

Particle Separation by Dielectrophoresis

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Abstract— Dielectrophoresis (DEP), the movement of particles induced by polarization effects in non-uniform electric fields, has been proved to be a promising particle manipulation and separation candidate. In the past, a number of researches have been carried out to separate particles using DEP, where inhomogeneous AC electric field is generated by divergent electrode geometries or electrode arrays. Recently, it has been demonstrated that electrodeless dielectrophoresis can be used for particle separation, which has more advantages than using electrodes. In this paper, the conventional dielectrophoretic separation methods are reviewed. Furthermore, we proposed a novel continuous electrodeless dielectrophoresis method, in which a circular chamber is utilized. Simulation results showed that it has the potential to fulfill particle separation.

Keywords— Separation; Dielectrophoresis; Polarization; Electrodeless dielectrophoresis

I. 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, cell purity, sample size, and device cost. Therefore, novel physical methods by which different particle types may be 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 a number of DEP methods have been proposed and realized the separation of particles, which include DEP migration [2,3], DEP affinity/DEP retention [4,5], dielectrophoretic field flow fractionation (DEP-FFF) [1,6], and traveling wave dielectrophoresis (TWD) [7-10]. Recently, electrodeless dielectrophoresis (EDEP) [11-14] has been proposed, by which the structure is tending to be more mechanically robust and chemically inert.

In this work, the conventional methods are reviewed briefly in the later sections. After that, a novel electrokinetic DC-EDEP method is proposed. Using a circular chamber, with the FEMLab simulation result, we show that at the correct applied voltage and channel geometry, it can be a versatile separation candidate for particles of different DEP properties and sizes.

II. 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]

$$F_{DEP} = 2\pi\epsilon_m R_p^3 \operatorname{Re}[K(\omega)]\nabla E^2 \quad (1)$$

where ∇E^2 is the gradient of electric field squared, ϵ_m is the permittivity of the suspending medium, R_p is the radius of the particle, and

$$K(\omega) = \frac{\epsilon_p^* - \epsilon_m^*}{\epsilon_p^* + 2\epsilon_m^*} \quad (2)$$

$K(\omega)$ is the frequency dependent Clausius-Mosotti factor, ϵ_p^* and ϵ_m^* represent the frequency dependent

complex permittivities of the particle and medium, respectively, The complex permittivity is defined as $\epsilon_p^* = \epsilon_p - j(\sigma_p / \omega)$ and $\epsilon_m^* = \epsilon_m - j(\sigma_m / \omega)$, where $j = \sqrt{-1}$, ϵ is the permittivity, and σ is the conductivity of the dielectric.

The Clausius-Mossotti factor not only depends on the dielectric properties of the particle and medium, but also on the frequency of the applied field. Variations in this factor give rise to a dielectrophoretic force that is frequency dependent and unique to a particular particle type. For a sphere, the real part of $K(\omega)$ is bounded by the limits $-0.5 < \text{Re}[K(\omega)] < 1$ and varies with the frequency of the applied field and the complex permittivity of the medium. Positive DEP occurs when $\text{Re}[K(\omega)] > 0$, the force is toward the high electric field. The converse of this is negative DEP, which occurs when $\text{Re}[K(\omega)] < 0$, the force is in the direction of decreasing field intensity.

At low frequency, because the dominant electrostatic effect is conduction, $\text{Re}[K(\omega)]$ depends solely on the conductivity of the particle and suspending medium. In many practical systems, at frequency below 100 kHz, the CM factor can be approximated in terms of the real conductivities as

$$K(\omega) = \frac{\sigma_p - \sigma_m}{\sigma_p + 2\sigma_m} \quad (3)$$

where σ_p and σ_m represent the conductivities of the particle and medium, respectively. So, if the conductivity of the particle is greater than the conductivity of the medium, the particle will exhibit positive DEP, and vice versa. This is more applicable for our proposed method, in which DC voltage is applied to generate electro-osmotic flow and DEP force simultaneously.

III. CONVENTIONAL ELECTRODE METHODS

A. DEP migration

DEP migration can be utilized to isolate different particles from particle mixture through their migration to, and collection in, different field region. The most commonly used electrode geometry to generate the non-uniform electric field is shown in Fig. 1. As can be seen, four electrodes are utilized to produce a quadrupole geometry where the electrodes are offset by 90 degree. Voltage application is accomplished by wiring electrodes diagonally opposite one another identically. Once voltage

is applied after sample introduction, particles experiencing positive DEP will move to the electrode edges, and those experiencing negative DEP will move into the center, where, if they have negative buoyancy, they will remain trapped. The principal draw back of this method is that particles cannot be separately collected for further downstream process.

