Experiments and simulation of a dielectrophoretically oscillating microparticle

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Abstract Understanding the hydrodynamic interactions between a fluid dynamics and a particle in suspension is important for a variety of hydrodynamic phenomena. Such observations at the microfluidic scale are important to understand critical biological particle-fluid interactions, for example oceanic microorganisms like phytoplankton or physiological cells like erythrocytes. Here, a simple single-particle dielectrophoretic chip is fabricated from commercially available components. The trapping and preliminary experimental observation of a single 10.1 µm diameter spherical particle in a microfluidic channel is demonstrated. Numerical simulation of the dielectrophoretically agitated microparticle is compared to experimental observation. Results and challenges of incorporating micro-resolution particle image velocimetry (µPIV) with this electrokinetic agitation technique is discussed.

1. Introduction

A complete understanding of fluid-particle interactions is important in understanding the dynamics between biological microorganisms and their environment. It is necessary to observe these and similar particles in suspension in order for a complete investigation of particle-fluid interactions. However, previous investigations of cellular response to fluid flow have limited their analysis to rigidly adhered cells to the wall of microchannels (Pommer and Meinhart 2005; Leyton-Mange et al. 2006). These type of experiments are not representative of their biological environments where the bioparticle (for example: red blood cells or phytoplankton) are freely suspended within the liquid. Rather, observation of suspended particles would better resemble their environment. Further, if these suspended particles could undergo experimentally-controlled translation within the fluid (while remaining in suspension), additional time-transient microfluidic phenomena could be observed. The technique described herein involves a dielectrophoretic technique to trap and translate a particle within a microchannel. Flow visualization including µPIV have been incorporated to enable hydrodynamic investigations. A spherical polystyrene bead 10.1 µm in diameter is trapped in suspension within a microchannel with DEP forces. For this investigation the trapped particle is translated laterally in a periodic manner, oscillating a distance of approximately 40 µm at a velocity which is proportional to voltage squared.

µPIV is an established method enabling fluidic velocimetry measurements with sub-micrometer resolution (Santiago et al. 1998). In brief, the positions of illuminating tracer particles are recorded and their displacement between successive images is obtained through correlation methods. Fluid velocity fields are acquired from mathematical correlations between successive image pairs. µPIV has been used previously to investigate cellular mechanisms in response to fluid flow, specifically their response to shear (Pommer and Meinhart 2005; Leyton-Mange et al. 2006).

There are challenges with the incorporation of µPIV techniques with the visualization of a suspended particle. Usually a particle trapping technique, like optical tweezers, can be used to hold the particle within the observation area. Optical tweezers utilize highly focused lasers to generate attractive or repulsive forces resulting from refractive index mismatching (Ashkin et al. 1987). By dynamically and precisely manipulating the illumination, one can capture and position multiple particles in suspension within a microchannel (Grier 2003). Optical tweezers and µPIV have been simultaneously applied to investigate fluid flow around particles in suspension (Neve et al. 2008), a
technique the investigators have termed µ-PIVOT. If the optically trapped particle is large with respect to the focused laser spot, the surrounding tracer particles are unaffected. However, as the size of the particle becomes small (< 10 µm) the tracer particles in close proximity to the laser spot become influenced by the optical trapping forces. In addition, some optical trapping system configurations are such that the viewing plane and optical trapping plane are synonymous, thus µPIV analysis would be restricted to the optical trapping plane. In general, optical trapping systems are relatively more expensive than electrokinetic lab-on-a-chip units.

An alternative particle trapping technique that has been widely used on the microscale is dielectrophoresis (DEP). Dielectrophoresis refers to the electrokinetic forces generated when an electrically neutral particle is polarized when subjected to a non-uniform electric field. Early experiments were conducted by H.A. Pohl (Pohl 1978) and its theory and applications are covered extensively elsewhere (Jones 1995; Morgan and Green 2003). A conducting, electrically neutral particle will induce a dipole in the direction of the applied electric field. The magnitude and charge orientation of the induced dipole depends on the dielectric properties of both the fluid and the particle as well as the frequency of the applied AC field. In a non-uniform electric field the induced charges on the particle are unbalanced, resulting in unbalanced electrokinetic forces and subsequent particle translation. Due to the small size of the electrodes (micrometers) the relatively large electric field strength can be applied with moderate signal magnitudes. Dielectrophoretic AC signals usually have frequencies typically greater than 100 kHz and magnitudes below 20 V pk-pk (Volts peak-to-peak).

