1-1-2013

Continuous particle manipulation and separation in a hurdle-combined curved microchannel using DC dielectrophoresis

Ming Li
University Of Wollongong, ml433@uowmail.edu.au

Shunbo Li
Hong Kong University of Science and Technology

Weihua Li
University of Wollongong, weihuali@uow.edu.au

Weijia Wen
Hong Kong University of Science and Technology

Gursel Alici
University of Wollongong, gursel@uow.edu.au

Continuous particle manipulation and separation in a hurdle-combined curved microchannel using DC dielectrophoresis

Abstract

This paper presents a novel dielectrophoresis (DEP)-based microfluidic device which combines round hurdle with an S-shaped curved microchannel for continuous manipulation and separation of microparticles. Local nonuniform electric fields are generated by means of both constricted gaps and curved sections having equal width. Under the effect of negative DEP, particles transporting throughout the microchannel electrokinetically will be directed away from either inner wall or hurdle edge. Both experiment and numerical simulation were conducted, the results of which showed that the trajectories of fix-sized (i.e. 10 or 15 μm) polystyrene (PS) particles could be controlled by adjusting applied voltage, and continuous size-based separation of 10 and 15 μm particles was achieved. Compared to other microchannel designs that make use of either obstacle or curvature individually for electric field gradient, the developed microchannel offers advantages such as improved controllability over particle motion, lower requirement of applied voltage, reduced fouling and particle adhesion, etc. © 2013 AIP Publishing LLC.

Keywords

dc, curved, combined, dielectrophoresis, hurdle, microchannel, separation, manipulation, particle, continuous

Disciplines

Engineering | Science and Technology Studies

Publication Details

Li, M., Li, S., Li, W., Wen, W. & Alici, G. (2013). Continuous particle manipulation and separation in a hurdle-combined curved microchannel using DC dielectrophoresis. In A. Yu, K. Dong, R. Yang & S. Luding (Eds.), Proceedings of the 7th International Conference on Micromechanics of Granular Media (pp. 1150-1153). Australia: AIP Publishing.

Continuous Particle Manipulation and Separation in a Hurdle-combined Curved Microchannel Using DC Dielectrophoresis

Ming Li[1], Shunbo Li[2], Weihua Li[1], Weijia Wen[2] and Gursel Alici[1]

[1] *School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, Wollongong, NSW, 2522, Australia*
[2] *Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong*

Abstract. This paper presents a novel dielectrophoresis (DEP)-based microfluidic device which combines round hurdle with an S-shaped curved microchannel for continuous manipulation and separation of microparticles. Local nonuniform electric fields are generated by means of both constricted gaps and curved sections having equal width. Under the effect of negative DEP, particles transporting throughout the microchannel electrokinetically will be directed away from either inner wall or hurdle edge. Both experiment and numerical simulation were conducted, the results of which showed that the trajectories of fix-sized (i.e. 10 or 15 μm) polystyrene (PS) particles could be controlled by adjusting applied voltage, and continuous size-based separation of 10 and 15 μm particles was achieved. Compared to other microchannel designs that make use of either obstacle or curvature individually for electric field gradient, the developed microchannel offers advantages such as improved controllability over particle motion, lower requirement of applied voltage, reduced fouling and particle adhesion, etc.

Keywords: hurdle-combined curved microchannel, particle manipulation, particle separation, DC dielectrophoresis
PACS: 47.57.jd, 47.85.Np, 85.85.+j, 87.50.ch

INTRODUCTION

Dielectrophoresis (DEP), first adopted by Pohl [1], is a phenomenon that occurs due to a translational force exerted on a dielectric particle in a nonuniform electric field. With the rapid development of lab-on-a-chip (LOC) devices, DEP has been widely used to manipulate various micro/nano scale bioparticles (i.e. DNA, protein, bacteria, virus, mammalian and yeast cells) in microfluidic systems [2, 3], due to its great advantages including label-free nature, favourable scaling effects, simplicity of the instrumentation, ability to manipulate neutral bioparticles, and analysis of high selectivity and sensitivity [4-6].

