Trapping and manipulation of nanoparticles by using jointly Dielectrophoresis and AC electroosmosis

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Abstract. In this paper the concept of micro- and nano-particle trapping, by jointly utilizing Dielectrophoresis (DEP) and AC Electroosmosis (ACEO), is investigated in a system of parallel electrode arrays. The ACEO fluid velocity is studied by solving a numerical model based on the Debye-Huckel theory.

Furthermore, trapping is studied in a configurable asymmetric electrode array system. A method to trap and manipulate particles is presented that uses an asymmetric configurable electrode system and joint ACEO and DEP in order to move and trap particles at desired locations for further processing. The method is analyzed using a modified Smoluchowski equation that describes the time evolution of the concentration of particles, while limiting the maximum possible concentration to physically realistic limits.

1. Introduction

There has been a lot of research recently in the enhancement of the concentration of bioparticles in sensor devices, so that their amplification using some agent (that is often necessary for further processing) can be avoided [1]. Such devices are expected to no longer rely solely on the sample diffusing onto a detection surface but instead they will depend on the use of electric fields to manipulate the particles and the fluid in which they are suspended, therefore reducing the required minimum concentration for detection.

Investigations into the stability of nanoparticle traps formed in parallel electrode arrays by joint DEP and ACEO have shown that there is trapping both at positive and negative DEP which changes form as the particle size varies [2] [3]. This is an important phenomenon with many applications, such as in sensor devices where one needs to selectively trap and manipulate nanoparticles for detection purposes. What is also important is that the method can operate at very small scales and can be used for mass processing of a sample, in contrast to mechanical methods.

The trapping and manipulation of nanoparticles by joint ACEO and DEP is investigated in this paper. The combination of DEP with AC electrokinetic methods (ACEO and Electrothermal) is a very promising technique due to the properties of each phenomenon. DEP is very strong close to the electrodes and can trap the particles once there, while ACEO or Electrothermal phenomena have a longer reach due to the fact that they mobilise the surrounding fluid. The current state of the art uses combined ACEO with DEP [4] [5] [6] or combined Electrothermal with DEP [1] [7].
In this paper, nanoparticles are used in a solution over an array of parallel or configurable asymmetric electrodes [8] and a potential is applied on the electrodes, to cause the DEP force on the particles and induce the ACEO fluid motion. The concept of nanoparticle trapping by joint DEP and ACEO is extended in this work by using a configurable asymmetric electrode system to create stable trapping zones of which the location can be changed by altering the electrode excitation. These zones are observed at the location where an electrode of finite height meets the substrate, instead of the electrode edge as ACEO is also strong at the edge and hence carries the particles away.

2. Theory

The DEP force is given by

$$F_{\text{DEP}} = \frac{Vol \times \epsilon_m \times Re(Cm) \times \nabla E^2}{4}$$

where $Re(Cm)$ is the real part of the Clausius-Mossotti factor of the medium-particle system, $Vol$ is the particle volume and $E$ the peak electric field applied.

In order to obtain the effect of ACEO, Poisson’s equation for the potential is solved, and the potential at the edge of the double layer is given by [9]

$$\sigma \nabla \phi_{ep} = \frac{\phi_{ep} - V_0}{Z_{DL}}$$

where $\phi_{ep}$ is the potential at the edge of the electrical double layer, $\sigma$ the fluid electrical conductivity, $V_0$ the absolute value of the voltage applied at the electrodes, $Z_{DL}$ the impedance of the double layer, $C_{DL}$ the capacitance of the double layer, $\omega$ the angular frequency of the electric field and $\lambda_{Debye}$ the Debye length. A coupled Navier Stokes model is solved to find the resulting fluid flow (under no external forces on the fluid).

3. Results

In this investigation a device is simulated that consists of an array of identical parallel electrodes 20 $\mu m$ wide and placed 20 $\mu m$ apart. A potential is applied on the electrodes and as a result a dielectrophoretic force is exerted on the particles in the fluid. The fluid is mobilized by the AC electroosmotic phenomenon, and therefore through drag a force is also exerted on the particles. The important feature that is of interest here is the particle radius at which the stable DEP/ACEO traps form over the electrodes, which are defined as the points where the particle velocity is zero. The stable trapping points are those with restoring velocity near the point, whereas unstable are the points for which if the particle moves even by an infinitesimal degree away from the point, it will be carried away from the point.