The dielectrophoretic force for a homogenous, spherical particle is expressed as

\[
\langle F_{\text{DEP}} \rangle = \pi \varepsilon_m r^3 \text{Re} \left( \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*} \right) \nabla |E|^2
\]

where \( r \) is the radius of the particle, \( \varepsilon \) is the permittivity of the medium (\( m \)) or particle (\( p \)), \( E \) is the electric field, and the asterisk denotes the complex permittivity, \( \varepsilon^* = \varepsilon_r \varepsilon_i - i \sigma / \omega \), with conductivity \( \sigma \), relative permittivity \( \varepsilon_r \), permittivity of free space \( \varepsilon_0 \), and applied frequency \( \omega = 2\pi f \). The DEP force is a function of frequency and the dielectric properties of the medium and particle. The bracketed term in the above equation is called the Clausius Mossotti factor, and its real part has a value from -0.5 to 1.0. Particles that experience positive DEP, or a positive value of the Clausius Mossotti factor, are attracted to areas of high electric field gradients. Particles experiencing negative DEP are repelled from these regions. Negative DEP forces are typically used to trap a suspended particle within a microchannel typically using a three-dimensional arrangement of electrodes (as we have done herein). Examples of DEP electrode geometries for trapping suspended particles include octopole traps (Schnelle et al. 1993; Schnelle et al. 2000), interdigitated arrays (Suehiro and Pethig 1998), and electroplated quadrupole pillars (Voldman et al. 2003).

The above DEP force calculation assumes that the trapped particle is homogeneous and spherical. Biological particles, though, are neither homogenous nor spherical, although there are simplified ellipsoidal and shelled models that can be used (Jones 1995; Morgan and Green 2003). For single-particle DEP traps, higher order multipoles (quadrupoles, octopoles) need to be considered for more accurate analyses (Washizu and Jones 1994). In one specific application using DEP as a biological filter, taking these higher order poles into numerical simulation accounted for 20% increase in trapping forces (Li et al. 2005). Further, multipole DEP analysis for non-spherical particles has been shown in a work by N. Green and T. Jones (Green and Jones 2007) in which the drawbacks of the “spherical assumption” of particles are discussed.

From the above equation, DEP forces are proportional to the square of the applied voltage and the cube of the particle radius. If tracer particles for µPIV are at least ten times less in diameter
than the trapped particle, then the DEP forces exerted on them will be over one thousand times greater. Therefore a proper voltage could be applied to minimize electrokinetic effects on the tracer particles. However, there are additional AC electrokinetic mechanisms that occur that will induce fluid motion and could potentially disrupt PIV measurements. These issues will be discussed later within this manuscript.

2. Materials and Methods

The experimental chip used for the dielectrophoretic trapping and controlled agitation of a single 10.1 µm microparticle was created from commercially available components. The three-dimensional electrode configuration is illustrated in Figure 1a with the image of the final chip shown in Fig. 1b. The device was constructed of two identical glass chips (0.71 mm thick) with patterned indium tin oxide (ITO) electrodes. The microelectrodes were independently addressable strips 20 µm wide with a 20 µm pitch. The ability to independently address each electrode is necessary for the controlled translation of a trapped particle. The translation of individual particles using a simple three-dimensional arrangement of independently addressable electrode strips has been previously realized (Suehiro and Pethig 1998). The ITO chips used here were commercially available (ABTECH Scientific Inc.); although gold or platinum electrodes could have been selected, ITO was chosen based on its transparent characteristics which aid in µPIV analyses. Fluidic ports were manually drilled and a microchannel was manually cut from double-sided adhesive tape (Adhesive Research Inc.) and provided a 50 µm space between the substrates. The microchannel was approximately 2 mm wide and ran perpendicular to the length of the electrode strips.