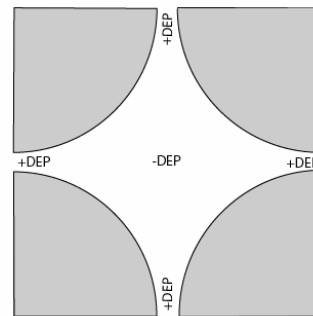


Fig. 1. A polynomial electrode

B. DEP affinity/DEP retention

In DEP affinity or DEP retention, a strong positive DEP force selectively traps target particles from a particle mixture at electrode edges and holds them against an imposed fluid flow stream, while a negative DEP force repels other particles from the electrodes so that they are levitated in the channel and subsequently swept out of the chamber by fluid flow.

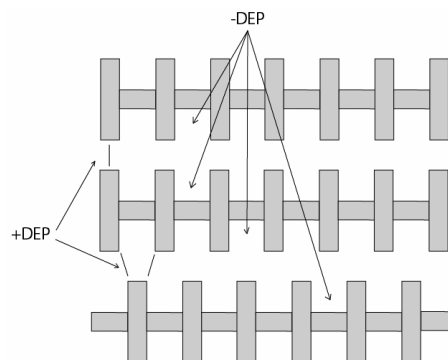


Fig. 2. Castellated electrode geometry

Fig. 2 shows the typical electrodes utilized in DEP affinity or DEP retention device. As shown in the figure, castellated electrodes can be configured in two manners: directly opposite or with offset. With either case, the device is wired so that every other electrode has the same voltage input. In the case of castellated electrodes that are directly opposite each other, particles focused in the positive dielectrophoresis region will be found between the faces of the electrodes located across from each other. Negative dielectrophoresis will congregate particles in

the rectangular areas between the castellated electrodes. In the case of castellated electrodes with offset, the positive dielectrophoretic particle collection again occurs in the region between castellated electrodes located across from each other, the difference being that the positive region is now found between the corners of the electrode faces. And the negative dielectrophoresis region is located in the rectangular “wells” between electrodes.

Based on the castellated electrodes, G.H. Markx proposed to use gradients in conductivity to separate particles with similar dielectric properties [16]. The conductivity of the flushing liquid is gradually and continuously increased so as to produce a conductivity gradient with time. The particles trapped by positive DEP force will be released from the electrodes according to their own dielectric properties and as a function of flow rate and medium conductivity.

C. DEP-FFF

Dielectrophoretic field-flow-fractionation (DEP-FFF) has been demonstrated to exhibit a high and electrically controllable discrimination for particle separation. DEP forces produced by microelectrodes are used to levitate particles in a thin chamber to equilibrium heights where sedimentation forces balance the vertical DEP force components. A carrier fluid moves through the chamber and establishes a parabolic hydrodynamic velocity profile causing cells of different dielectric and density properties levitated to different equilibrium heights to be transported through the chamber at different velocities and thereby separated.

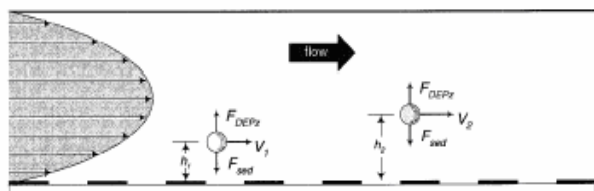


Fig. 3. DEP-FFF principle illustration

D. TWD fractionation

Traveling wave Dielectrophoresis (TWD) is the motion of polarisable particles induced by high-frequency traveling electric fields [17]. Traveling electric fields are generated by rows of parallel electrodes address with three-phase or quadrature sinusoidal potentials, as shown in Fig. 4, in which particles are induced to move asynchronously at speeds of up to 100

um/s. The dielectrophoretic force in the vertical direction, which is determined by the real part of the CM factor, balances the other vertical forces levitating the particles in the chamber. The TWD force inducing the movement of the particle is given by [18]

$$F_{TWD} = -\frac{4\pi\epsilon_m R_p^3 \text{Im}[K(\omega)]E^2}{\lambda} \quad (4)$$

where λ is the wavelength of the traveling wave and is usually equal to the distance between electrodes which have signals of the same phase applied.