3.1. Positive DEP

In this part of the work, the voltage settings are 5 $V$, 10 $kHz$. The particle radius is varied and the flows shown in figure 1 are observed. In figure 1 (a) it can be seen that for particle radius of $a = 0.1 \mu m$ there are two unstable trapping points formed inside the ACEO whirls. The points here are formed because ACEO is dominant at lower particle radii as it does not scale with particle radius while DEP scales with the particle volume. The points are unstable for positive DEP because when the particle is disturbed (say by Brownian motion) from the zero velocity point, it will move towards the electrodes. Therefore the instability is in the vertical direction. This is not the case for negative DEP, where the DEP and ACEO also balance in the vertical direction, therefore making these trapping points stable. As the particle radius increases, the trapping point moves towards the electrodes. The ACEO-induced velocity is constant, therefore
Figure 1. Plot of overall velocity of a particle at (a) 10 kHz for particle radius $a = 0.1 \mu m$, (b) $a = 2 \mu m$. (c) Plot of the unstable trapping point (point where the curves cross the x-axis) movement as the particle size changes from 0.1 – 2.5 $\mu m$. (d) Plot of the stable trapping point over electrode at 10 kHz, for particle radius 900 nm and electrode excitation of 0.5 V.

as the particle gets larger the positive DEP has a longer reach and the trapping point will move further away from the electrode, as seen in figures 1 (b) and (c). The meaning of this is that for all points vertically above the electrode center and closer to the electrode than this point, the velocity field is pointing vertically downwards, and therefore the particle will move towards the electrode.

In this investigation, it was also found that a situation arises in positive DEP where a stable trapping point forms on the electrode surface in the middle, as shown in figure 1 (d). This situation arises when DEP is stronger than ACEO in the vertical direction and ACEO is stronger in the horizontal direction. The same phenomenon has also been observed in [3], where diffusion is not taken into account.

3.2. Asymmetric electrodes
Trapping is also investigated for the case of configurable asymmetric electrodes. The system is described in detail in [8] and consists of arrays of three identical electrodes. The grouping of electrodes in terms of excitation creates an asymmetry that is configurable. For example, if the two electrodes on the left are grouped together the asymmetry is reversed from the case where the two electrodes on the right are set at the same AC potential. This method of configurable
asymmetry has already been demonstrated to be capable of creating a reversible pumping effect. Here it is demonstrated that it can be used to create stable trapping points whose position can be changed by altering the electrode grouping.

3.3. Asymmetric electrode simulation for the concentration of finite size particles

It is of great interest to describe not only the velocity field for a particle, but also the concentration distribution of an ensemble of particles of finite size, taking into account that some diffusion is present. To describe the particle concentration one may use the Smoluchowski equation, as described in [10].

The particles described in the previous section are large enough for diffusion to be very small compared to the velocities induced here. This causes two major problems in the simulation of the concentration for such a system. The first one is that the very high spatial concentrations require the use of a very high number of mesh points. The second problem is that in the Smoluchowski equation, the finite size of the particles, and therefore the maximum possible volume fraction of particles at close packing is not taken into account. In order to avoid the above issues, some modifications have been implemented. Firstly, a function is applied that multiplies the DEP velocity so that it takes into account the fact that as particles come close to maximum close packing, their velocity decreases. Secondly, the diffusion constant is modified to include a step function which introduces large diffusion in the system so that the concentration does not exceed the value of \( C = 0.64 \) for maximum close packing of spheres [11].

These modifications effectively limit the maximum concentration and achieve convergence without compromising the physical insight. The results obtained for an initial volume fraction of \( 1 \times 10^{-4} \) of 600 nm radius particles under the same parameters as in the previous section are displayed in figure 2 for the symmetric and asymmetric excitation of the electrodes, after they have reached steady state. The main distinguishing features are that the particles are not trapped at the electrode centre in the symmetric excitation, as shown in figure 2, and that in both cases the particles are trapped at the interface between the electrode and the substrate and not at the electrode edges. This can be attributed to the fact that while DEP is strongest at the electrode edge, so is ACEO, therefore carrying the particles away (an issue that is pointed out in [12] as a possible disadvantage when using ACEO to collect particles to sensor surfaces located at the electrode edges). In relation to the trapping at the electrode centre, taking diffusion into

![Figure 2](image_url). Volume fraction of particles of 600 nm particle radius at 10 kHz, 0.5 V under both DEP and ACEO at a) steady state symmetric excitation and b) at steady state asymmetric excitation, where electrodes 1 and 2 are in-phase.
account makes trapping at the electrode centres disappear for this system. It must be noted that these observations are valid for the system examined subject to these particular parameters. The observation that particles gather preferentially to one side due to higher DEP in that region, can be useful for many applications, such as moving a particle to different sensor surfaces in sequence or assembling different particles to different positions on a surface.

4. Conclusions
A numerical model was used here to investigate the existence and behaviour of trapping points in parallel electrode and configurable asymmetric electrode systems, under the combined influence of positive DEP and ACEO.

It was found that using a configurable asymmetric system it might be possible to trap particles either in a symmetric or an asymmetric manner, with the degree of precision and flexibility being related to the device characteristic scale and number of electrodes in an array. Therefore, such a system might be useful in devices where small scale precision manipulation of particles is required, such as in sensor devices.

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