Continuous Electrodeless Dielectrophoretic Separation in a Circular Channel

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Abstract. We present a novel continuous electrodeless separation structure based on dielectrophoresis (DEP). The non-uniform electric field is generated by applying voltage over a circular channel. Driven by the electro-osmotic flow, the particles with different dielectric properties move continuously to the different location across the channel as they flow due to the different DEP force, thus continuously separated into the different outlets. The finite element modelling and simulation results show it can separate particles of different dielectric properties in both spatial and time domain. Compared with the previously reported dielectrophoretic separation using electrode arrays [1-10], this structure is more easily fabricated, mechanically robust and chemically inert. And compared with the previously reported electrodeless dielectrophoretic separation methods [11-14], this structure achieves higher throughput and continuous separation.

1. Introduction
Modern particle separation techniques have been fundamental to many advances in cell biology, molecular genetics, biotechnological production, clinical diagnostics, and therapeutics [1]. A number of methods have been developed to separate particles, including the ubiquitous techniques of filtration, centrifugation, electrophoresis, and both fluorescence-(FACS) and magnetic-activated-cell sorting (MACS), taking advantage of differences in particle size, density, electrical charge, and specific immunological surface markers. As these technologies have reached maturity, it has become more difficult to make fundamental improvements in separation resolution, system complexity, sample size, and device cost. Therefore, novel physical methods by which different particle types may be effectively discriminated and selectively manipulated are desirable. To this end, particle dielectric properties have been explored through dielectrophoresis (DEP) for developing particle separation techniques.

In the past numerous dielectrophoretic methods including DEP migration [2,3], DEP affinity [4,5], dielectrophoretic field flow fractionation (DEP-FFF) [1,6] and traveling wave dielectrophoresis (TWD) [7-10], the inhomogeneous AC electric fields are normally generated by various electrode geometries or electrode arrays. Those tiny electrodes made to generate high gradient field, however, will cause gas evolution due to the electrolysis effect. In order to avoid this problem and make the structure more mechanically robust and chemically inert, works [11-14] are carried out to explore electrodeless DEP separation. However, none of these electrodeless DEP methods could achieve high throughput.
continuous separation. So, there is a need for new electrodeless dielectrophoretic separation methods in a continuous manner. In this report, we present an idea of continuous dielectrophoretic separation in a circular channel. The modeling and simulation carried out will hopefully provide some insight into the particle behaviors in the proposed channel structure. Thus fabrication, experiments and further optimization of the structure can be planned.

2. Theory
The time averaged dielectrophoretic force acting on a spherical particle, immersed in a medium and exposed to a spatially non-uniform electric field can be described by [15]

\[ F_{DEP} = 2\pi \varepsilon_m R_p^3 \text{Re}[K(\omega)] \nabla E^2 \]  

(1)

where \( \nabla E^2 \) is the gradient of electric field squared, \( \varepsilon_m \) is the permittivity of the suspending medium, \( R_p \) is the radius of the particle, and

\[ K(\omega) = \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*} \]  

(2)

\( K(\omega) \) is the frequency dependent Claussius-Mosotti (CM) factor, \( \varepsilon_p^* \) and \( \varepsilon_m^* \) represent the frequency dependent complex permittivities of the particle and medium, respectively. The complex permittivity is defined as \( \varepsilon_p^* = \varepsilon_p - j(\sigma_p / \omega) \) and \( \varepsilon_m^* = \varepsilon_m - j(\sigma_m / \omega) \), where \( j = \sqrt{-1} \), \( \varepsilon \) is the permittivity, and \( \sigma \) is the conductivity of the dielectric.

For small particles (low Reynolds numbers) ignoring Brownian motion and the buoyancy force, the DEP force moving the particle is balanced with the fluid drag force slowing it down.

\[ F_{DEP} = -F_{\text{drag}} = 6\pi \eta R_p v_p \]  

(3)

where \( v_p \) is the particle velocity and \( \eta \) is the medium viscosity. So that for a spherical particle the dielectrophoretic mobility will be

\[ \mu_{DEP} = \frac{R_p^2 \varepsilon_m \text{Re}[K(\omega)]}{3\eta} \]  

(4)

in the direction of \( \nabla E^2 \). It can be seen that for a spherical particle moving in an electric field gradient, the dielectrophoretic mobility is proportional to the surface area of the particle and the CM factor and the direction of the particle movement is dependent on the sign of CM factor.