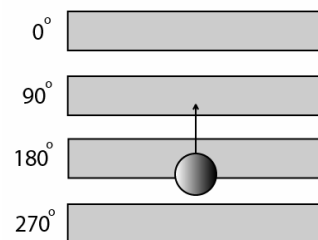


Fig. 4. A schematic showing TWD fractionation

IV. CONVENTIONAL ELECTRODELESS METHODS

A. Dielectric Constrictions

In [11,12], C.F. Chou and his fellows reported an alternative way to construct DEP traps by patterning geometrical constrictions in an insulating substrate instead of metallic microelectrodes and demonstrated DNA trapping using this device. As shown in Fig. 5 in a microfluidic channel, the constriction is used to squeeze the electric field in a conductive solution, such as ionic buffer, thereby creating a high electrodeless dielectrophoresis (EDEP).

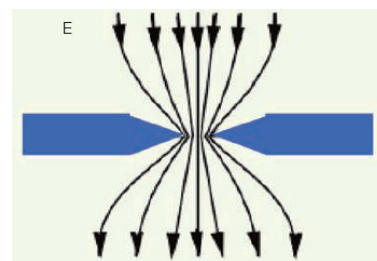


Fig. 5. A dielectric constriction

B. Insulating Post Array

In [13,14], another EDEP method, the insulating post array based dielectrophoresis for separation of live

bacteria is proposed. Fig. 6 is a presentation of an EDEP device using an array of insulating posts, in this case circular insulators. The non-uniform electrical field is produced by compressing the electric field, applied by the electrodes on both sides of the post array, through the gaps between the insulating posts. The high electric field intensity region is located between the insulators where the electric field is compressed. And the low electric field density region is located at the crossroad of the insulators where the electric field is less compressed.

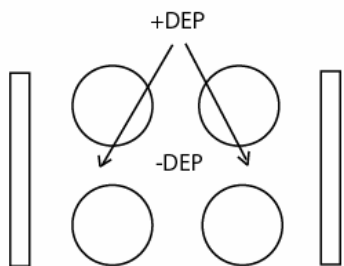


Fig. 6. An insulating post array

In the dielectric constriction device [11,12], the target particles are trapped at the constriction region by a strong dielectrophoresis force while the other particles are flushed out the channel by fluid flow devices. In order to collect the target particles, the applied voltage has to be lowered down or cut off. And in the insulating post array device [13,14], the particles are attracted to the different potential region according to their dielectric properties, and like electrode DEP migration, the particles are difficult to be separately collected. Thus, none of them could realize a continuous separation.

V. PROPOSED METHOD

In order to automate the process, we propose a high-throughput continuous separation method using an electrokinetic EDEP process.

Fig. 7 illustrates the basic principle of the proposed method. By applying a DC voltage on two electrodes over the circular chamber, a non-uniform electric field $E(r)=V/\theta \cdot r$ is obtained, where V is the voltage difference across the electrodes and θ is the opening angle between them. Thus, the gradient of the electric field squared is $\nabla E^2(r)=-2(\frac{V}{\theta})^2 \frac{1}{r^3} \bar{r}_0$, which 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.

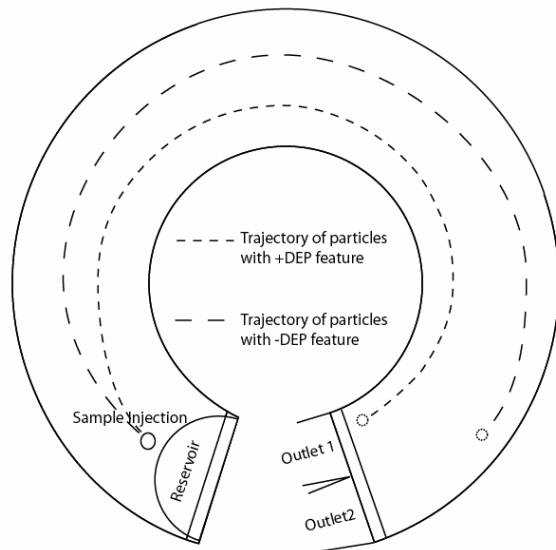


Fig. 7. Conceptual view of proposed electrokinetic EDEP separation method

As illustrated in Fig. 8, for a particle running in a circular channel, it is exerted three forces, the centrifugal force which is a fictitious inertia force compelling the particle away from the center, the dielectrophoretic force and the fluid drag force. In the tangent direction, the fluid drag force component keeps on dragging the particle until it reaches the same velocity as the fluid. The centrifugal force is in the radius direction, which is given by

$$F_{cent} = \frac{4}{3} \pi R_p (\rho_p - \rho_m) \frac{V_{tan}^2}{r} \quad (5)$$