Traditionally, the spatial nonuniformities required for DEP are generated by applying alternative current (AC) electric fields to the microelectrodes patterned within microchannels [6], however, such electrode-based systems suffer from fabrication complexities, electrode fouling [5], and electrochemical reactions on the electrode surface [7]. These problems are avoided in insulator-based DEP microdevices, where direct current (DC) electric fields are applied via external electrodes submerged in reservoirs, and electric field gradients are induced around insulating objects. In such devices, two main approaches have been used to generate required electric field gradient [8]: obstacles and microchannel curvature. However, microdevices with electrically insulated obstacles (i.e. posts, rectangular/triangular hurdles, ridge, oil droplet and oil menisci) embedded in straight microchannels, have such limitations as locally amplified electric fields, large trans-membrane voltages and shear stresses on cells, Joule heating, and fouling due to particle clogging or adhesion [9]. Although high-intensify local electric fields can be avoided in insulating curved (i.e. sawtooth, serpentine, circular, spiral and waved) microchannels, this curvature-based method requires sufficiently large applied DC voltage and/or long curved section for effective performance of the device, and the microchannel is more sensitive to contamination (i.e. particle adhesion on channel wall).

In this work, we developed a novel design coupling the effects of obstacle and curvature to generate electric field gradient required for the DEP effect, where multiple round hurdles are embedded within an S-shaped microchannel. The aforementioned adverse effects of using each approach individually, therefore, have been significantly reduced. The manipulation functioning of the design was demonstrated by directing 10 or 15 μm polystyrene (PS) particles to distinct outlets via adjusting applied voltages. In addition, the separation functioning was verified by the effective and successful separation of 10 and 15 μm PS particles according to their difference in size. Both experimental and numerical results were presented, which showed a reasonable agreement.

THEORY AND MECHANISM

Particles suspended in an electrically conducting liquid under the influence of external electric field are subjected to electrophoretic, electroosmotic and dielectrophoretic effect. The combination of fluid electroosmosis (EO) and particle electrophoresis (EP) is termed electrophoretic (EK) flow, resulting in the electrokinetic velocity of particles written as [10]

$$\mathbf{u}_{EK} = \mu_{EK}\mathbf{E} = \mathbf{u}_{EO} + \mathbf{u}_{EP} = (\mu_{EO} - \mu_{EP})\mathbf{E} \quad (1)$$

where μ_{EK}, $\mu_{EO} = -\varepsilon_m \zeta_w / \eta$, and $\mu_{EP} = -\varepsilon_m \zeta_p / \eta$ are electrokinetic, electroosmotic and electrophoretic mobility, respectively. ε_m and η are the permittivity and dynamic viscosity of the suspending medium, respectively. ζ_w and ζ_p represent, respectively, the zeta potentials of the channel wall and particle.

The time-average DEP force acting on a dielectric spherical particle in a nonuniform DC electric field, and the induced dielectrophoretic velocity are given by [11]

$$\mathbf{F}_{DEP} = (1/2)\pi\varepsilon_m d^3 f_{CM}(\mathbf{E}\cdot\nabla\mathbf{E}) \quad (2)$$

$$\mathbf{u}_{DEP} = \mu_{DEP}(\mathbf{E}\cdot\nabla\mathbf{E}) = (\varepsilon_m d^2 f_{CM}/6\eta)\cdot(\mathbf{E}\cdot\nabla\mathbf{E}) \quad (3)$$

where d is the particle diameter, $f_{CM} = (\sigma_p - \sigma_m)/(\sigma_p + 2\sigma_m)$ is known as the Clausius-Mossotti (CM) factor, σ_p and σ_m are, respectively, the electric conductivities of the particle and the suspending medium, μ_{DEP} represents dielectrphoretic mobility. If the particle is less conductive than the suspending medium, CM factor will be negative, inducing a negative DEP force that repels particle away from the region of higher electric field.

In this study, we utilized the effect of both obstacle and curvature to generate local electric field gradient throughout the microchannel, which contributes to a novel technique for the continuous control of particle movement in microfluidic devices using DEP effect. The mechanism of the proposed design is illustrated schematically in Fig. 1, where a semi-circular microchannel combined with a round hurdle is presented along with the electric field lines (or equivalently the streamlines with black arrows indicating the direction) and contours of the electric field strength (the darker the stronger). Consider a particle subjected to negative DEP effect passing though the microchannel under the combined effect of EOF and EP, repulsive DEP forces (dark blue arrows, relatively weak in the curved section, while strong in the constricted region) are exerted on the particle all along its movement.

