DIELECTROPHORETIC FOCUSSING AND SEPARATION OF NANOPARTICLES: EXPERIMENTAL MEASUREMENT AND NUMERICAL SIMULATION

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ABSTRACT

This paper presents results of the focussing and separation of particles in microchannels using specially designed and integrated microelectrodes. The behaviour of a range of particle sizes, down to ~50nm, were numerically simulated in microchannels containing the electrodes. The results of the simulations were then compared with the experimental results and discussed with regard to both the underlying theory and the potential for developing design tools. The separation of mixtures of different sub-micrometre particle types in flow-through microelectrode structures was also demonstrated.

KEYWORDS

Dielectrophoresis, particle focussing, nanoparticles

1. INTRODUCTION

AC Electrokinetic methods can be used for the non-contact manipulation and separation of particles in suspension [1,2]. One of these methods: dielectrophoresis, involves the use of non-uniform AC electric fields to induce an effective dipole moment on the particle and, as a result of the imbalance in the force on the dipole, movement of the particle. The net force on the particle depends on the dielectric properties of the particle and the suspending medium, as well as the frequency of the applied field, providing a means of particle characterisation and identification [2]. Dielectrophoresis has been used on a wide range of particles, such as cells and bacteria, but more recently on sub-micrometre and nanoparticles such as viruses and DNA [1]. Dielectrophoresis has also found application in Micro Analysis Systems [3] as a manipulation and separation technology, both for particles [1,2] and microdroplets [4].

This paper presents experimental results of the focussing and separation of particles in microchannels using a variety of specially designed microelectrode geometries. A range of particle sizes were examined, down to the scale of viruses or protein macromolecules. Particles were both individually manipulated and focussed into particle streams. The separation of mixtures of different sub-micrometre particle types in flow-through microelectrode structures was also demonstrated.

2. THEORY

The behaviour of sub-micrometre particles in microfluidic devices was simulated using a custom Brownian dynamics code. The dielectrophoretic force is given by:

$$\langle \mathbf{F}_{DEP} \rangle = \frac{1}{4} \upsilon \, \mathrm{Re}[\tilde{\alpha}] \nabla |\mathbf{E}|^2 \quad (1)$$

where υ is the volume of the particle and $\tilde{\alpha}$ is the complex effective polarisability of the particle. It can be seen that the force depends on the volume of the particle (radius cubed) and the gradient of the field magnitude squared. Dielectrophoresis (DEP) on the sub-micrometre scale therefore requires a substantial electric field, in order to both produce appreciable particle motion and overcome the randomising effects of Brownian motion. The strong electric fields lead to induced fluid motion, specifically AC Electroosmosis [5] and Joule heating induced electrothermal flow [6]. The simulations of the dielectrophoretic devices included the complex nature of the coupled forces in the system.

The motion of particles was calculated by numerical simulation of the Langevin equation [1]

$$m \frac{d\mathbf{v}}{dt} = \mathbf{F} + \mathbf{u} - f\mathbf{v} \quad (2)$$

where m is the mass of the particle, f is the friction factor, **u** is the velocity of the fluid, **F** is the total force experienced by the particle and **v** is the velocity of the particle.

3. RESULTS AND DISCUSSION

The electrode array used in this work is similar to that shown in figure 1, consisting of two long thin electrodes. The AC potential is applied to one electrode and the other electrode is grounded. In the actual device, a microfluidic channel is fabricated along the electrode array to carry the suspension of particles. As can be seen from equation 1, the dielectrophoretic force depends on the gradient of the field magnitude squared and the real part of the polarisability. This can be either positive or negative depending on the dielectric properties of both the particle and the fluid, as well as the frequency of the applied field. The frequency of the applied field can therefore be adjusted to attract particles to regions of high field strength

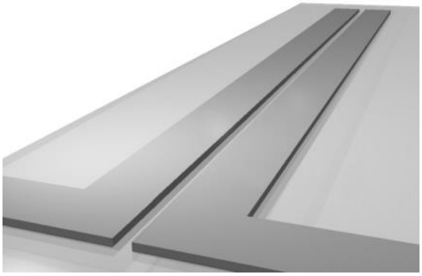

Figure 1. Schematic diagram of the microelectrode array

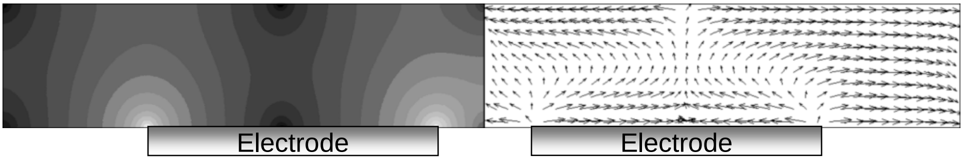

Figure 2. The numerically calculated field gradient term for the dielectrophoretic force, plotted as log base 10 of magnitude on the left and direction on the right. In this case, the direction vectors have been reversed to indicate the direction of negative dielectrophoresis