Each electrode was either grounded (-) or had an AC signal (0-25 Vpk-pk, 2.0 MHz) applied (+), as illustrated in Fig. 1a. The inside electrode pair on the bottom substrate were oppositely polarized to trap a particle suspended above one of these electrode strips. The trapped particle was oscillated by simultaneously switching the polarity of the inside electrode pair, resulting in particle translation to the adjacent interior electrode. In order to precisely control the oscillation of the DEP trapped particle, a multiplexer (MAX333A) was used and controlled with a pulse generator (BNC 500).

The medium was prepared by adding 50 µL of a solution containing 0.1% solids of 10.1 µm polystyrene particles (Duke Scientific) to 1.0 mL of DI water. For µPIV experiments 50 µL of a solution containing 2.0% solids of 300 nm red fluorescent particles (Duke Scientific) were added to the same 1.0 mL sample.

Experiments were conducted in a standard µPIV setup consisted of an inverted Nikon TE2000U microscope equipped with a Nikon 60X water-immersion objective lens (0.8 NA and 2.0 mm working distance). An interline transfer Charge Coupled Device (CCD) camera (PCO 1600) with a 7.4 µm x 7.4 µm pixel pitch was used with PCO Camware to acquire images. For DEP-agitation experiments, images were acquired at a rate of 15 frames per second. For µPIV experiments, images were acquired every 0.12 seconds. µPIV images were analyzed with a software package called Enhanced Digital Particle Image Velocimetry (EDPIV), developed by Dr. Lichuan Gui (Gui and Merzkirch 1998).

3. Numerical Simulation

COMSOL Multiphysics was used for numerical modeling of the electrokinetic chip (Fig. 1a) to determine the electric field. Electric field data was exported to MATLAB where dielectrophoretic forces from induced dipoles, quadropoles, and octopoles were calculated. DEP forces as well as hydrodynamic drag were incorporated into a program to track a particle when the electrode polarization (Fig. 1a) were switched. This numerical data will be compared to experimental results.
The problem space and boundary conditions for the electrical problem is modeled similarly to work by Green, et al. (Green et al. 2001). The electrical problem is bounded to within the fluid medium. The Laplace equation for a potential ($\phi$) in a homogeneous medium is first solved with (Green et al. 2001)

$$\nabla^2 \phi = 0, \quad E = -\nabla \phi$$

The first order (dipole) DEP force approximation is not sufficient for when the trapped particle is close to electrode edges, the particle diameter is on the order of the electrode length scale, and/or when the particle is at a field null. The later is the case when a particle is captured with negative DEP forces. Higher order moments are accounted for with (Washizu and Jones 1994)

$$\vec{F}_{total} = \sum_{0}^{\infty} \vec{F}_n = \sum_{0}^{\infty} -\nabla U_n$$

where $n$ refers to the force order ($n=1$ dipole, $n=2$ quadrupole, $n=3$ octopole, ...) and

$$U_n = -\frac{2\pi \epsilon_0 \epsilon_m K_n (2n+1)!}{(2n+1)!!} \sum_{i+j+k=n} \frac{1}{i!j!k!} \left[ \frac{\partial^2 \phi}{\partial x^i \partial y^j \partial z^k} \right]^2$$

where $K_n$ is the $n$th-order Clausius Mossotti factor this analysis. From electric field, the dielectrophoretic force was calculated with

$$K_n = \frac{n(2n+1)(\epsilon_m^* - \epsilon_p^*)}{n\epsilon_p^* + (n+1)\epsilon_m^*}$$

Within the model an assumption was made that the complex permittivity of the medium is much greater than that of the particle ($\epsilon_m^* >> \epsilon_p^*$). This will generate the greatest negative dielectrophoretic force, where $K_n$ has the most negative value. This assumption is feasible especially for biological samples were culture media has a larger conductivity than cells.