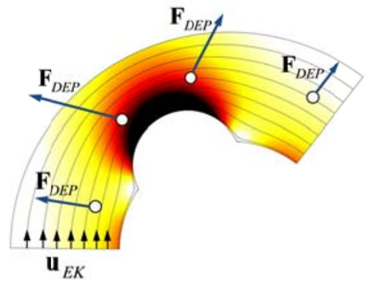

FIGURE 1. Illustration of the negative dielectrophoretic separation and manipulation of particles in a curved microchannel embedded with a round hurldle.

EXPERIMENT

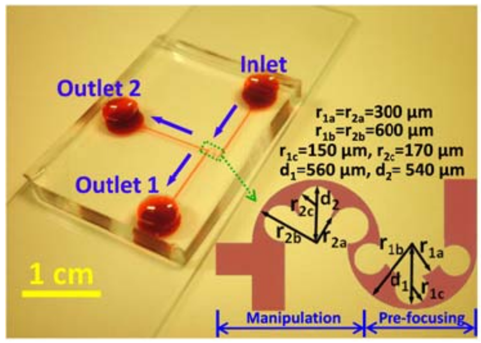

FIGURE 2. Photograph of the proposed DEP-based microfluidic chip. The inset indicates the structure and dimensions of the design.

The detailed fabrication process of the polydimethylsiloxane (PDMS)-based microfluidic device can be found in our previous work [12]. As shown in Fig. 2, the microfluidic chip is composed of two semi-circular channels integrating with three round hurdles from inner wall, which are responsible for particle pre-focusing and manipulation, respectively; one inlet and two outlet reservoirs; and three straight connecting microchannels. The dimensions of the microchannel design are indicated in the inset. All three straight connecting channels have a width of 300 μm and a length of 1 mm, and the microchannel is anywhere 40 μm deep.

In this study, we used two types of particles with varied diameters (Fluospheres, Invotrogen, CA, USA):

yellow-green fluorescent 10 μm and blue fluorescent 15 μm polystyrene (PS) microspheres. Both original particle solutions were diluted by deionized (DI) water 15 times. For separation experiment, the diluted 10 and 15 μm particle solutions were mixed at a volume ratio of 1:1. The electric field was generated by a DC power supply (SL10P300/200, Spellman High Voltage Electronics Corp., Hauppauge, NY). The motion of particle through the microchannel was monitored and recorded by an inverted microscope (Olympus IX71, Tokyo, Japan) equipped with a CCD camera (DP 70, Olympus, Tokyo, Japan). All the videos and images were post-processed by MATLAB (Mathworks Inc., Natick, MA), and the particle trajectories were obtained by superimposing consecutive images converted from videos.

NUMERICAL SIMULATION

In the simulation, we used a two-dimensional (2D) model that first developed by Kang et al [13], to predict the particle motion throughout the microchannel. By introducing a correction factor c to account for the effects of particle size, particle-particle interaction, etc. on the dielectrophoretic velocity, the velocity of particle can be written as

$$\mathbf{u}_p = \mathbf{u}_{EK} + c\mathbf{u}_{EOF} = \mu_{EK}\mathbf{E} + c\mu_{EOF}(\mathbf{E}\cdot\nabla\mathbf{E}) \quad (4)$$

The above equation was performed in COMSOL 4.0 (COMSOL Inc., Burlington, MA) to compute the particle trajectory, where the electrokinetic and dielectrophoretic mobility were calculated by Eq. 1 and 3, respectively. The zeta potential values of PS particles and channel wall in 10 mM NaCl solution were set to be -33 and -54 mV, respectively [14, 15]. The dynamic viscosity, $\eta = 0.9\times10^{-3}\ kg/(m\cdot s)$, and permittivity, $\varepsilon_m = 6.9\times10^{-10}\ C/(v\cdot m)$ for pure water at 25°C, were also used. As the electric conductivity of polystyrene particle in DC electric field is much smaller than that of suspending medium (i.e. 10 mM NaCl solution) used in our experiments, the CM factor was set to -0.5.

