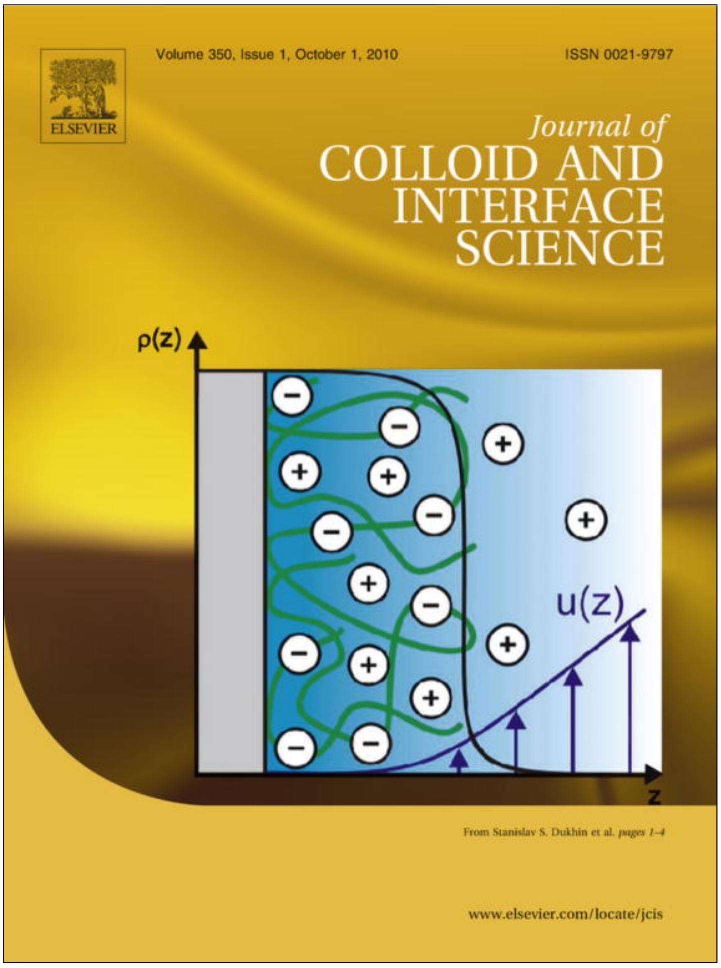
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Short Communication

Three-dimensional electrokinetic particle focusing in a rectangular microchannel

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ABSTRACT

We extend an earlier study (Liang et al., 2010 [1]) to demonstrate a three-dimensional focusing of neutrally buoyant particles in electrophoresis through a rectangular microchannel as a result of the wall-induced lateral migration.

In an earlier paper [1], we observed that particles in electrophoresis through a straight rectangular microchannel migrate toward the centerline in the horizontal plane. Such lateral migration is attributed to the wall-induced electrical force arising from the non-uniform electric field around the particles [2,3]. Here, we utilize this dielectrophoresis-resembled motion to demonstrate a three-dimensional particle focusing in a rectangular microchannel.

The microchannel we used is 2 cm long with a uniform cross-section of 50 × 50 μm. It was fabricated with polydimethylsiloxane (PDMS) using the standard soft lithography method. The fabrication procedure is given elsewhere [1]. In our experiments, polystyrene particles of 5 μm and 10 μm in diameter (Sigma–Aldrich, USA) were re-suspended in a solution with neutral buoyancy to a concentration of about 10^7 particles per mL. The solution was made by mixing 1 mM phosphate buffer and glycerol at a volume ratio of 7.8:2.2 [4]. Its mass density matches that of the particles. The particle transport was driven by a DC electric field supplied by a power supply (Glassman High Voltage Inc., High Bridge, NJ), and visualized with a CCD camera (Nikon DS-Qi1Mc) through an inverted microscope (Nikon TE2000U, Nikon Instruments, Lewisville, TX).

The finite-size particle distorts the electric field lines, resulting in electric field gradients formed around it; see the field contour over the channel cross-section in Fig. 1. The presence of the channel walls breaks the symmetry of these field gradients, which yields an electrical force, $\mathbf{F}_w$, pointing away from the nearby walls [1–3]. As a consequence, particles of neutral buoyancy are ultimately pushed toward the center of the channel cross-section, forming a three-dimensionally focused stream along the channel axis. The effectiveness of this electrokinetic focusing is determined by the ratio of the distance the particle moves laterally to the distance it travels longitudinally. Equivalently this focusing depends on the ratio of the $\mathbf{F}_w$-induced velocity to electrokinetic particle velocity and the ratio of channel length to width (or the hydraulic diameter). The dielectrophoresis-resembled force, $\mathbf{F}_w$, decays rapidly when the particle is away from the channel wall(s), but increases quadratically with both the particle size[1] and the applied electric field [2,3]. Therefore, the induced lateral particle migration is proportional to the particle size and the electric field squared. In contrast, the electrokinetic particle velocity is a linear function of the electric field [5] while insensitive to the particle size unless the particle closely fits the channel [6]. Hence, increasing the electric field and/or particle size should in principle enhance the wall-induced electrokinetic particle focusing.

