Supplementary Material (ESI) for Lab on a Chip

An impulsive, electropulsation-driven backflow in microchannels during electroporation

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Formulation of Eq. 1 for the resultant EOF

The pressure driven flow of an incompressible fluid through a straight channel is the Poiseuille flow. We found that a sudden pressure difference Δp by gases formed at the electrodes resulted in an impulsive flow rate Q_G. This result can be summarized in the Hagen-Poiseuille law

$$Q_G = \frac{1}{R_{hyd}} \Delta p, \tag{S1}$$

where the proportionality factor R_{hyd} is a hydraulic resistance. The Hagen-Poiseuille law of Eq. S1 is completely analogous to Ohm's law ($I=\Delta V/R$). For the straight channel with a rectangular cross-section, the R_{hyd} can be described as follows

$$R_{hyd} = \frac{12\eta L}{1-0.63\alpha} \frac{1}{h^3 w}, \tag{S2}$$

where η is the viscosity of liquid, α is the aspect ratio of the microchannel(=h/w), h is the height, w is the width, and L is the length of the microchannel, respectively.

Typically, the flow rate by the electric double layer (EDL) for a cross sectional area, A $(=wh)$ can be represented as

$$Q_{EDL} = Av_{EDL}, \text{ for } \lambda_D \ll \tfrac{1}{2}h \tag{S3a}$$

$$v_{EDL} \equiv \frac{\varepsilon\zeta E}{\eta}, \tag{S3b}$$

where v_{EDL} is the velocity of the liquid driven by the EDL, λ_D is the thickness of Debye layer, ε is a dielectric constant of the liquid, ζ is zeta potential of the microchannel and E is the electric field strength across the microchannel $(=\Delta V/L)$. The flow rate of the resultant EOF with impulsive back pressure can be simply derived into the following form,

$$\begin{aligned} Q_{EOF} &= Q_{EDL} - Q_G \\ &= Av_{EDL} - \frac{1}{R_{hyd}}\Delta p \\ &= \frac{A\varepsilon\zeta}{\eta L}\Delta V - \frac{1-0.63\alpha}{12\eta L}wh^3\Delta p \\ &= C_1\Delta V - C_2\Delta p \end{aligned} \qquad \text{for } \lambda_D \ll \tfrac{1}{2}h \tag{S4}$$

where C_1 and C_2 are coefficients for the EDL and gas evolution which result in the EOF. Note that the vapor pressure is in general increasing exponentially with the temperature. In addition, there is a close correlation between the temperature rise and electric current by Joule's law. At the moment of electropulsation, the impulsive back pressure cancels the flow by Q_{EDL} and instantly changes the direction of EOF in microchannels.