RESULTS AND DISCUSSION

Continuous Manipulation of Particles

Figure 3 shows the comparison between experimental (left column) and numerical (right column) results of 10 μm particle trajectories under varied inlet voltages. It can be found that all particles were moved from outlet 1 at lower inlet voltage (a: 180 V), while particles were directed to a narrower stream in outlet 2 at higher applied inlet voltage (b: 320 V). This is because larger applied voltage can induce larger repulsive DEP force (see Eq.1), which can deflect particles further away from hurdle and inner wall. In the simulation, the correction factor was set to be 0.5 by matching the simulated results to those of superimposed images, which remained constant for particles of fixed size in all the cases.

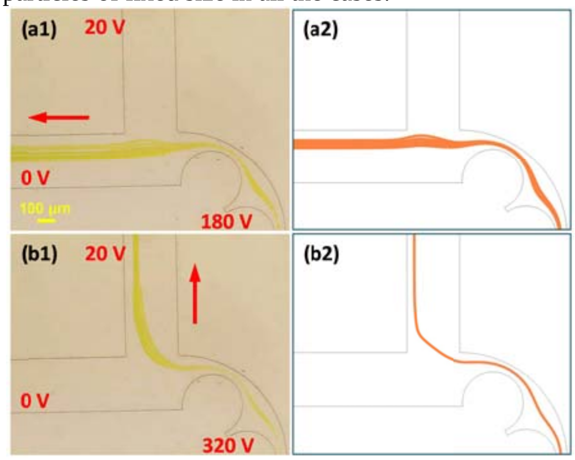

FIGURE 3. Experimental (left column: superimposed images) and numerical (right column) demonstration of manipulating 10 μm particles.

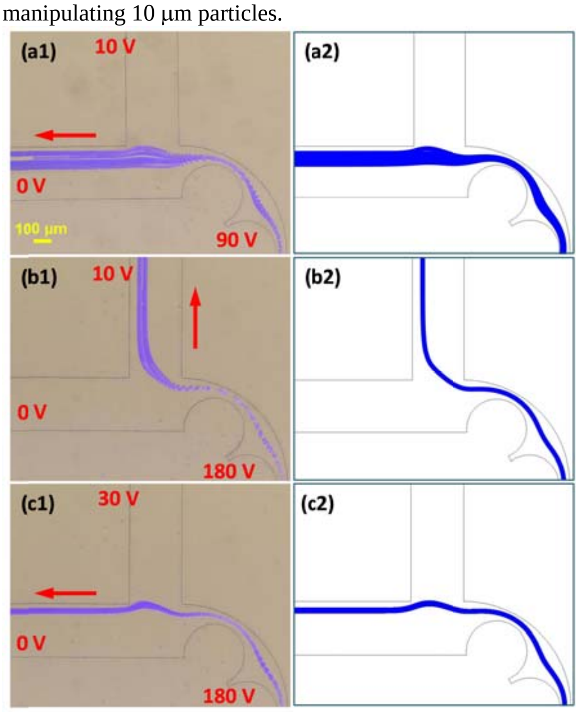

FIGURE 4. Experimental (left column: superimposed images) and numerical (right column) demonstration of manipulating 15 μm particles.

In similar analysis, we studied experimentally and numerically how to control the motion of 15 μm particles by adjusting inlet and outlet voltages. As shown in Fig. 4, (a) when applied voltages at inlet, outlet 1 and outlet 2 were, respectively, 90 and 0 and 10 V, particles moved from outlet 1 in a confined stream; (b) by increasing the inlet voltage to 180 V, particles were pushed further and directed to outlet 2 in a narrower stream; (c) further increased the outlet 2 voltage to 30 V, particles were diverted to outlet 1 again. It could be found that applied voltages at both inlet and outlet could affect particle trajectory, and 15 μm particles can be directed into either outlet 1 or outlet 2 depending on the applied voltages. In addition, with the increase of inlet and/or outlet voltage, 15 μm particles were observed to obtain a better focusing effect (forced into a narrower stream), which corresponds to our pervious founding [12]. By setting the correction factor to be 0.4 for 15 μm particles, the numerically predicted results (right column) coincide acceptably with the experimentally obtained superimposed images.