Fig. 2 shows the snapshot top-view images of 10 μm particles flowing through the inlet (a), middle (b), and outlet (c) of the rectangular microchannel. The applied DC voltage drop across the 2 cm long channel was 400 V, producing a 20 kV/m electric field. The focal plane of the microscope objective was positioned approximately to the middle of the channel depth. At the channel inlet, both off-centered (in the horizontal or channel width direction, highlighted with squares for clarity) and defocused (in the vertical or channel depth direction, highlighted with circles for clarity) particles are seen in Fig. 2a. This is attributed to the uniform spreading

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[1] Note that the traditionally-defined dielectrophoretic force is proportional to the particle volume.

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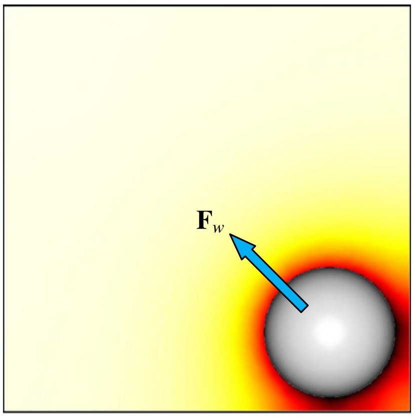

Fig. 1. The non-uniform electric field around a particle (indicated by the background contour that was obtained from COMSOL®, the darker the larger) generates an electrical force, $\mathbf{F}_w$, pushing the particle away from the walls to the center of the channel cross-section.

of neutrally buoyant particles in the upstream reservoir. When particles have travelled through half of the channel length, however, defocused particles are rarely observed in Fig. 2b and most of them are moving in a narrow region about the channel centerline. Further, in Fig. 2c neither off-centered nor defocused particles are seen, indicating that a nice three-dimensional particle focusing has been formed at the channel outlet. This trend indicates that the autonomous focusing of particles in electrophoresis through a rectangular microchannel increases with the channel length.

Fig. 3 compares the snapshot images of 5 μm particles at the outlet of the rectangular microchannel under different electric fields. The particle image at the channel inlet is also included in Fig. 3a for a clear comparison, where, once again, both off-centered (highlighted with squares for clarity) and defocused (highlighted with circles for clarity) particles are present. As expected, the electrokinetic particle focusing is enhanced with the rise of the electric field. Specifically, at the 10 kV/m electric field, many particles are

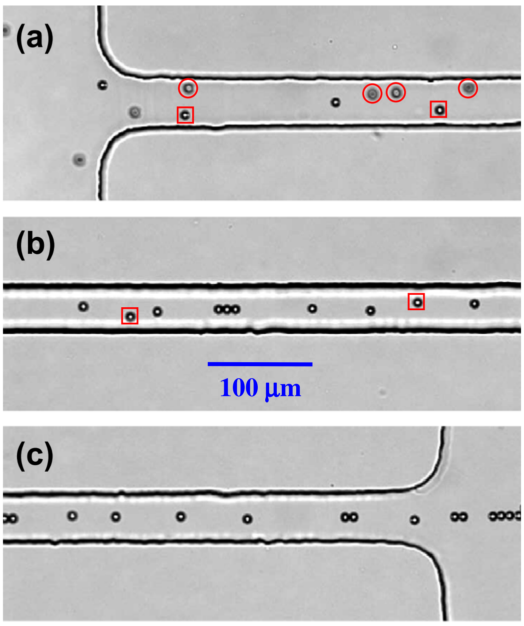

Fig. 2. Snapshot top-view images of 10 μm particles moving through the inlet (a), middle (b), and outlet (c) of a rectangular microchannel at the electric field of 20 kV/m. For clarity the off-centered and defocused particles in (a) and (b) are highlighted with boxes and circles, respectively. The flow direction is from left to right.

