the electokinetics effects when $U_{HS} = +1$ with $\kappa = 5$ and $\zeta = -5$. The results are shown at different time snapshots during the squeezing cycle.

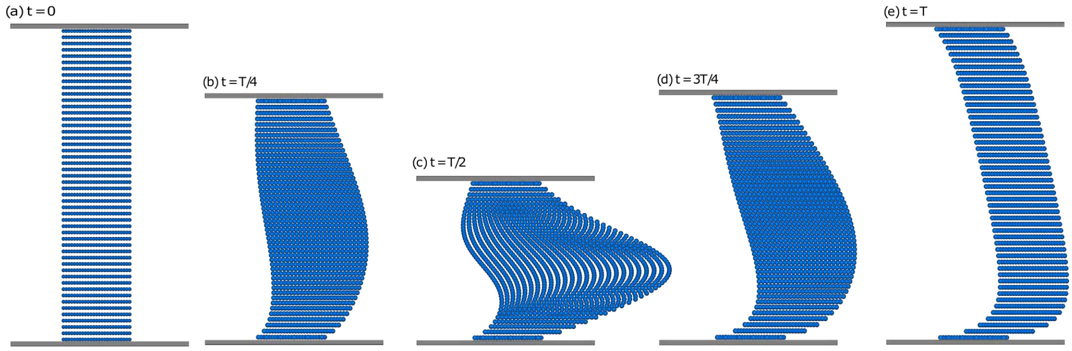

Figure 3: Passive particles tracking simulations during a complete squeezing cycle are shown to show the cyclic net flow pumping produced by the wall motion combined with electrokinetic effects. The results are shown at t = 0, T/4, T/2, 3T/4, and T, respectively.

3 Results

The induced flow motion by the squeezing upper wall profile is calculated in the absence of any electrokinetic effects as a validation step. The results are found to be consistent with the classical theory of flow between two plates. The velocity profiles during expansion are exact mirror of the results during compression. After one complete squeezing cycle, the channel shape will return to the initial configuration and there will be no net flow (i.e., no pumping) due to wall squeezing motions.

These results are expected to change once the electrokinetic effects are added to the system by assigning a zeta-potential distribution to the channel lower wall as shown in Fig.1. To show the effects of the z-potential surface patterning on the entire flow motion inside the microchannel, the contour lines rendered by the axial velocity at different time snapshots are given in Fig. 2. The velocity field represented by the vector plots is also shown on the same figure panels. The results show that when no electrokientic effects is used, the flow motions during wall expansion has shown to be an identical with opposite sign to the flow during the squeezing phase. Moreover, the flow is characterized by zero flow motion. This scenario is changed and a bulk flow motion toward the channel right exit was induced when positive zeta potential is used. The contour lines clearly show the progression of the flow maximum velocity as the upper wall squeezes and expands back. The results indicate that electrokinetic phenomena can be used as a powerful technique to customize the flow motion inside micro-geometries. This system can actually be used to generate net flow motions according to the assigned surface potential.

For example, passive particles tracers are used to track the flow motion and show that this set up can be used to produce a unidirectional net flow and act as a pumping mechanism. Particle tracking technique is used herein to visualize the time-averaged net flow induced by the electrokinetics effect. This particle simulation results are then used to validate the above derived mathematical model. For example, the instantaneous particle tracking simulations for a collection of particles at different times, t = 0, T/4, T/2, 3T/4 and T are shown in Fig.3. These time points represent the initial particles positions, motions during squeezing and expansion phases, respectively. The simulated particles have shown after a complete squeezing cycle, i.e., at t = T, there is a unidirectional flow motion and a net particle displacement (net flow) toward the right direction.

4 Conclusions and Contributions

An electroosmotic pumping flow model in a microchannel with a squeezing upper Wall is presented in this article. The lubrication flow theory is used to derive analytical solution to the coupled flow electrokinetics problem without having to use the classical Debye Hückel linearization method. The effects of several electrokinetic parameters such as, the Helmholtz-Smoluchowski, zeta potential and Debye length on the potential distribution, velocity profiles and net flow rate are studied. The results show that the induced pumping rate depends strongly on the combined effects of the Helmholtz-Smoluchowski, zeta potential and EDL. Moreover, the produced net flow directionality can be controlled effecicently the manipulating the Helmholtz-Smoluchowski and/or the wall zeta-potential. This electroosmosis pumping mechanism can provides some initial guidelines for the fabrication of novel microfluidics devices that can be useful in many biomedical applications.

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