Control of particles using multi-frequency DEP

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ABSTRACT

We present numerical simulations and experiments on dielectrophoretic (DEP) separation and trapping performed in a titanium-based microchannel linear electrode array. The device is designed to allow for effects driven by inhomogeneities in electric-field magnitude driven (p-DEP and n-DEP) and inhomogeneities in electric-field phase-driven (travelling wave) DEP. It is also capable of inducing multi-frequency DEP, in contrast with most of the previous, single-frequency, designs. The advantages of two-frequency DEP were shown by theoretical work (Chang et al. 2003) and permit precise control of particles movements. We show that fluid flow effects are substantial and can affect the particle motion in a positive (enhanced trapping) and negative (trapping when separation is desired) way. To model the AC-electroosmosis, we use the theory developed by Gonzalez et al.

Keywords: dielectrophoresis, multi-frequency, electroosmosis, bioparticles

1 INTRODUCTION

The use of electric field and in particular dielectrophoresis (DEP) have a great potential to help miniaturize and increase the speed of biomedical analysis [6]. Indeed, precise control and manipulation of micro/nano/bio particles inside those miniaturized devices depend greatly on our understanding of the phenomena induced by AC electric field inside microchannels and how we take advantage of them.

It is well known that an electric field induces a dipole in an uncharged particle and the interaction between the dipole and a nonuniform electric field generates a force on the particle. The resultant motion is called dielectrophoresis. Dielectrophoresis is an efficient and increasingly popular method for separating particles according to their electrical properties, one of the generic operation needed for biochemical analysis. In this paper, we will show experiments where the use of multi-frequency DEP permitted the separation of two entities when single-frequency DEP could not. The use of multi-frequency DEP to improve separation techniques was suggested in [2] through a systems theory approach of dielectrophoresis. This intriguing idea is thanks to this paper validated by a specific experimentation. However, knowing the theory of dielectrophoresis is not enough to precisely control particles by an AC electric field. We also need to study the induced fluid flow: AC electroosmosis and thermal effect. Theoretical predictions of AC electroosmosis in the case of electrodes separated by small gap has been carried out, for example by Ramos et al in [3]. Nevertheless the available results are not valid for our device which consists of arrays of electrodes separated by a large gap. We present here numerical results for the AC electroosmosis characteristics of our device.

This paper is organized as follows. In §II, we develop basic theoretical ideas and give some numerical results. In §III, we present the experimental set-up and results.

2 BASIC THEORY AND NUMERICAL RESULTS

2.1 Electrical force on particles: dielectrophoresis

The essential idea begins with the observation that the induced dipole moment, $\mathbf{m}(\mathbf{x},t)$, in a particle due to an external electric field of frequency ω, $\mathbf{E}(\mathbf{x},t)$, depends linearly on the electric field [4], where $\mathbf{x}$ is a spatial variable. This relation can be written as:

$$\mathbf{m}(\mathbf{x},t) = G(\omega)\mathbf{E}(\mathbf{x},t) \quad (1)$$

For example, when a spherical particle with the permittivity ϵ_p, the conductivity σ_p and radius r, lies in a medium with the permittivity ϵ_m and the conductivity σ_m, the function $G(i\omega)$ is given by

$$G(i\omega) = 4\pi r^3 \epsilon_m \frac{\left(\epsilon_p + \frac{\sigma_p}{i\omega}\right) - \left(\epsilon_m + \frac{\sigma_m}{i\omega}\right)}{\left(\epsilon_p + \frac{\sigma_p}{i\omega}\right) + 2\left(\epsilon_m + \frac{\sigma_m}{i\omega}\right)} \quad (2)$$

where $G(i\omega)/(4\pi r^3\epsilon_m)$ is called the Clausius-Mossotti function [4]. The dielectrophoretic force, $\mathbf{F}_{\text{dep}}$, on the particle due to the interaction between the induced dipole and the electric field, is given by

$$\mathbf{F}_{\text{dep}}(\mathbf{x},t) = (\mathbf{m}(\mathbf{x},t)\cdot\nabla)\mathbf{E}(\mathbf{x},t). \quad (3)$$

Let us now consider the following form of electric field:

$$\mathbf{E}(\mathbf{x},t) = \mathbf{E}_1(\mathbf{x})u(t). \tag{4}$$

For convenience, we assume that $u(t)$ is periodic of some period, $T = \frac{2\pi}{\omega}$, so that we can Fourier-expand it as follows:

$$u(t) = a_0 + \sum_{n=1}^{\infty}(a_n \cos(n\omega t) + b_n \sin(n\omega t)). \tag{5}$$

It follows from [2] that the averaged dielectric force is:

$$\langle \mathbf{F}_{\text{dep}} \rangle (q) = C(u) \times \nabla |\mathbf{E}_1(q)|^2 \tag{6}$$

where

$$C(u) = \frac{1}{2}G(0)a_0^2 + \sum_{n=1}^{\infty}\frac{1}{4}Re[G(jn\omega)](a_n^2 + b_n^2). \tag{7}$$