Stoke’s drag will influence the velocity of the particle and has been included within the numerical model. At low Reynolds number, Stoke’s drag for a sphere is given as $F_D = 6 \pi \eta r V$ where $V$ is the velocity of the fluid and $\eta$ is the fluid viscosity. However, there is a correction factor that needs to be included to account for the geometry of the particle and the microchannel. The diameter of the particle (10.1 $\mu$m) is on the order of the height of the microchannel (50 $\mu$m). The hydrodynamic drag incurred is influenced by these geometries as well as the particle’s location between these parallel plates. Using an analysis by Ganatos et al. (1980), it was determined that there was an additional 25% increase in Stoke’s drag.

4. Results

The experimental trapping of a captured 10.1 $\mu$m particle and its final location after translation is demonstrated in Figure 2. This process is completely reversible, the particle can return to its original position by switching back the polarity of the electrodes. By altering the applied voltage and timing of the multiplexer, the particle oscillation period between trapping locations could be controlled. Due to limitations of available equipment, a maximum voltage of 20 volts peak-to-peak was experimentally tested resulting in an oscillation period of 2 seconds. Its speed could be increased by (i) using a signal amplifier, (ii) oscillating a larger particle as the DEP forces scales with its radius cubed, or (iii) utilize smaller electrodes which will generate sharper electric field gradients, increasing DEP forces.

The particle also translated in a straight-line path (Fig. 2), it travelled vertically to its new trapped location. However, the particle would drift due to unwanted fluid drag from bulk fluid motion and careful preparations was made to prevent this from occurring. Due to its straight-line...
trajectory, the numerical analysis was simplified to a two-dimensional analysis. A three-
dimensional model was used to obtain the resultant electric field. The electric field along the plane
of particle motion was used to calculate dielectrophoretic forces and subsequent particle motion.

The half-cycle of particle translation was experimentally observed for an applied voltage of
20 volts peak-to-peak and compared to numerical simulations (Figure 3). It takes approximately one
second for the particle to translate its half-cycle distance of 40 µm. This particle experiences near-
constant velocity during the middle half of this translation. The velocity for this translation was
extracted from a linear slope fit of its position data (Fig. 3) and plotted against applied voltage in
Figure 4. Each trial of five applied voltages was repeated at least three times. This data suggests that
the particle velocity is proportional to voltage squared ($V^2$), which is consistent with dipole theory.

In order to properly analyze particle translation with µPIV, it is important to minimize out-
of-plane particle motion. No out-of-plane motion was visually observed experimentally as the
particle translated. However, the out-of-plane motion from numerical simulations is plotted in
Figure 5. The maximum calculated out-of-plane distance is 1.58 µm, although the majority of its
translation occurs within 0.5 µm of its initial starting plane.

Next, fluorescent polystyrene particles (300 nm) were introduced for µPIV investigations
of fluid flow around a DEP trapped particle. Figure 6 shows the x- and y-velocity components of
µPIV measurements from bulk fluid flow ($V_{ave} = 26$ µm/s) around a DEP captured, suspended 10.1
µm particle and compared with computer simulated results.

The influence of DEP forces on tracer particles is minimal when compared to the trapped
particle. DEP forces are proportional to particle volume, such that the force exerted on a 10.1 µm
particle is over 38,000 times greater than that of a 0.3 µm particle. Therefore, for moderately
applied voltages tracer particles will remain unaffected by DEP forces and instead follow fluid
motion. However, there are additional electrokinetic hydrodynamic phenomena that occurred that
need to be addressed.