Where the R_p is the radius of the particle if assuming the particle is sphere, ρ_p and ρ_m are the mass density of the particle and the medium liquid, respectively, and V_{tan} is the velocity component of the particle in the tangent direction. To simplify the analysis, we assume $\rho_p = \rho_m$, so that the centrifugal force exerting on the particle will be zero and the particles will go along the fluid streamline if ignoring the DEP force. Now if we take the DEP force into account, the resultant force in the radius direction acting on the particle at a distance r from the center is

$$\Sigma F_r = F_{Dr} + F_{DEP} \quad (6)$$

where F_{Dr} is the component of fluid drag force in the radius direction. Thus

$$\Sigma F_r = 6\pi\eta R_p (-\bar{v}_{pr}) - 4\pi\epsilon_m R_p^3 \text{Re}[K(\omega)] \left(\frac{V}{\theta}\right)^2 \frac{1}{r^3} \bar{r}_0 \quad (7)$$

where v_{pr} represent the particle's velocity component in the radius direction, which is always the same direction as the DEP force acting on that particle. From the above equation, it can be seen that the particles with positive DEP feature $\text{Re}[K(\omega)] > 0$, will be driven away from the center. While the particles with negative DEP feature $\text{Re}[K(\omega)] < 0$, will be attracted towards the center. As a result, these particles with different DEP polarities will end up at the different outlets.

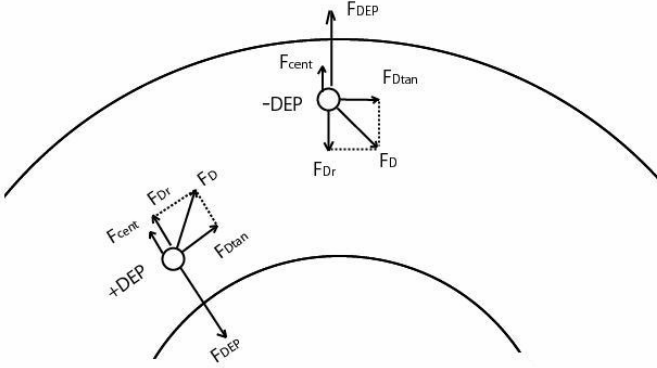


Fig. 8. Force diagram for the particles

The acceleration of the particle in the radius direction is given by

$$a_r = \left\{ 4.5\eta \frac{1}{R_p} (-\bar{v}_{pr}) - 3\epsilon_m \text{Re}[K(\omega)] \left(\frac{V}{\theta}\right)^2 \frac{1}{r^3} \bar{r}_0 \right\} / \rho_p \quad (8)$$

From the above equation, it can be seen that for the particles with the same dielectric property, the larger the particle is, the higher acceleration component in the radius direction it will have and the faster it will move towards the inner wall or outer wall of the channel. Taking advantage of this characteristic, we could also use this channel to separate the particles with the same DEP properties but different sizes.

Since the velocity of the electro-osmotic flow 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. Thus the time taken by particles

with different dielectric properties and sizes to reach the destination is different. This also separates particles in the time domain, as illustrated in the Fig. 7, the particles passing through the inner circles will leave behind those particles passing through the outer circles.

VI. SIMULATION RESULTS

In the FEMLab, a 2D model of the circular channel is created. The channel is enclosed by a 50 μm inner circle and a 100 μm outer circle. A 10V voltage is applied over the channel. Fig. 9 shows that the field density is maximum at the inner side of the channel. The DEP force normalized to polarizability, ∇E^2 is depicted in Fig. 10. As shown in Fig. 10, the normalized DEP force orients towards the center point. The force magnitude drops as the radius increases.