In the case of a periodic array of interdigitated microelectrodes, the dielectric force is such that the particles with $C(u) > 0$ get attracted to the edge of the electrodes, and the particles with $C(u) < 0$ get repelled away from the electrodes. Let us consider signals which are the sum of two sinusoidal waves with different frequencies as follows:

$$u(t) = \frac{1}{\sqrt{2}}\left(cos(\omega_1 t) + cos(\omega_2 t)\right) \tag{8}$$

To achieve the separation of two types of particles A and B, we need to choose a pair of frequencies, ω_1 and ω_2, that produces the dielectric forces in (6) with:

$$\begin{cases} Re[G_A(j\omega_1) + G_A(j\omega_2)] < 0, \\ Re[G_B(j\omega_1) + G_B(j\omega_2)] > 0. \end{cases} \tag{9}$$

Then, the dielectric force on type A and type B have opposite directions. Particles of type A get away from the electrodes and particles of type B get attracted to the electrodes. This technique of separation of particles with multi-frequency DEP was achieved in the experiment described in §III.

2.2 Fluid flow due to AC-electroosmosis

Electrical forces also act on the fluid and indirectly cause particle movement through the Stokes force. When applying an AC electric field in a fluid, two phenomena have been identified: AC-electroosmosis and electrothermal fluid flow. We focus here on AC-electroosmosis which has not been well studied in the case of large gap between electrodes. We exploited the theoretical approach using double layer analysis described in [5] to design a numerical simulation with Femlab3.1 to predict the fluid flow due to AC-electroosmosis in our device. The results in Fig. (1) give us an appropriate idea about the flow shape and strength. Due to the size of the particles used in the experiments, the DEP force is dominant with respect to the AC-electroosmosis effect.

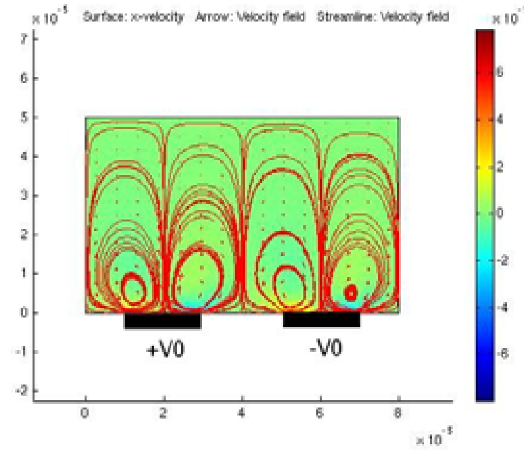

Figure 1: AC electroosmosis fluid velocity vector field. Streamline and contour of the velocity values in the x-direction with a frequency of 1kHz.

3 EXPERIMENTAL RESULTS

We present an experiment where dielectrophoretic forces are used to separate particles based on their properties such as permittivity and conductivity. In order to achieve our goal we use multiple-frequency dielectrophoresis. In this paper we present preliminarily results where two frequencies are used to separate particles.

3.1 Experimental set-up

The experiment was conducted using the titanium based dielectrophoresis channel described in [6]. The bulk titanium-based DEP device consists of two components, the Electrode Substrate and the Channel Die.

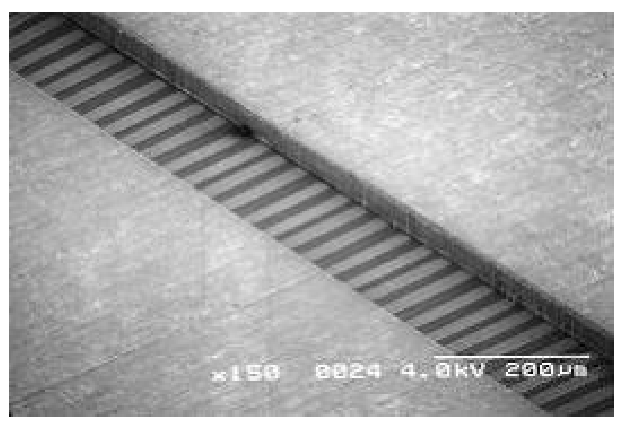

Figure 2: SEM image of the titanium DEP chip where 24 parallel electrodes sit underneath the Titanium Channel Die.

The Electrode Substrate is fabricated by patterning two layers of titanium electrodes onto a silicon dioxide covered thick bulk titanium substrate. Large fluid reservoirs (2 mm in diameter) are then machined through the bottom of the substrate using traditional macromachining methods (i.e. drilling) to provide fluidic interconnection to Fluid Supply Stage. The Channel Die is formed by through-etching thin titanium foil (25 μm thick). Then a 7 μm thick photo-BCB polymer layer was patterned on top of the Electrode Substrate and on one side of the Channel Die to form the bond. The scanning electron microscope image of the chip is shown in Fig. (2). Fig. (3) illustrates the assembled device.

