

Electroosmotic Pumping of Nonconducting Liquids by Viscous Drag from a Secondary Conducting Liquid

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ABSTRACT

A novel electroosmotic pump design relying on two-liquid viscous drag to pump nonconducting liquids is presented and analyzed theoretically. We denote the pump a two-liquid viscous EOF pump. A conducting pumping liquid driven by electroosmotic flow (EOF) drags a nonconducting working liquid by viscous forces. In particular liquids such as oil, which normally cannot be moved by EOF, may be pumped. This allows for new types of analysis in the field of micro Total Analysis Systems (μ TAS) which may prove important in the drug industry and for environmental monitoring. The characteristic flow rate Q and pressure p of the pump is in the range nL/s and kPa, respectively, but depends largely on achievable geometrical dimensions and applied voltage. This paper presents a theoretical and modeling study of the novel design.

Keywords: electroosmotic pump, viscous drag, two-phase flow, circuit modeling, CFD simulation

1 INTRODUCTION

Electroosmotic pumps are suitable for microfluidic applications since (1) they do not have moving parts, (2) they do not produce pulsating flows, and (3) they are easier to integrate. The liquids are pumped by applying an electric field to the electric double layer which forms in the liquid by Debye screening of the immobile charges on the pump walls. In order for such a double layer to form, the liquid needs to have significant electrical conductivity i.e. a sufficiently high concentration of dissociated ions. Nonpolar liquids with very low conductivity ($< 10^{-6}$ S/m), such as oil, cannot form the necessary double layer and therefore cannot be pumped in this way [1]. However, this problem is circumvented in our design by introducing a secondary conducting liquid.

2 DESCRIPTION

The aim is to have a thin layer of conducting liquid surrounding and dragging the nonconductive liquid. A schematic view of the novel viscous pump is shown in

Fig. 1. To realize this we have developed three new features that are essential for the design: pressure valves, reduced flow, and optimized potential drop.

2.1 Pressure Valves

Two pressure valves, the two sets of four narrow channels shown in Fig. 1, prevent the working liquid from entering the electrode reservoirs. The electrode reservoirs are open and thus bubble formation from electrolysis is not a problem. Furthermore the pressure valves allow for placing the pump anywhere in a fluidic network, which is usually not possible. The pressure valves have a width a , and the design utilizes the fact that the electroosmotic flow rate $Q_{eo} \propto a^2$, whereas the hydraulic flow rate $Q_{hyd} \propto a^4$. Hence the pressure driven flow will be effectively reduced for small values of a . Reactive ion etching systems can deliver narrow and deep channels with aspect ratio as high as 40. So if a valve channel is $1 \mu\text{m}$ wide it can be $40 \mu\text{m}$ deep.

2.2 Reduced Flow

The flow from the side channels must be reduced compared to that of the main channel in order to enable pumping between Inlet A and Outlet B in Fig. 2. The reduced flow may be obtained in two different ways.

(1) A lower EOF mobility can be present in the pressure valves in comparison to the main channel to optimize the amount of the working liquid going through the pump, see Fig. 1.

(2) A flow reduction can also be achieved by making the channel dimensions so small that the Debye layers overlap. Typically the Debye layers are 1-100 nm wide.

2.3 Electric Potential Drop

One narrow valve channel has a large flow resistance but also a large electrical resistance. This means that the main potential drop would occur in the valve channels and thus not contribute to any pressure build up. The electrical resistance is inversely proportional to the area of the cross section. So by making many short, and narrow channels a low electrical resistance and high hydraulic resistance is obtained.