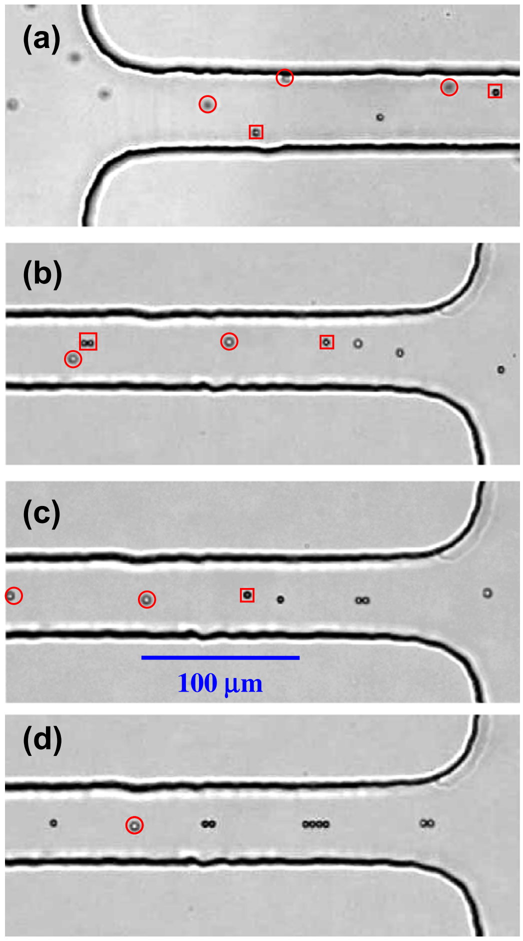

Fig. 3. Snapshot top-view images showing the electric field effect on the three-dimensional focusing of 5 μm particles at the outlet of a rectangular microchannel: (b) 10 kV/m, (c) 30 kV/m, and (d) 50 kV/m. The particle image at the channel inlet is shown in (a). For clarity the off-centered and defocused particles are highlighted with squares and circles, respectively. The flow direction is from left to right.

still off-centered and defocused at the channel outlet while at a lesser extent than at the channel inlet. This is identified from the clear edges of most particles in Fig. 3b. When the electric field is increased to 30 kV/m, an apparently better focusing is obtained in the channel width (or horizontal) direction because much less

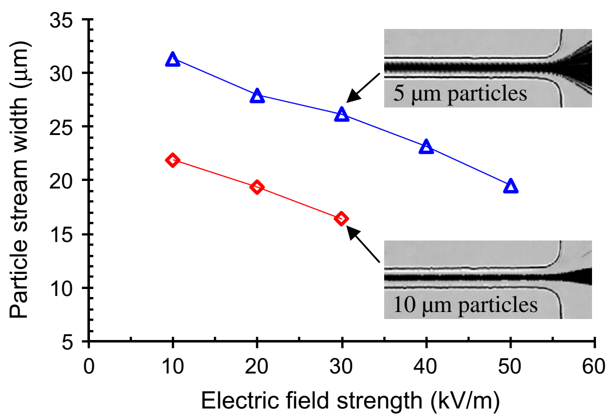

Fig. 4. Electric field and particle size effects on the width of the focused particle stream in the horizontal plane at the outlet of a rectangular microchannel. The lines are used solely to guide the eyes. The two insets display the superimposed images at the 30 kV/m electric field.

off-centered particles are observed in Fig. 3c. However, the improvement in the vertical particle focusing is not as evident as in the horizontal focusing, which may be partially due to the limited depth of focus of our optical microscope. As the electric field further increases to 50 kV/m, a tightly focused particle stream is observed along the channel centerline in Fig. 3d where few defocused particles are seen.

Fig. 4 compares the widths of the focused 5 μm and 10 μm particle streams in the horizontal plane at the channel outlet at different electric fields. The data points (symbols, averaged over three measurements for each size of particles) were obtained by measuring the widths of the particle trajectories in the superimposed images (see the inset sample images in Fig. 4). Apparently, 10 μm particles gain a better focusing than 5 μm particles, where the measured stream width of the former is on-average 30% smaller for the range of 10–30 kV/m electric field. This is because 10 μm particles experience a larger wall-induced lateral velocity than 5 μm particles while their electrokinetic velocities are nearly identical. The measured electrokinetic mobility (i.e., electrokinetic velocity per unit field) is about $1.1 \times 10^{-8}\ m^2/(V\,s)$. In addition, similar to what one has seen in Fig. 3, increasing the electric field leads to a reduction of the stream width for both sizes of particles.

In summary, we have demonstrated a three-dimensional electrokinetic focusing of particles in a straight rectangular microchannel. Due to the wall-induced electrical repulsion force, neutrally buoyant particles in electrophoresis were observed to migrate toward and travel along the channel axis. Non-neutral particles are, however, anticipated to flow in a focused stream near the top or bottom wall, onto which sensing electrodes may be fabricated for improved electrical detections [7]. Such autonomous particle focusing in a rectangular microchannel may potentially be used in microflow cytometers.

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References

[1] L. Liang, Y. Ai, J. Zhu, S. Qian, X. Xuan, J. Colloid Interface Sci. 347 (2010) 142–146.
[2] E. Yariv, Phys. Fluid 18 (2006) 031702.
[3] E. Young, D. Li, Langmuir 21 (2005) 12037–12046.
[4] N. Cheng, Ind. Eng. Chem. Res. 47 (2008) 3285–3288.
[5] J.L. Anderson, Annu. Rev. Fluid Mech. 21 (1989) 61–99.
[6] E. Yariv, H. Brenner, Phys. Fluid 14 (2002) 3354–3357.
[7] Y. Yang, H. Zhang, J. Zhu, G. Wang, T. Tzeng, X. Xuan, K. Huang, P. Wang, Lab Chip 10 (2010) 553–555.