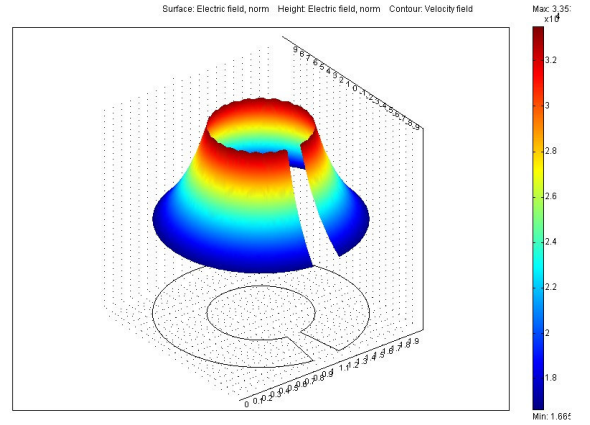


Fig. 9. Simulation of Electric Field

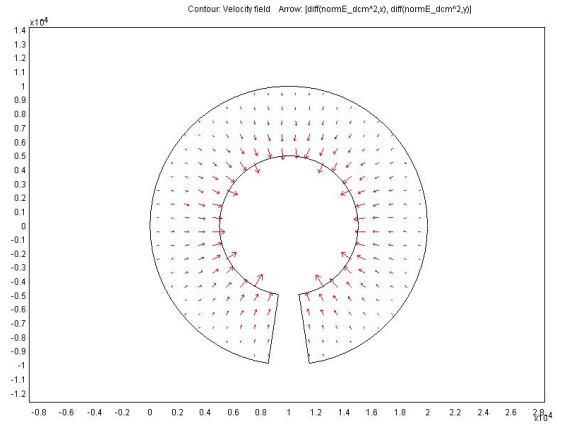


Fig. 10. DEP force normalized to polarizability, ∇E^2

To predict the particle movement in the channel, the particle tracing is performed in the FEMLab. Firstly, the sample injection point is set at the middle of the channel. Two particles with the same radius (5 μm) and opposite DEP polarities are used. The result in Fig. 11(a) shows that the positive DEP particle will end up at the inner side

of the channel while the negative DEP particle will end up at the outer side of the channel. Thus spatial separation can be achieved for those particles with different DEP polarities. Secondly, the sample injection point is placed adjacent to the inner side wall of the channel. Two particles with different sizes but both negative DEP properties are employed. The left figure of Fig. 11(b) plots the trajectory of the particle with 2.5 μm radius, and the right figure of Fig. 11(b) plots the trajectory of the particle with 7.5 μm . It can be seen that both particles are repelled away from the center, but the larger particles will be driven more outside than the smaller particles, thereby getting separated. Finally, the sample injection point is set adjacent to the outer side wall of the channel and two particles with both positive DEP properties but 2.5 μm and 7.5 μm radius, respectively, are used. The results plotted in Fig. 11(c) exhibit that both particles are attracted towards the center, but the difference between the large particles and the small particles are not as obvious as in the previous case shown in Fig. 11(b). That is due to the dramatically dropped DEP forces at the outer side of the channel, which is clearly shown in Fig. 10.

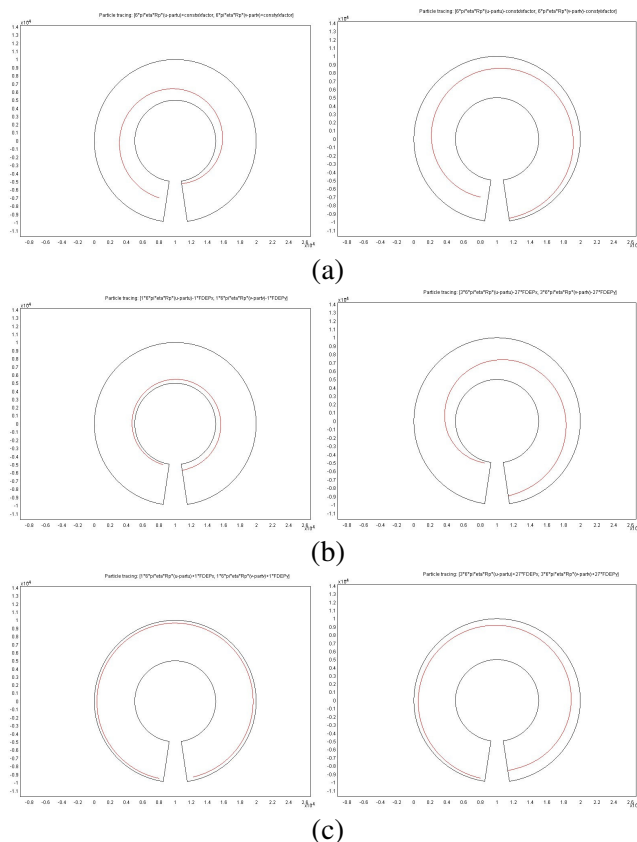


Fig. 11. Particle tracing results for (a) left, 5 μm radius +DEP, (a) right, 5 μm radius -DEP, (b) left, radius 2.5 μm -DEP, (b) right, radius 7.5 μm -DEP, (c) left, radius 2.5 μm +DEP and (c) right, radius 7.5 μm +DEP

VII. CONCLUSION

In summary, we have proposed a novel continuous EDEP method to separate particles with different dielectric properties and sizes, in which the non-uniform electric field is generated by applying a DC voltage on two electrodes over the circular chamber. And the momentum of the carrier fluid is provided by the electro-osmotic flow. FEMLab simulation results prove that this method is capable for different kinds of separation. By patterning the channel geometry carefully, we expect this method to be used in many applications.

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