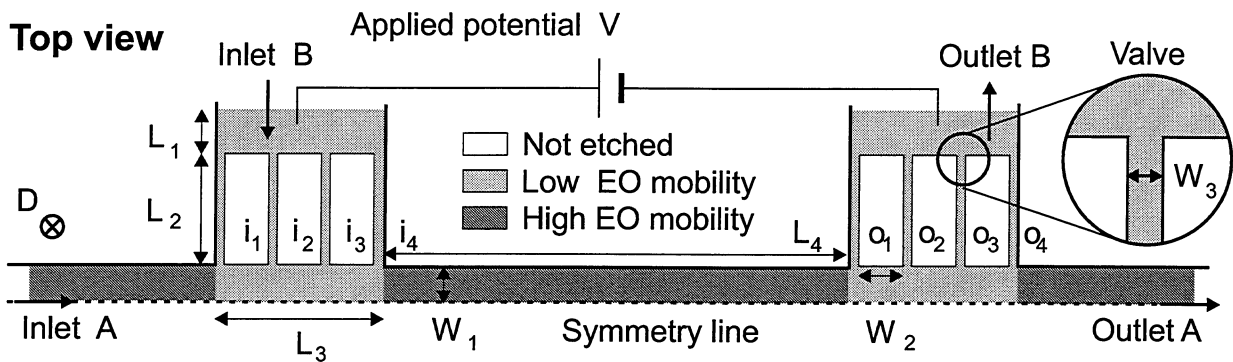


Figure 1: Layout of one half of a two-liquid viscous EOF pump. The pump is mirror-symmetric around the central vertical plane, and only one half is shown. The working liquid A is driven by the pumping liquid, B. The pumping liquid enters at inlet B, goes through the narrow valves, moves along the wall, and exits through the valve and finally through outlet B. The two electrode compartments each have four narrow channels of width W_3 . The channels/valves ensure that the working liquid does not enter inlet or outlet B. Two regions with different EO mobilities are identified. The ratio between the mobilities roughly governs the layer thickness of the pumping liquid. The high EO mobility area between the valves is the EO section. The valve regions should be given a coating with low EO mobility.

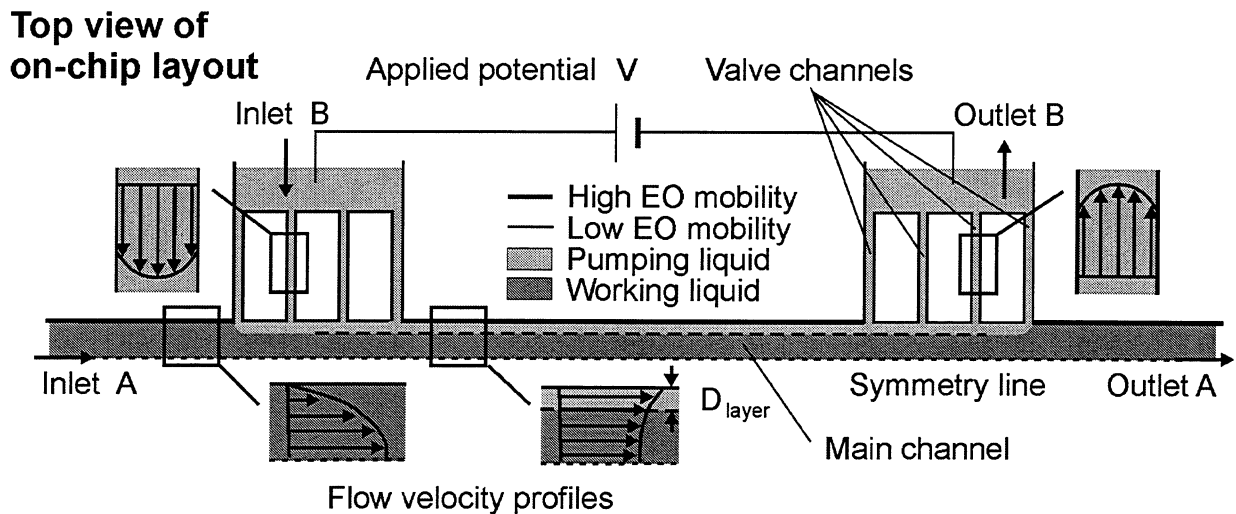


Figure 2: The working liquid is shown in dark gray. It is being dragged by the EOF driven pumping liquid (shown in light gray) that flows along the edge of the main channel. The pump is mirror-symmetric around the central vertical plane, and only one half is shown. The following specific parameters are chosen to predict the performance of the pump. The displayed micro-channels are all etched $40 \mu\text{m}$ down into the substrate (either siliconoxide or plastic), and after etching the entire structure is closed with a lid. The main channel where the working liquid flows is $150 \mu\text{m}$ long and $10 \mu\text{m}$ wide. The narrow valve channels are $1 \mu\text{m}$ wide and $42 \mu\text{m}$ long. The uncoated walls are marked as the thick edges of the main channel. Coated walls are marked with thin edges (see also Fig. 1).

