# Applications of Dielectrophoretic / electrohydrodynamic electrodes for concentration of biological nanoparticles

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## ABSTRACT

Dielectrophoresis (DEP) is a phenomenon of induced particle motion in non-uniform electric fields. The effect is frequency dependent; by monitoring the motion of particles in AC fields and analyzing the change in motion with frequency, it is possible to determine the electrical properties of single cells in lab-on-a-chip systems. By combining two common electrokinetic phenomena - dielectrophoresis and electrohydrodynamic fluid flow - we demonstrate that it is possible to manipulate, concentrate and trap particles from cell to molecular scale, and show how the trapping phenomenon is not related to particle size. We also discuss application of the phenomenon, from particle preconcentration in sensor systems to the deposition of particles on sensor surfaces.

***Keywords***: concentration, electrohydrodynamics, nanoparticles

## 1 INTRODUCTION

Detection technologies such as evanescent light scattering or surface plasmon resonance use surface interactions to detect the presence of particles on a metal surface[1]. In order to be an effective method of pathogen detection, such a system is required to attract pathogens over a wide range of sizes, from nanometres to micrometers in size. However, the detection of bacteria or viruses is often hampered because such particles are small enough for Brownian motion to prevent them precipitating onto the sensor surface.

In order to enhance the effectiveness of such a detection system, AC-electrokinetic forces have been employed to pull particles from solution and concentrate cells on a sensor surface by exploiting two phenomena observed in cells suspended in a liquid medium and exposed to a low-frequency (~1kHz), non-uniform electric field. The first, *dielectrophoresis,* is the motion of suspended particles caused by polarization effects induced by an inhomogeneous electric field. Depending on the properties of the particle and the surrounding medium the particle can be attracted to (positive dielectrophoresis) or repelled from (negative dielectrophoresis) the electrodes. In addition to dielectrophoresis, *electro-hydrodynamic* (EHD) flow of the suspending liquid due to electroosmosis is also observed above adjacent electrode surfaces. As a result of the combination of these phenomena, a vortex of liquid is formed over the electrode edge that pushes particles onto the electrode surface.

In this paper we report that these effects can be used to concentrate nanoparticles, such as latex nanobeads, spores and proteins, from flow. We demonstrate that the particle collection of zipper electrodes is independent from the particle size and can therefore be used on an unlimited number of particles, describe how the system can be used to concentrate particles from a flow and compare the efficacy of EHD-assisted vs. conventional dielectrophoretic trapping. These results indicate that EHD has tremendous potential for the development of electrostatic tools for trapping of particles in lab-on-a-chip systems.

## 2 THEORY

Dielectrophoresis, the phenomenon of induced motion in particles suspended in non-uniform electric fields [1-3], is well-characterised and understood. However, in addition to this phenomenon, other electrokinetic phenomena exist which exhibit themselves under similar circumstances to those usually used for dielectrophoresis – that is, using particles suspended in ionic aqueous media, and using planar electrode arrays. One such phenomenon is the induction of fluid flow across the electrode surfaces, which causes particles collecting by dielectrophoresis to move over the electrodes. This effect was first observed in 1988 and described by Price *et al.* [4], who noted in early experiments using planar electrodes that, at low frequencies, particles trapped by positive dielectrophoresis moved to form diamond-shaped aggregations on the upper surface of the electrode arrays. Investigations of the electric field across the electrode array surface [5] determined that these diamond-shaped areas corresponded both in location and shape to regions of low electric field strength, and it was thus attributed to being due to an unexplained form of *negative* dielectrophoresis. Particle collection due to combined dielectrophoretic/fluid flow phenomena were subsequently described by Pethig et al. in 1992, where cells were observed to collect on the upper edges of castellated electrode structures at low frequency

[6]. This behavior was attributed to an unknown dielectrophoretic effect and dubbed "anomalous dielectrophoresis". The effect was revisited and explained by Green and Morgan [7] as being due to the balance of dielectrophoretic force and the action of fluid flow. The source of this fluid flow was revealed by Ramos *et al* [8] who described how the electric field generated by planar electrodes is such that field lines pass through the electrical double layer surrounding the electrodes tangentially; this can be considered to consist of a component orthogonal to the electrode surface, plus a second component, tangential to the surface, which acts to move the charge accumulated in the double layer, creating an electro-osmotic flow.

When particles collect on planar electrode arrays by dielectrophoresis alone, they do so at the points of highest electric field strength; that is, at the edges of the electrodes. However, as frequency is decreased, fluid flow due to electro-osmosis becomes increasingly prominent; as described above, the location where this is strongest is where the electric field intercepts the double layer at the sharpest angle, which is across the electrode surfaces where the electrodes are closest together. Therefore, those particles which have collected by positive dielectrophoresis are those that experience the greatest fluid motion, causing them to be "swept back" on to the electrode surface. As they move further from the electrode edge, the angle of the electric field becomes more orthogonal and the fluid flow diminishes; eventually the two processes are in equilibrium and the particles remain at rest; this is at the center of the array and is responsible for anomalous collection behaviour. The effect was actually used by Green and Morgan [7] to demonstrate that the phenomenon could be used on micro-arrays to separate two sizes of nanoparticle.

