Electro-osmotic Flow through a 1D-screen or a 2D-array Pump Filter

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Abstract. The efficiency of electro-osmotic pumping (EOP) can be improved greatly by using porous channels. Two types of screen-array pump filters are proposed and analyzed for their performance in driving electro-osmotic flow in micro-ducts. A 1D-screen pump filter (SPF) is made of a line array of evenly spaced identical rectangular solid blocks, and a 2D-array pump filter (APF) is made of a 2D periodic array of parallel slats. It is shown, based upon the Debye-Hückel approximation for the charge distribution and the Stokes equations applied for the flow analysis, that under certain geometric and physical conditions, the efficiency of the 1D SPF approaches that of a continuous channel of equal cross section, while the 2D APF may improve the EO flow rate by a factor of 10 or more for the cases of overlapped electric double layers. The performance for the 2D APF is further checked for its validity by examining analytically the conditions underlying the equations such as the end effects and its relation to the equilibrium Poisson-Boltzmann charge distribution.

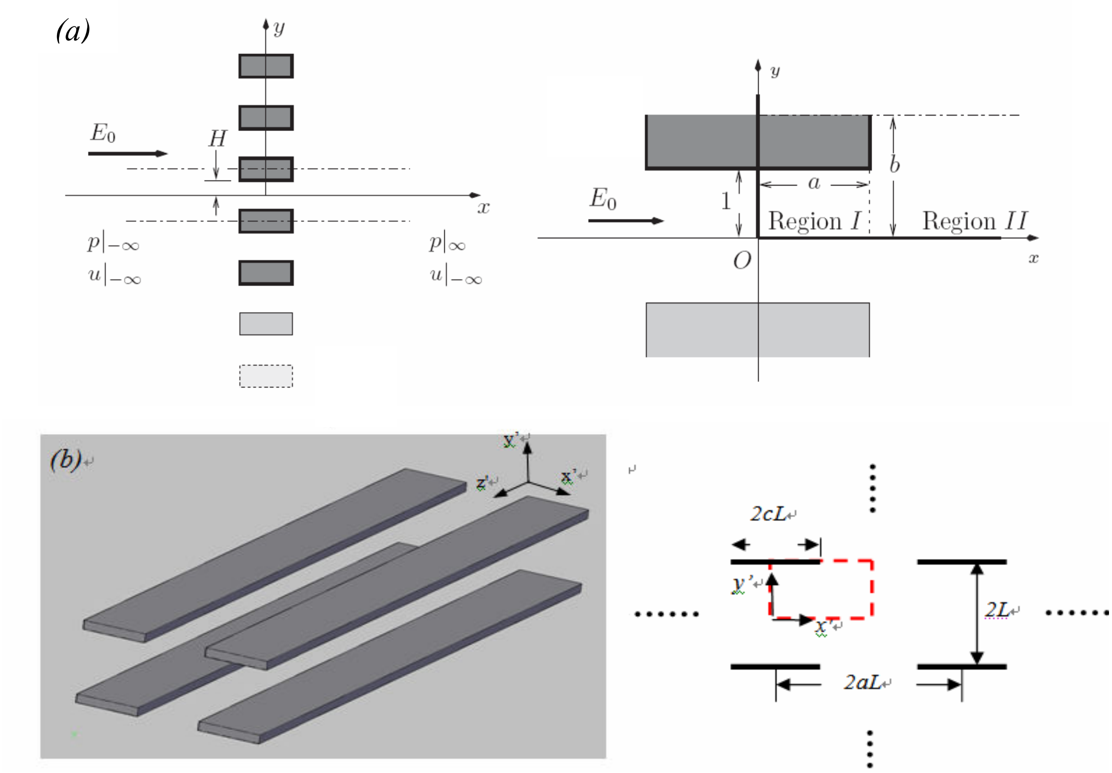

Figure 1 (a) The cross section of the 1D screen pump filter (1D SPF) where the electric-osmotic flow passes through; (b) Schematic of the 2D array pump filter (2D APF). The slats extend periodically in both *x'* and *y'* directions, z' denotes the longitudinal direction.

Introduction. The EO pumping mechanism is the result of the interaction between the applied external electric field and the electric charge potential in the fluid. Once applied with electric field, the electrokinetic body force is formed and drives the fluid. In common applications the applied electric field is a unidirectional static field, and, subsequently, the EO force results in a shear layer flow. In the shear layer, the flow speed increases exponentially and asymptotes to the free-flow field outside the electric double layer (EDL) next to the walls. This sharp velocity profile may enhance the mixing or dispersion of sediments in the shear layer. This property leads to the flow in a straight fluidic channel forming a plug-like velocity profile rather than a parabolic (Poseuille) shape as in pressure-driven flows. In contrast, this may reduce some desired flow motion in the free flow, such as mixing. Therefore, more sophisticated proposals have been emerging for special circumstances, such as the AC electro-osmotic pump for high flow rates or for controlling the flow direction. Nowadays, multicomponents are often integrated on LOC devices to perform multistage laboratory functions. These components include mixers, screen filters, flow splitters, etc. The interaction of these components with the external electric field is one of the major concerns in EO devices. If we enter into the regime of nano-scale widths, the values of the electrokinetic width K may be around 1 or less, the EDLs from both sides are overlapped, the EO flow rate Q is extremely small as