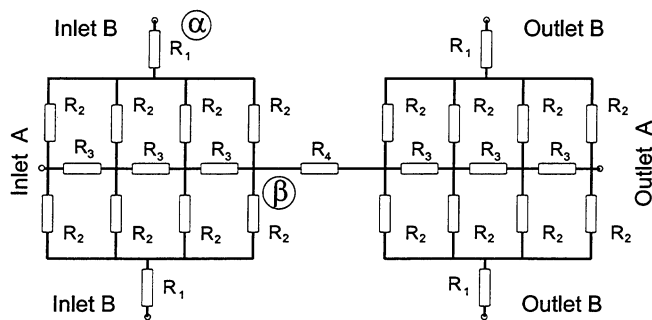


Figure 3: The equivalent electric circuit of the two-liquid viscous EOF pump. Note that the whole pump/circuit is depicted. The overall resistance is calculated as $R_{\text{total}} = 2R_{\alpha\beta} + R_4$, where $R_{\alpha\beta}$ is the electrical resistance between node point α and β . R_4 is the resistance of the EO section.

2.4 Flow Profiles

The resulting flow will be a superposition of an EOF and a pressure driven flow. Since the Debye layer is roughly 10^4 times smaller than the total width of the channel, we do not resolve it in the following modeling of the pump. The EO velocity appears simply as a non-zero velocity u_{eo} at the walls. In the absence of any backpressure the velocity would simply be constant u_{eo} across the channel. However the presence of pressure gradients induces the characteristic parabolic velocity profiles in the laminar regime, $Re \sim 0.01$. For such low Reynolds numbers the flow is said to be creeping, i.e., inertia can be neglected. Some velocity profiles are shown in Fig. 2. A characteristic feature for creeping flow is that it is free of vorticity. This means that the valve channels may be positioned perpendicular to the main channel without generating any eddies. For a more detailed discussion see Ref. [2].

3 RESULTS

We have analyzed the performance of the pump using two methods. The pressure and flow rates have been calculated by equivalent circuit theory, and in addition, a set of computational fluid dynamics (CFD) simulations was carried yielding more detailed information about the distribution of pressures and velocities. The two methods, which yield the same results within a few percent, were applied to the cases of both immiscible and miscible liquids.

3.1 Equivalent Circuit Model

The aim is to establish a model that can predict the Q - p characteristic. In this respect, the pumping layer thickness, D_{layer} , is important. The EOF depends on the electric field, which depends on the flow in the case of different conductivities. A rigorous model of the two-

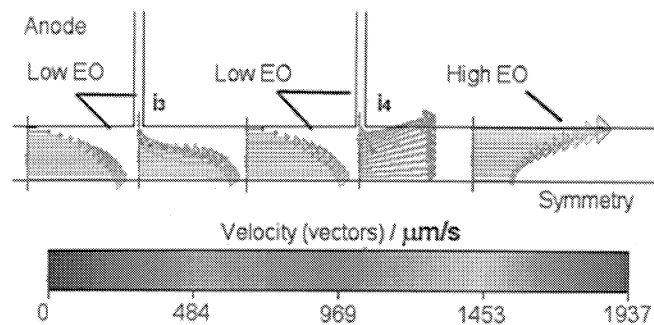


Figure 4: The velocity field in the pump near inlet B calculated by use of CFD. The velocity vectors are positioned in the symmetry plane. The transition from pressure driven flow to EOF is clear: in the regions with low EO mobility, the flow profile is a positive parabolic, but after the last junction, inlet i_4 , the EOF drags the liquid, which results in a negative parabolic profile.

liquid pump is therefore a complex matter. In this context only an outline will be presented.

The first step is to find the effective potential drop across the EO section. The procedure is to analyze the equivalent electric circuit shown in Fig. 3. The result is that 52% of the applied voltage is dropped over the EO section, R_4 in Fig. 3.

The next step is to find the hydraulic resistance R_{hyd} of each of the channel segments. The channel cross sections are all rectangular with width W and height H . The channel length is denoted L .

$$R_{\text{hyd}} = 12\mu L \left\{ H^3 W - \frac{192}{\pi^5} H^4 \times \sum_{m=0}^{\infty} (2m+1)^{-5} \tanh \left[\frac{(2m+1)\pi W}{2H} \right] \right\}^{-1}, \quad (1)$$

where μ is the dynamic viscosity. R_{hyd} is calculated using Eq. (1), remembering that there are four channels in the valves. For the present geometry, the overall hydraulic resistance of the valves is 26 times larger than that of the EO section, implying that the unintended cross flow is small.

The electroosmotic pressure buildup Δp_{eo} is given by

$$\Delta p_{eo} = \alpha_{eo} V_{\text{eff}} R_{\text{hyd}}^{\text{eo}} \frac{HW}{L}, \quad (2)$$

where α_{eo} is the electroosmotic mobility, V_{eff} the effective potential drop, and $R_{\text{hyd}}^{\text{eo}}$ the hydraulic resistance of the EO section. In Eq. (2) the Debye layer is assumed infinity thin.