The first is electrothermal in nature. An applied electric field will heat an aqueous medium
(Joule Heating) and temperature gradients are produced. The electric field will interact with
gradients in the fluid’s permittivity and conductivity as a result of Joule heating, inducing fluid motion
(Ramos et al. 1998; Green et al. 2001). A numerical analysis similar to previous investigations
(Ramos et al. 1998; Green et al. 2001; Williams et al. 2008) has been used to
determine the temperature gradient and subsequent fluid motion from electrothermal fluid motion.
It has been shown that the location of particles trapped with DEP are influenced by this fluid motion
(Green et al. 2000). However, the DEP force will be the dominant force for larger particles as DEP
is proportional to radius cubed ($r^3$) while fluid drag is proportional to radius ($r$), assuming Stokes
Drag. However, for smaller particles photobleaching becomes problematic especially if there is no
bulk fluid motion and fresh tracer particles are introduced into the measurement region (for
oscillating particle experiments). Alternatively, the tracer particle could chosen such that at a
particular AC frequency the DEP trapped particle of interest experiences negative DEP forces
(Clausius Mossotti factor < 0) while the tracer particles experience minimum DEP forces (Clausius
Mossotti factor ~ 0).

It was observed that motion of tracer particles was significantly affected by electrothermal
fluid motion when the applied voltage was increased. The maximum fluid motion occurred near the
edge of the electrode strip. Electrothermal fluid motion is proportional to $\sigma V^4$ due to Joule heating
of the fluid being proportional to $\sigma V^2$ (Ramos et al. 1998; Green et al. 2001). These unwanted
effects can be minimized with low medium conductivity. However, this system may prove
problematic with biologically-relevant media whose high conductivity can lead to significant
increased temperatures. Further, to reduce electrothermal fluid motion the applied voltage should
not be much greater than that necessary to successfully trap a particle with DEP at the expense of
reduced oscillation velocity.

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The second AC electrokinetic mechanism that induces fluid motion is termed AC electroosmosis (ACEO) and refers to the electrokinetic pumping of ionic fluids (Ajdari 2000; Studer et al. 2004). The tangential component of the electric field near the electrode interface acts upon charges in the ionic double layer, resulting in fluid motion. Fluid velocities in the order of millimeters per second can be achieved with an applied potential of a few volts (Studer et al. 2004). However, particles are not influenced by ACEO at frequencies below 0.5 MHz (Ramos et al. 1998) and therefore ACEO is significant from this DEP oscillation experiment.

5. Conclusions

A system capable of dielectrophoretic trapping and oscillation of microparticles has been demonstrated. Preliminary investigations with a 10.1 µm particle herein are critical for future biologically relevant adaptations and subsequent μPIV analyses. Hydrodynamic fluid-particle interactions can be investigated with a static or oscillating particle. With this system a microsphere can be subjected to an oscillating motion in an otherwise undisturbed liquid. In a macroscale adaptation (Karanfilian and Kotas 1978), resistance to motion was represented by three terms: the steady motion drag, a term due to the ‘added mass’ and a term due to the history of the motion. An investigation of this ‘history force’ at the microscale will be a future focus. Fluid-particle interactions with non-spherical particles are also of interest. With appropriate planning, PIV tracer particles can be minimally influenced by unwanted AC electrokinetic effects and future DEP systems can be optimized to reduce Joule heating. These preliminary results demonstrated with commercially available items provide an important foundation for future adaptations investigating microfluidic-particle interactions incorporating μPIV.

References

Engineering 128: 271-278.
Fig. 1. An illustration of the electrothermal flow setup. A cross-sectional view is shown. The tracer particles appear as ellipses, whose shape depends on their out-of-plane location.

Fig. 2. A top-view image showing a captured 10.1 µm particle with the electrodes. The inside pair of electrodes was altered resulting in particle translation to the neighboring electrode.

Fig. 3. The position of a particle (●) as it translated approximately 40 µm from one trapped location to another (refer to Fig. 2) for an applied voltage of 20V_{pk-pk}. The simulated translation of the particle is shown with the dashed line.
**Fig. 4.** The measured velocities for DEP translated particles for five applied voltages. Error bars represent one standard deviation.

**Fig. 5.** Numerical simulations of out-of-plane particle displacement at it translates a lateral distance of 40 µm between trapping locations.
Fig. 6. Measured (a) x- and (b) y-components of fluid flow obtained from μPIV results. Computer simulated results showing the expected (c) x- and (d) y-components of fluid velocity around a sphere.