$Q=Q_0K^2+O(K^4)$. In the present paper, we propose a 1D SPF (Liu et al. 2011), which is composed of a line array of evenly spaced identical rectangular blocks (Fig. 1a). Because of their surface zeta potential, when applied with an external electric field, the device component itself generates electrokinetic pumping forces. In laboratories, a similar screen filter is applied to capture suspended particles, such as cells and vescules in LOC devices. Moreover, we propose to consider a 2D APF (Kung et al. 2011), as shown in Fig. 1b, i.e. an array of parallel slats either as a model for porous medium (such as paper fibers) or as a means for EO pumping. The fluid near the slats dissociates and creates an EDL. If an external electric potential is applied in either x or z direction, due to EO, the fluid would move in that direction. The main interest is to investigate how the EO pumping rate at a given K is influenced by the geometric parameter a, and the ratio c/a, especially when the pumping may be enhanced significantly, and study the range of validity.

Results and Discussion.

First, we consider the 1D SPF for electro-osmotic flow without an external driving pressure. Under the Debye-Hückel approximation, the analytic solutions for the applied potential, EDL field, flow stream function, and pumping rate were obtained in the form of series expansions. By letting $a\rightarrow\infty$, the analytic solutions converge to the exact solution of the electro-osmotic flow in an infinitely long microchannel (continuous channel). The approaches to the exact solution of the continuous channel are different with different values of the Debye-Hückel parameter K. For small K, because of the thick EDL, the volume flux approaches decreasingly the exact solution of the continuous channel with increasing the channel length a. On the other hand, for large K, the volume flux approaches increasingly the exact solution of the continuous channel. It is obvious that the electro-osmotic flow rate of the screen pump is a function of the geometric parameters a, b and the Debye-Hückel parameter K. In general, when $a \geq 1$ the electrokinetic volume flow rate increases with increasing b. This trend is because the total electric-kinetic driving force increases as these parameters increase. However, there are more delicate influences by these parameters on the flow field. It happens when a is small (a < 1): The screen pump blocks the flow because the viscous drag force outperforms the electrokinetic driving force, and the total resultant force becomes reversely dependent on b. One intriguing reverse flow is also found when the ratio a/b is small and the Debyue-Hückel parameter K is large. This screen pump is composed of thin vertically aligned screen blocks. The thin EDL, large K, indicates the electrokinetic force propels the flow in the thin boundary layer against the block surface, and the diffusive viscous force induces recirculating eddies attached to the screen block. Then these recirculating eddies induce a reverse flow. It is therefore possible to design the direction of the flow in microfluids using this screen pump device.

Next, we consider the 2D APF either as a model for porous medium or as a means for electro-osmotic pumping (EOP). This is a delicate problem as four length scales are involved and the slats are finite in widths and infinitely thin. In order to solve the problem accurately, we developed series expansions with boundary collocation, performed for both longitudinal and transverse electro-osmotic pumping (LEOP and TEOP) by solving the Debye–Hückel approximation and viscous electro-kinetic equation. In summary, we have the following conclusions: (i) Porosity introduced in a small channel made of a periodic array of slats enables us to take the reference potential $\varphi_c \approx 0$ in the middle of the porous channel for small K (with overlapped EDLs), but not too small, in particular when the period is long and the porosity is large (a>>1 and c/a<<1). (ii) Another advantage of using porosity is to reduce the viscous effect that drags the fluid flow because of the no-slip condition imposed on the solid wall. However, as EO flow is driven by the EDLs, it is impractical to use a very large porosity (very small c/a) because the transient time is scaled as $(a/c)^2$. (iii) The increase in the EO flow rate of a porous channel relative to the continuous channel is a very significant factor for small K (<1.5). In this regards, LEOP improves the EO pumping rate much better than TEOP because the latter type of EO flows may introduce entrance and exit effects in the channel when the fluid is passing transversely to each slat. (iv) As expected, at a large K the EO flow is plug-like, and there should be little difference in the flow rates no matter whether we use a porous or a continuous channel. But still LEOP and TEOP perform differently at moderate or large K (>3). In this range, the porous channel has a larger flow rate than the continuous channel in LEOP, while the porous channel has a lower flow rate than the continuous channel in TEOP. Take K=5 for example, porosity may increase the flow rate by 25% for LEOP, but may reduce the flow rate by 20% for TEOP. These findings for the 2D APF have physical implications that microtubes with different fibrous (porous) structures may find their optimal applications in their respective ranges of usefulness in EO pumping, in particular for nano-fluidics (small K).

References

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