3. Working principle and design
The basic principle of the proposed method is illustrated in Figure 1. By applying a DC voltage on two electrodes over the circular chamber, a non-uniform electric field is generated, whose gradient directs towards the center of the circle. The sample mixture is driven along the channel by the electro-osmotic flow. Due to the different DEP force magnitudes and directions, the particles with different DEP responses move continuously to the different location across the channel as they flow, thus continuously separated into the different outlets.
In the micro-channels the Reynolds number is low enough for inertial effects to be irrelevant so that the centrifugal force on the particles could be ignored. Thus along the radius direction, as expressed in equation (4), the particle mobility depends on the CM factor and the particle size for a given suspending medium. The particles with positive DEP response $\text{Re}[\bar{K}(\omega)] > 0$, will be driven away from the center. While the particles with negative DEP response $\text{Re}[\bar{K}(\omega)] < 0$, will be attracted towards the center. As a result, the positive DEP particles will end up inner than the initial injection point while the negative DEP particles will end up outer than the initial injection point. For the particles with the same DEP polarity, the larger the particle is the higher mobility it has along the radius direction and the faster it will move towards the inner sidewall or outer sidewall of the channel. Therefore, this channel can be utilized to separate the particles of different DEP polarities and of the same DEP polarities but different sizes.

![Figure 1. Schematic diagram of the dielectrophoretic separation in a circular micro-channel](image)

Along the tangential direction, the low Reynolds number particles adapt to the fluid flow instantly. Since the velocity of the electro-osmotic flow on the sidewall is proportional to the electric field intensity, the flow velocity at the inner side of the channel where the highest electric field intensity exists will be faster than at the outer side of the channel. Therefore, the time taken by particles with different dielectric properties to reach the outlets is different as shown in Figure 1. The particles following the inner side path run faster than those following the outer side path, thereby getting separated in the time domain.

4. Simulation results and discussion
To simulate the particle behavior in the circular micro-channel, the trajectory calculations are implemented in Matlab 7.0 after the field calculations are performed with Femlab 3.1i. The goal of the simulation is to prove the hypothesis introduced earlier in previous section, that the particles of different dielectric property can be separated in both spatial and time domain in the proposed circular micro-channel.

The 3D model of the circular channel is created in Femlab 3.1i. The channel is enclosed by a 50 µm inner circle and a 100 µm outer circle and the height of the channel is 20 µm. A 10V voltage is applied over the channel. Water is used as the suspending medium and the zeta potential is chosen to be 0.1 V. Figure 2 (left) shows that the field density is the maximum at the inner side of the channel.
The DEP force normalized to polarizability \( \nabla E^2 \), depicted in Figure 2 (right), orients towards the center point. The force magnitude drops as the radius increases.

For the sphere low Reynolds number particles running in the uniform viscous flow with dielectrophoretic force acting on them, the velocity of the particles can be calculated as

\[
v_{\text{particle}} = \frac{F_{\text{DEP}}}{6\pi \eta R_p} + v_{\text{fluid}}
\]

The position of the particle after a certain time can be approximated by summing the distances traveled in a short period of time with the velocities calculated by above formula.

Figure 2. Simulation of (left) Electric field distribution and (right) normalized DEP force

Figure 3. Simulation result of particle trajectories

The trajectories of four particles with different dielectric properties are calculated and plotted in different color as shown in Figure 3. They are positive DEP particles with 5 µm and 10 µm radiiues, and negative DEP particles with 5 µm and 10 µm radiuses, respectively. For the sake of conformability, the CM factor is chosen to be 0.5 for positive particles and -0.5 for negative particles. From Figure 3 it can be seen, the 10 µm positive DEP particles end up closest to the inner sidewall while the 10 µm negative DEP particles are driven farthest away from the inner sidewall. The 5 um particles are less departing from the contour line of the injection point. From the figure we can also see
the time difference for the particles to reach the outlets. Obviously, the particles following the inner side path will leave behind those particles following the outer side path.

Varying the voltage parameter over the channel, we simulated the particle trajectories in the channel with different electric field intensity from the previous case. They are shown in Figure 4.

![Figure 4. Simulation results of particle trajectories with (left) three times less electric field intensity and (right) three times more electric field intensity than the previous case](image)

For the less field intensity case, the particles move slower due to the slower electro-osmotic flow which is proportional to the electric field intensity, so they have longer time to reach the end of the channel. Nevertheless, as can be seen in Figure 4 (left), they can be hardly separated even in longer time. That is due to the dramatically reduced DEP force which is proportional to the squared field gradient. For the more field intensity case, the particles move faster as the electro-osmotic flow is raised, so it takes particles less time to arrive at the end of the channel. However, the greatly enlarged DEP force makes those particles over-separated with respect to the outlets as can be seen in Figure 4 (right). Therefore proper voltage difference should be carefully chosen to apply over the circular channel if good separations are desired.

5. Conclusion
We have shown in this report, design, modeling and simulation of a novel continuous electrodeless separation structure based on dielectrophoresis (DEP). The results indicate its promising utilization for particle separation in various biochemical applications. The fabrication and experiments are about to carried out to verify the design and the simulation method.

Acknowledgement
This research is under grants from The Dutch Technology Foundation (STW), Applied Science Foundation of NWO and the technology programme of Ministry of Economic Affairs, the Netherlands.

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