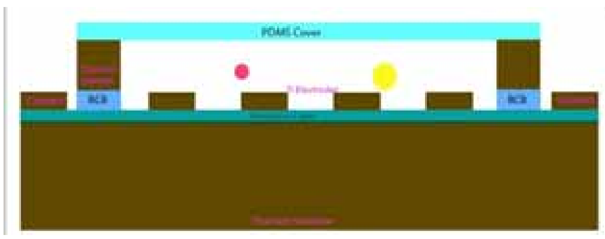

Figure 3: Schematic of the titanium DEP Chip (each electrode is 20 μm wide and 0.5 μm thick).

The AC electric field is provided by a function generator (Wavetek model21) allowing a frequency range up to 11MHz. The DEP properties are analyzed using an epifluorescent microscope (Nikon eclipse), a 20X water immersion lens and a CCD camera Hamamatsu (C7300 10 12NRP). For multiple frequencies, a signal adder was constructed in the lab. The particles used are polystyrene spheres (Duke Scientific) of density ($1.05 g.cm^3$) close to the water to avoid any sedimentation. The particles are coated with fluorescent dye. Each dye has different conductivity properties. Thus the conductivity varies with particle size. We use two particle sizes of nominal diameter 0.71 μm and 1.9 μm. The solution used for the experiment is a dilution of particles into deionized water (initial conductivity of $2\mu S.cm^{-1}$). The final solution has the same concentration of each type of particle. Its conductivity is $13\mu S.cm^{-1}$. The concentration is set to have 4 particles of each size in $10^3 \mu m^3$. Before each experiment the channel is filled with the solution using a syringe pump (Harvard Apparatus 2000) and the flow is stabilized.

3.2 Use of single and multiple frequencies

Before using multiple frequencies, the experiment was run with a single frequency. At 100 KHz both particle sizes undergo positive-DEP. They are attracted towards the electrodes. At 1 MHz they undergo negative-DEP. Fig. (4) shows the channel filled with particles without external electric field. Big particles appear brighter. The focus plane, is in the plane of the electrodes. There is no flow in the channel, the particle motion is only due to the Brownian agitation.

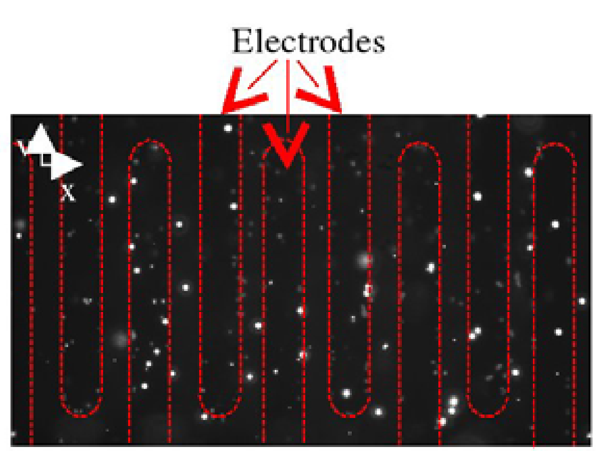

Figure 4: Top view of the channel filled with particles. The electric field is off.

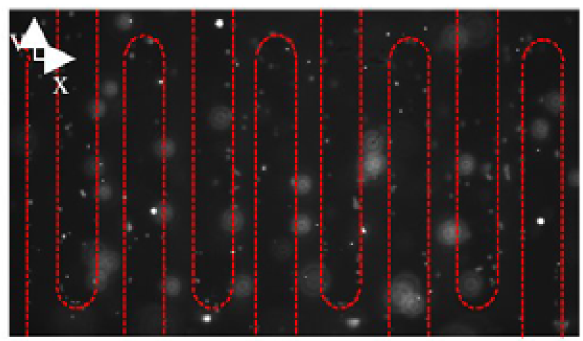

Figure 5: Top view of the channel filled with particles. The electric field is on.

Fig. (5) shows the particle distribution 0.5s after the electric field was turned on. Big particles are moving away from the electrodes. They appear out of focus because they are moving in the vertical direction. Smaller particles are moving towards the electrodes. Positive DEP forces move smaller particles to the electrode edges, as they correspond to highest field gradients. Small and big particles are then separated.

Fig. (6) is a drawing of the particle motion in the x-z plane. Fig. (5) shows some big particles still in the electrode plane. These particles did not move because they became chemically bonded to the electrodes surface before the electric field was applied.

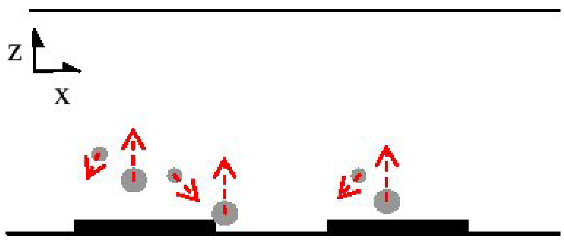

Figure 6: Drawing. Side view of the channel. In black are the electrodes. Arrows show the particle motion. Electric field is on.

4 CONCLUSION

Here has been presented preliminarily experiments where we were able to separate particles based on their conduction properties (directly linked to their size) using double frequency dielectrophoresis. In this experiment, even if the DEP effect is dominant, electroosmosis and electrothermal effect are present and will be studied in more detail in future work.

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