DYNAMICS OF DIELECTROPHORETIC FIELD-FLOW FRACTIONATION (DEP-FFF) BASED MICRO SORTER FOR CELL SEPARATION

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Dielectrophoretic Field-Flow Fractionation (DEP-FFF) is a technique that selects particles of interest from a mixture of many samples. Conventional DEP-FFF technique used DEP force to levitate particles to different heights according to their dielectric properties. Levitated particles are then separated by their velocity difference in a microchannel. Numerical simulation and experimental results found that particles become wavy trajectory when the ratio of levitation height ($h_p$) and average of electrode width and spacing ($d$) is below 0.6 ($h_p/d<0.6$). In the mean time, sorted particles disperse randomly in Y-direction, too. The wavy trajectory and random distribution cause cell separation imprecisely. A novel MEMS-fabricated DEP-FFF based micro sorters is designed to improve these problems. The experimental results show that the particles can be levitated to a constant height and focus into a single particle stream along the centerline in the new micro sorter design. One can conclude that the new design leads to better cell separation in a DEP-FFF based micro sorter.

Keywords: DEP-FFF, micro sorter.

1. Introduction

Separating cells of interest from mixtures of various kinds of cells is widely used in biotechnology, from blood cell separation to flow-assisted immunoassays. It has been widely acknowledged that the effective sorting in many Lab-On-A-Chip devices provide many advantages over the conventional fluorescent activated cell sorting (FACS), such as low consumption of samples without sacrificing sensitivity, closed system reducing the potential biohazard risks and preventing cross-contamination, and feasibility of making portable and disposable devices. Over the years, the scientists have developed many particle and cell handling microfluidic devices. For examples, there are micro-fabricated fluorescence-activated cell sorting (µFACS), magnetic-activated cell separation (µMACS), automated single-cell sorting using dual-beam optical trapping, and optoelectronic tweezers for particle manipulation. In this paper, an on-chip sorting for particle separation using dielectrophoretic field flow fraction (DEP-FFF) is studied. Figure 1(a) shows schematic diagram of the separation principle in a conventional DEP-FFF micro sorter. DEP-FFF technique firstly used interdigit electrodes to generate DEP force that levitate particles to different heights according to their dielectric properties.
Levitated particles are then separated by their heights or velocity difference in a microchannel. This technique is also label-free, i.e. a unique advantage that cells are unaltered during the measurement process. The instrument can easily discriminate differences in calibrated particles. Since there is no mechanical structures moved by an actuator, the flow in the DEP-FFF micro sorter is smooth and, meanwhile, without dead spaces. These features obtained in the design of this paper are, in fact, required by many microfluidic systems.

![Diagram of cell separation principle in a conventional DEP-FFF micro sorter](a)
![Diagram of the novel design of DEP-FFF based micro sorter with focusing capability and no wavy trajectory behavior](b)

Fig. 1. (a) The cell separation principle in a conventional DEP-FFF micro sorter. (b) The novel design of DEP-FFF based micro sorter with focusing capability and no wavy trajectory behavior.

2. Numerical Simulation

In order to solve the dynamic equation for particle motion in a coupled manner with the fluid flow equations, a numerical simulation by using CFD-ACE+, CFDRC is applied. The numerical results have been tested and calibrated to make sure grid independence and accuracy by comparing with theoretical levitation heights \( \Delta h_p \). One can obtain the theoretical solution for the particle levitation height from Ref. 7 by balancing DEP forces with the gravitational and buoyant forces as:

\[
\Delta h_p = \frac{d}{\pi} \ln \left[ \frac{3\pi^3 \epsilon_m V_{rms}^2 \text{Re}(f_m)}{2\Delta \rho d^3 K^2 \left( \cos \frac{c}{2} \right)} \right].
\]  

where \( \epsilon_m \) is permittivity of medium, \( V_{rms} \) is root mean square voltage of the applied ac signal to the interdigit electrodes, \( f_m \) is Clausius-Mossotti factor\(^7\), \( \Delta \rho \) is the density difference between particle and medium, \( d \) is the average of electrode width \( \left( d_1 \right) \) and spacing \( \left( d_2 \right) \), \( c \) is defined as \( c = \pi d_1 / 2d \), and \( K \) is complete elliptic function of the second kind.\(^7\)

Simulation of particle trajectory, as well as the electric field intensity distribution, in a conventional DEP-FFF micro sorter is shown in Fig. 2. For levitation height \( \Delta h_p / d > 0.6 \) case (Fig. 2(a)), particles will be levitated to a constant height. When levitation height is
below $h_p/d < 0.6$, particle trajectory becomes wavy from upstream (left) to downstream (right), as shown in Fig. 2(b). Particles in this region ($h_p/d < 0.6$) experience relatively non-uniform electric field intensity along X-direction.

![Fig. 2. The particle trajectory at different levitation height (a) $h_p/d > 0.6$, (b) $h_p/d < 0.6$ in a DEP-FFF micro sorter.](image)

For levitation height $h_p/d > 0.6$ case, the numerical simulation and analytical solution show excellent agreement. When levitation height is within $h_p/d < 0.6$, the comparison between theoretical prediction and numerical result starts to show discrepancy. Therefore, the wavy trajectory for $h_p/d < 0.6$ case causes cell separation imprecisely.

3. Novel Design of DEP-FFF Micro Sorter

To improve the above-mentioned problems, a novel DEP-FFF based micro sorter is designed. Figure 1(b) shows the schematic design of the new DEP-FFF micro sorter. The new DEP-FFF micro sorter has convergent electrodes with interdigit electrodes parallel to the X-direction. The convergent electrodes first focus particles into a single particle stream along the centerline, as shown in Figure 1(b). Photograph of the new DEP-FFF based micro sorter and image sequences of particle trajectory during operation are shown in Fig. 3. As shown in Fig. 3(c), particles have been focused into a single particle stream along the convergent electrodes within the channel. After particle focusing, particles are levitated to a specific height when they enter into streamwise DEP-FFF electrode region. By simply designing DEP-FFF electrodes parallel to the flow direction, the electrical fields become uniform along X-direction. Particle wavy trajectory behaviors disappear. The experimental results show the all particles have been focused and levitated to different heights on $Y = 0$ plane according to their dielectric properties.

4. Conclusions

In this study, a novel design for particle separation is studied to improve the wave particle trajectory problem in conventional DEP-FFF micro sorters. Convergent and parallel-to-the-flow interdigit electrodes are designed to generate the focusing and levitation forces. The experimental results indicate that the wavy particle trajectory is improved and the new focusing capability is implemented. One can conclude that the new design leads to better cell separation in a DEP-FFF based micro sorter.
Fig. 3. (a) Photograph of a DEP-FFF microsorter. (b) Close-up view near the convergent electrodes and (c) Image sequence of particle trajectory before focusing.

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References