The two-dimensional model of particle trajectories

In order to estimate the effective barrier size (d_e) of the virtual pillar, we derive a two-dimensional model (Fig. 3) of particle trajectories in the virtual pillars. We assume that particle flow induced by hydraulic force is uniform flow and particle flow induced by dielectrophoretic (DEP) force is irrotational radial flow originated from an edge of one spot electrode. Thus, the particle trajectories can be simply modeled by superposition of uniform flow and irrotational flow and we can get particle trajectories[16] from the stream function by simple analytic calculation.

We can get a stream function (ψ) for net particle trajectories with polar components (r and θ) as follows:

$$\psi = \psi_{Hydraulic} + \psi_{DEP} \tag{S1a}$$

$$\psi_{Hydraulic} = v_{Hydraulic} r \sin\theta \tag{S1b}$$

$$\psi_{DEP} = v_{DEP} r\theta \tag{S1c}$$

where, $\psi_{Hydraulic}$ and $v_{Hydraulic}$ denote the stream function and the velocity of the uniform hydraulic flow; ψ_{DEP} and v_{DEP} denote a stream function and velocity of the irrotational DEP flow.

Because Stokes approximation for the drag force is valid in our experiments (low Reynolds number, about 0.01), we get time-averaged DEP velocity of the particle (eqn (S2)).

$$\mathbf{v_{DEP}} = \frac{\varepsilon_m D^2 \operatorname{Re}[K(\omega)]\nabla|\mathbf{E}|^2}{12\eta} \tag{S2a}$$

$$K(\omega) = \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*} \tag{S2b}$$

$$\varepsilon^* = \sigma + i\omega\varepsilon_0\varepsilon \tag{S2c}$$

where ε_m is the permittivity of the medium; D is the particle diameter; ω is the angular frequency; $K(\omega)$ is the Clausius-Mosotti factor; $\mathbf{E}$ is the root mean square (rms) value of the electric field vector; η is the dynamic viscosity of the medium; ε^*, σ, ε_0, and ε are the complex permittivity, the conductivity, the permittivity of vacuum, and the relative permittivity; ε_p^* and ε_m^* are the complex permittivity of the particle and the medium, respectively.

The electric field (**E**) is proportional to gradient values of applied voltage ($\nabla \mathrm{V_{DEP}}$). We can simplify the electric field (**E**) is inversely proportional to distances from the center of the electrode (r) (eqn (S3)).

$$\mathbf{E} \propto \frac{\mathrm{V_{DEP}}}{r}\mathbf{e_r} \tag{S3}$$

where V_{DEP} is the rms value of the applied voltage; $\mathbf{e_r}$ is the radial direction vector. Due to DEP force and buoyancy force, heights of particles in the designed microchannel (the height: 15 μm) are also dependent to the particle diameters. The electric field (**E**) is a function of the height of the particle and the distance from the center of the electrode (*r*). However, we assume it to be proportional to particle diameters for conveniences of calculation (eqn (S4)). From these assumptions, we get the gradient term ($\nabla|\mathbf{E}|^2$) of eqn (S2a) as a function of the particle diameter (D), applied voltage, and distance from the center of the electrode (*r*) (eqn (S5)).

$$\mathbf{E} \approx (\alpha D + \beta)\frac{V_{DEP}}{r}\mathbf{e_r} \tag{S4}$$

$$\nabla|\mathbf{E}|^2 \approx -2(\alpha D + \beta)^2 \frac{{V_{DEP}}^2}{r^3}\mathbf{e_r} \tag{S5}$$

where α and β are the correction factors converting three-dimensional electric field distribution around an electrode as linear functions of particle diameter (D).

Finally, we get the stream function of our model after inserting the eqn (S5) and eqn (S2a) to the eqn (S1) as follow:

$$\psi = v_{Hydraulic}\, r\sin\theta - \frac{(\alpha D + \beta)^2 \varepsilon_m D^2 \,\mathrm{Re}[K(\omega)]{V_{DEP}}^2}{6\eta r^2}\theta \tag{S6}$$

Therefore, from the stream function of eqn (S6), we get the effective barrier size (d_e) (eqn (S7)) and the radii of particle trajectory (eqn (S8)) as follow:

$$d_e = \left(-\frac{(\alpha D + \beta)^2 \varepsilon_m \,\mathrm{Re}[K(\omega)]}{6\eta v_{Hydraulic}}\right)^{1/3} D^{2/3}{V_{DEP}}^{2/3} \tag{S7}$$

$$|\mathbf{r}_\pi| = d_e + \frac{\lambda - d}{2} \tag{S8a}$$

$$|\mathbf{r}_{\pi/2}| \cong 2.96 d_e + \frac{\lambda - d}{2} \tag{S8b}$$

$$|\mathbf{r}_{\theta^*}| \cong \frac{\pi}{\sin\theta^*} d_e + \frac{\lambda - d}{2} \tag{S8c}$$

where $|\mathbf{r}_\pi|$, $|\mathbf{r}_{\pi/2}|$, and $|\mathbf{r}_{\theta^*}|$ are the radius of the particle trajectory at $\theta = \pi$, $\theta = \pi/2$, and $\theta = \theta^*$, respectively.