The fluid-flow effect is frequency-dependent, being strongest at low frequencies where the double layer has time to form, diminish and reform with opposing polarity for every cycle of the electric field, but becoming limited at high frequencies where the electrode polarity changes too fast for the double layer to form. Ramos et al. [8] and subsequently Green et al. [9] demonstrated that the velocity profile $v$ of the fluid, and hence the particles, follows a bell-shaped frequency dependence governed by the expression [8]

$$v = \frac{1}{8}\frac{\varepsilon V_o^2 \Omega^2}{\eta x \left(1+\Omega^2\right)^2} \qquad (1)$$

where $\varepsilon$ represents the permittivity of the medium, $V_o$ is the potential applied to the electrodes, $\eta$ is the viscosity of the medium, $x$ is the distance from the center of the inter-electrode gap, and $\Omega$ is a parameter given by the expression

$$\Omega = \frac{\omega x \kappa \varepsilon \pi}{2\sigma} \qquad (2)$$

where $\omega$ is the electric field frequency, $\sigma$ represents the conductivity of the medium, and $\kappa$ is the reciprocal double layer thickness. Since the direction of flow is dictated by the direction of the electric field vector, the fluid motion is always directed orthogonally to the electrode edges.

# 3 APPLICATIONS

## 3.1 Particle preconcentration

For any detection system, pre-concentration of the analytes is an important technique for improving system sensitivity. For the detection of bio-particles, this can be achieved by trapping the particles from a liquid flow over a period of time, and releasing these trapped particles simultaneously at a later stage, producing a concentrated band of particles (the so-called "trap-and-purge" technique).

Dielectrophoretic force has been used in the past to trap particles at an electrode edge, even against a hydrodynamic flow, at the edges of an electrode array. The particles can then be released by switching the field off or changing the frequency of the field. However, such a system has still some drawbacks. The electric field does not penetrate deeply dielectrophoresis into the liquid volume, which limits the height of a flow cell and thereby the throughput.

To overcome this, it is possible to exploit electroosmotic flow to induce a vortex flow in the bulk liquid over the electrode edge. This effect has been observed to extend over 100µm into the bulk liquid. This vortex pulls particles from the liquid above the electrode down to the electrode surface. In case of the zipper electrodes [10,11], this effect was used to collect particles on the electrode surfaces.

Initial experiments with zipper electrodes was demonstrated that broad electrode tracks (>200 µm) and narrow inter-electrode gaps (<100 µm) cause strong AC electroosmotic flow to occur, but that particles do not collect on the electrode surface but are held at the electrode edge by dielectrophoretic force. The particles are already held against a substantial electro-hydrodynamic flow over the electrode edge, so it is highly likely that an additional flow in the bulk liquid would not be able to remove then from the electrode edge. After a collection period, the frequency of the field can be switched in frequency, so that the dielectrophoretic force is weakened while the electroosmotic force is used to rapidly re-suspend the particles in the liquid volume above the electrode. This small but concentrated volume could be transferred to a detector for further analysis.

In order to assess the efficacy of such a system, a flow cell was built with conventional interdigitated electrodes with an inter-electrode gap of 30µm and an electrode width of 500µm. Suspensions of spores in 1mS/m KCl solution were pumped into a flow-cell using a syringe pump, with

flow rates varying between 1 and 6 ml/hr and with particle concentrations varying between $10^3$ and $10^7$ particles/ml. The electrodes were energised by a 10kHz, $10V_{pk-pk}$ signal, causing particles to be collected for 10 minutes as the solution was pumped across the array. At the end of this period, the electric field was removed and the number of cells released into the flow was measured. These cells were then added to the existing particles flowing through the system, resulting in a gain of particles in a band equal in volume to the volume enclosed by the inter-electrode gap, and from the electrodes to the top of the chamber (approximately 4.2µl).

Interestingly, the results do not scale linearly with particle concentration, and the improvement in concentration is low for relatively high particle concentrations. The cell count is the number of cells in the release volume, so the number of additional cells per µl is the number of cells divided by 4.2. This corresponds to an increase of over an order of magnitude at $10^4$ concentrations (from 10/µm to 10+96/µl) but much less at $10^7$ concentrations (from 10000/µl to 10000+311/µl).

### 3.2 Size independence

In order to assess the effect of particle size on trapping, the rate at which particles moved across the electrodes towards the middle of the electrodes was measured. Particles included yeast cells (approximately 6 µm diameter), BG spores (~1 µm), influenza viruses (100nm) and dissolved albumin protein, plus latex beed with diameters between 20nm and 500nm. In all cases, the particle velocity followed a negative-exponential profile, with the particles receding to a stable position away from the electrode edges. These distances are shown in figure 4 for conditions of $10V_{pk-pk}$, 800Hz applied field. Measuring the total distance this front had travelled after 1 second, it was noted that albumin was pushed furthest (average 59 µm) towards the centre of the electrode, while BG-spores travelled the smallest distance of all those bioparticles examined (28 µm). Influenza was moved an average of 44 µm, whilst yeast moved 29 µm within the same time period. Notably, for particles significantly less than 1 µm in diameter (and therefore technically colloidal), the velocity was the same indicating that the trapping of nanoparticles – including protein molecules – is size independent.

## 4 CONCLUSION

In this paper we have described how combining electrohydrodynamic flow and dielectrophoresis can be used for the manipulation of particles. The applications for focussing and concentrating virus particles, proteins and nanobeads on a large metal surface are great, particularly in medical applications.

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