(positive DEP) or repel them from the same regions (negative DEP). Different particle types can experience the two types of DEP at the same frequency, allowing mixtures to be spatially separated. The device in this work is designed to produce particle focussing by means of negative DEP.

The dielectrophoretic force for the electrode array was calculated numerically using the FlexPDE™, a finite element partial differential equation solver. The method used can be found in the literature [1,6], with the electrical potential simulated for boundary conditions determined by the experimental geometry. In this work, since the electrodes are much longer than their width and have translational symmetry along their length, the problem is assumed to be two dimensional. The boundary conditions for the electrodes are assumed to be constant potential and zero, ignoring electrode polarisation effects [1]. The results of the calculation of the field gradient term in equation 1 are shown in figure 2 for an applied potential of 1. As can be seen from the figure, the DEP force is maximum ($10^{19}V^2m^{-3}$) close to the edges of the electrodes and falling off rapidly. The direction vectors (shown for negative DEP) indicate that the particles will be repelled from the two electrodes into the centre of the gap between them, in the centre of this figure. In addition, some particles will be repelled from the electrode array to the edges of the microfluidic channel.

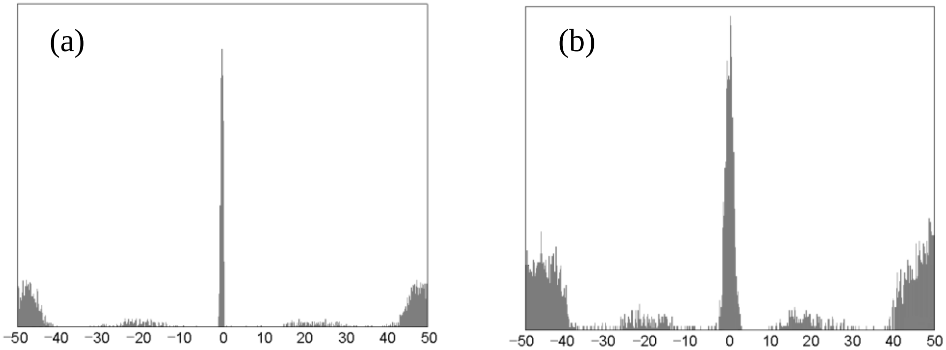

Figure 3. Steady state particle number versus distance in micrometres from the centre of the channel for (a) 100nm and (b) 50nm latex particles.

The results of the Brownian dynamics simulation of the particle motion over time are shown in figure 3 for particles of radius 100nm and 50nm. The plots show number versus distance across the electrode array at time infinity, which in the case of the simulations was for steady state distributions. The particles were assumed to be moving constantly at terminal velocity, since the momentum relaxation time for the particles is ~10^{-8}sec, which is much less than the time step in the simulation. As can be seen, the 100nm particles are more effectively focussed than the 50nm particles, which is to be expected since the force on them is 4 times larger. Figure 4 shows an experimental graph of intensity versus distance for 108nm radius latex particles, along with the numerical prediction. The predicted focussing is tighter than the experimental results, which is probably due to voltage drop along the electrodes.

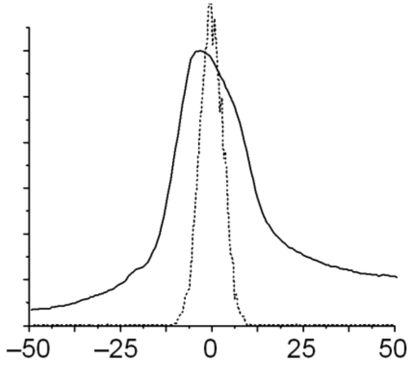

Figure 4. Comparison of numerical (dashed) and experimental (solid) results.

4. CONCLUSION

The focussing of sub-micrometre particles by dielectrophoresis in microelectrodes has been simulated numerically. Comparison with experimental results shows that the predicted behaviour overestimates the focussing produced by the microelectrode array.

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