Continuous Separation of Particles

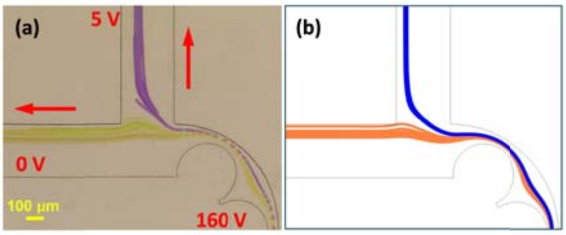

FIGURE 5. Experimental (left column: superimposed images) and numerical (right column) demonstration of separating 10 and 15 μm particles to distinct outlets.

A typical case of the separation of mixed 10 (yellow) and 15 μm (blue) PS particles with applied voltages at inlet, outlet 1 and outlet 2 of 160, 0 and 5 V, respectively, is shown in Figure 5. It can be seen that 10 and 15 μm particles were sorted and moved in a focused stream from outlet 1 and outlet 2, respectively. This is because DEP force is proportional to the cube of particle radius (see Eq.1), larger particles are subjected to larger DEP forces, and hence tend to be deflected further from the hurdle edge and inner wall. The separation performance was also reasonably predicted by numerical simulation (see right column of Fig. 5), in which the correction factors were fixed to be 0.4 and 0.5, respectively, for 10 (yellow lines) and 15 μm (blue lines) particles.

CONCLUSIONS

In this work, a curved microchannel embedded with multiple round hurdles for continuous manipulation and separation of microparticles using negative DC DEP was presented. The proposed microchannel has great advantages: (1) it provides more parameters (i.e. gap width, configuration of hurdle and curved channel) to be optimized, leading to increased controllability of the particle motion; (2) it relives or even eliminates the problems that occur in the insulator-based DEP microdevices that taking advantage of either obstacle or curvature effect individually for electric field gradient, allowing the improvement of device performance; (3) the upstream curved unit, a semi-circular microchannel combined with round hurdles, was designed to pre-focus particles into a stream close to the hurdle region, thus facilitates subsequent process of particle manipulation and separation. The novel design with demonstrated integrated functionality of focusing, switching and sorting microparticles is expected to be widely used in LOC devices for biological, chemical and medical applications.

REFERENCES

1. H. A. Pohl, Dielectrophoresis: *The Behavior for Nonuniform Electric Field*, Cambridge: Cambridge University Press, 1978.
2. R. Pethig, *Biomicrofluidics* **4**, 022811 (2010).
3. C. Zhang C, K. Khoshmanesh, A. Mitchell, and K. Kalantar-zadeh, *Anal. Bioanal. Chem.* **396**, 401-420 (2010).
4. P. R. C. Gascoyne and J. V. Vykoukal, *Proc. IEEE* **92**, 22–42 (2004).
5. J. Voldman, *Annu. Rev. Biomed. Eng.* **8**, 425-454 (2006).
6. K, Khoshmanesh, S. Nahavandi, S. Baratchi, A. Mitchell, and K. Kalantar-zadeh, *Biosens. Bioelectron.* **26**, 1800-1814 (2011).
7. A. Gencoglu A and A. R. Minerick, *Lab Chip* **9**, 1866-1873 (2009).
8. S. K. Srivastava, A. Gencoglu, and A. R. Minerick, *Anal. Bioanal. Chem.* **399**, 301-21 (2011).
9. X. Xuan, J. Zhu, and C. Church, *Microfluid. Nanofluid.* **9**, 1-16 (2010).
10. H. M. A. Ramosy, N. G. Greenz, and A. Castellanosy, *J Phys. D: Appl. Phys.* **31**, 2338–2353 (1998).
11. T. B. Jones, *Electromechanics of particles*, Cambridge: Cambridge University Press, 1995.
12. M. Li, S. Li, W. Cao, W. Li, W. Wen, and G. Alici, *J Micromech. Microeng.* **22**, 095001 (2012).
13. K. H. Kang, Y. Kang, X. Xuan, and D. Li, *Electrophoresis* **27**, 694–702 (2006).
14. N. Takahashi, A. Aki, T. Ukai, Y. Nakajima, T. Maekawa, and T. Hanajiri, *Sens. Actuators B* **151**, 410-415 (2011).
15. R. Venditti, X. Xuan, and D. Li, *Microfluid. Nanofluid.* **2**, 493-499 (2006).