3.2 Computational Fluid Dynamics

To obtain more detailed information a more advanced tool such as CFD is advantageous. The presented simulations are made with Coventor 2001.3. The program

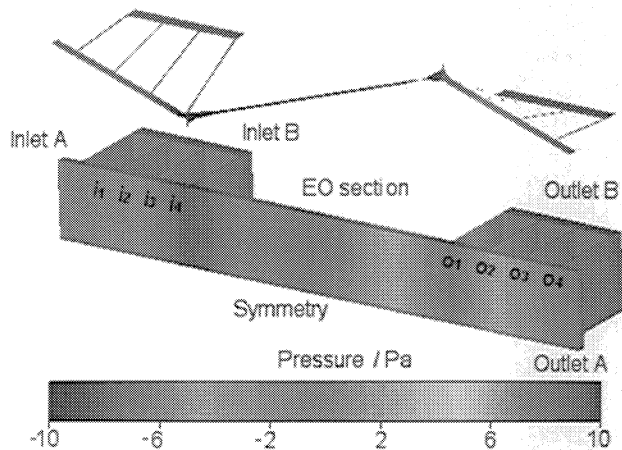


Figure 5: Visualization of the pressure distribution. The floating figure above the pump also displays the pressure. The float shows that the pressure varies linearly from junction to junction, implying uniform flow. There are no external pressure difference. So the pressure gradients originate from internal friction in the pump. Parameters: dimension as in Fig. 2, $\alpha_{eo}^{low} = 5000 \mu\text{m}^2 (\text{V s})^{-1}$, $\alpha_{eo}^{high} = 50000 \mu\text{m}^2 (\text{V s})^{-1}$, $p_{in} = p_{out} = 0$, $V = 10 \text{ V}$.

solves the Laplace equation for the potential and the Navier-Stokes equation for the velocity field.

In Fig. 4 the simulated velocity vectors are shown near the inlets to the main channel i_3 and i_4 , see Fig. 1.

If the pumping liquid is chosen to be water the EOF mobility along uncoated walls is typically $0.05 \text{ mm}^2/(\text{V s})$. In the valve channels the walls are coated to lower the EOF mobility by a factor 10. With these parameters numerical simulations yield a maximal flow rate per volt of $0.03 \text{ nL}/(\text{s V})$ and a backpressure capacity per volt of $3 \text{ Pa}/\text{V}$. The value for the flow rate is specific for the given geometry whereas the backpressure is independent of the length of the pump, refer Eq. (2). Visualizations of the pressure distribution and the streamlines are shown in Figs. 5 and 6 respectively.

4 CONCLUSION

The Q - p characteristic of the two-liquid viscous EOF pump largely depends on the geometrical factors and can be significantly enhanced by advanced etching techniques. The pump still works for miscible liquids, but here the working liquid gets mixed with the pumping liquid.

With these parameters numerical simulations yield a maximal flow rate per volt of $0.03 \text{ nL}/(\text{s V})$ and a backpressure capacity per volt of $3 \text{ Pa}/\text{V}$. These values are quite small and the pump is therefore suited for precise flow manipulation rather than pumping bulk volumes.

Future work involves time dependent two-phase simulations. Such work could perhaps give valuable in-

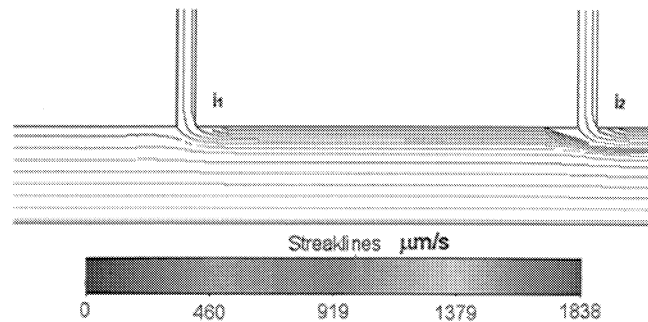


Figure 6: Streamlines at the anode junctions. Even though the channels are orthogonal, the lamination is clear. The Reynolds number is very small $Re \sim 0.01$, thus indicating creeping flow. In the case of immiscible two-liquid flow, the expected pumping layer thickness would be about 20% of the half-width. Please note that the figure is composed of three figures, so the density of the streamlines is not meaningful. The parameters are as in Fig. 5.

formation about stability and position of the pumping layer, and how to make the initial filling of the pump. Finally a prototype should be manufactured. Because of the possibility to pump all types of liquids in a precise and controlled manner, the described concept seems very promising.

5 ACKNOWLEDGEMENTS

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