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Dielectrophoresis and AC Electroosmosis Force on Fluid Motion in Microfluidic using Latex Particles

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ABSTRACT

The use of electroosmotic is fast becoming a proven technique for manipulating particles in microfluidic systems. Several approaches were experimented to improve the force and thus the moving particles in the fluid. This paper will study the effect of microelectrode on the moving particles in latex using a particle image velocimetry and to test the velocity of particles movement at various frequencies from 10kHz to 500kHz. The result shows the behaviour of latex particles at different frequencies varying from low frequencies up to high frequencies under AC electrokinetic forces such as dielectrophoresis (DEP) and AC electroosmosis (ACEO).

Keywords: Electrical field, microfluidic, dielectrophoresis, electroosmotic flow, particle image velocimetry, charge density, Clausius-Mossotti factor

INTRODUCTION

The considerable progress and development in the technology gave birth and growth to the miniaturisation, which is, integrated to all types of systems the thermal, chemical, and electronic. This leads to a new field called MEMS (Micro-Electro-Mechanical Systems), which allows the fabrication of the systems. MEMS creates other applications and lead to other fields to improve and develop. One of the fields that had attracted attention was the fluid motion under the unexplored and unusual conditions which later known as the *Microfluidic* (Tabeling, 2005). Microfluidic is defined as the study of flows that are simple or complex, mono- or multiphasic, which are circulating in synthetic microsystems, i.e. systems that are fabricated using new technologies (Tabeling, 2005; Pohl, 1978).

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Generally, the electrical field causes the particles in the fluid to move depend on the voltage applied. A non-uniform electrical field induces a net force on a polarizable particle (Pohl, 1978). The field applied is either produced by direct current DC or alternative current AC. This will cause an electrokinetic phenomena. An AC electrokinetic phenomena uses electric fields to generate forces that act on fluids or suspended particles (Jones, 1995).

The dielectrophoretic (DEP) force is one of AC electrokinetic forces. It depends on the particle radius, complex permittivity and the Clausius-Mossotti factor (Jones, 1995; Tabeling, 2005; Cheri et al., 2014). The other main AC electrokinetic influence is the electroosmosis flow (EOF) under AC electroosmosis force (ACEO), which is the projecting mechanism for controlling fluid flow in micro and nano channels with embedded microelectrode in it that requiring surface charges. The surface charge on the microelectrode surface causes a diffuse layer of counter ions to form. When an electric field is induced, the outer layer of ions is attracted toward the oppositely charged electrode dragging with it the majority solution and making a net flow referred to as electroosmotic flow (EOF) (Feshbach, 1953). This mechanism of fluid motion causes a uniform velocity spreading across the microchannel, which is often advantageous. The electroosmotic velocity is

$$v_{\varepsilon 0 f} = \frac{\epsilon \zeta E}{4\pi\eta} \tag{1}$$

where ϵ is the dielectric constant of the fluid, η is the fluid viscosity, E is the applied electric field strength, and ζ is the zeta potential of the surface (A. Kitahara, 1984). The electroosmotic velocity is proportional to the applied electric field strength. The mobility (μ_{e0f}) is the electroosmotic velocity normalised by the applied field:

$$(\mu_{e0f}) = v_{e0f} / E \tag{2}$$

Thus, altering the applied field, the properties of the solution, or altering the surface charge can affect v_{e0f} .

In this study, latex beads will be tested and compared with different frequencies to check the characteristic of electroosmotic flow. Latex was chosen due to its density, which has slightly greater than water (1050 kg m^{-3} compared to 1000 kg.m^{-3}) (Arnold, 1987). Its dielectrophoretic properties, which show polarization of particles is dominated by the surface conductance (Baker, 1995; M.P. Hughes, 1999; N.G. Green, 1999). Dielectrophoresis and AC electroosmosis are the alternating fields, which used to manipulate particles. Dielectrophoresis arises via contact of the induced dipoles with non-uniform field. The output force is reliant on the gradient of the field squared ΔE^2 and the particle volume r^3 , frequency and applied voltage (M.P. Hughes, 1999; Morgan, 2003). The dielectrophoresis force for spherical particle is written as

$$F_{DEP} = 2\pi\varepsilon_m r^3 \ Re[f_{CM}(w)]\nabla E^2 \tag{3}$$

where r is the radius of the particle and ε_m is the dielectric constant in the medium, f_{CM} is the Clausius-Mossoti factor the effective polarizability of the particle. f_{CM} depends on the applied frequency w. The term $Re[f_{CM}(w)]$ is bounded by -0.5 and 1. The sign of $Re[f_{CM}(w)]$ depends on the applied frequency. Dielectrophoresis is a local effect and the DEP force decreases rapidly away from the electrode (Yunus, 2010). Another long-range electric force called electroosmosis is effective in manipulating biosamples (Pohl, 1978). As the particles moves under the influence of DEP, it can be assumed that the instantaneous velocity is proportional to the instantaneous DEP force so that for spherical particles such as latex

$$V_{DEP} = \frac{\pi a^3 \varepsilon_m Re[\bar{f}_{CM}] \nabla |E|^2}{6\pi\eta a} \quad (4)$$

where V_{DEP} is dielectrophoretic velocity, particle radius, $\dot{f}_{CM}$ Clausius-Mossotti factor, medium permittivity. It can be seen that for a spherical particle the dielectrophoretic mobility depends on the radius of the particle squared and the real part of the Clausius-Mossotti factor, together with the permittivity and viscosity of the fluid (Morgan, 2003).

In methodology section, shows the experimental setup, which includes the chemical solution, channels, and measurement of the velocity of the particles. In results and discussion, the particles velocity with the effect of different frequencies and at different distance are presented and compared. Finally, the important of the paper is concluded.

METHODOLOGY

The paper presents a comprehensive study of electroosmotic properties of latex particles (test particle) as a function of fixed particle size, which is 2 µm and Potassium Chloride, KCl electrolyte, with conductivity of 14.5 µS/m acted as the medium (usually used in biology for normal cell respiration) and present viscosity (Pohl, 1978). The microfluidic chip was fabricated on glass substrate using direct-write electron beam lithography with Ti/Pt layer (10/200 nm thick) patterned and designed with a microchannel width of 500 µm and 40 µm height with array of interdigitated microelectrode of 20 µm in width size and the gap between the electrodes is 20 µm.

The electroosmotic flow (EOF) measured was based on placing the microchip under microscope with objective of 20x magnification until the particles are visible and easy to be captured. A series of video recording were accomplished under microscope and stored for later analysis as shown in Figure 1 below. Basically, the electrodes were supplied by an AC, 2Vpp power supply throughout the test, with varying the frequencies between 10kHz, 20kHz, 30kHz, 40kHz, 50kHz, 100kHz, 200kHz, 300kHz, 400kHz and 500kHz.

Particle Image Velocimetry Setup

After acquiring the video, the video is analysed using MATLAB software, which converts the video into a series of images. This includes a series of image processing, region of interest (ROI), eliminate and mask the distortion and invert the background to smooth the image to maximize the result. After that, a moving window or interrogation area will be chosen to fit the particles size for the whole ROI. Furthermore, vector validation will take place whereby it will select the most accumulated particles. Line graph will be drawn from the nearest point to electrode and to far point of the electrode, to study the velocity based on the movement of the particles (El-Gholabzouri, 2006). The velocity graph will be generated after calibrating the image to match the reality and this is done by selecting a reference point, which its length known prior to the study.

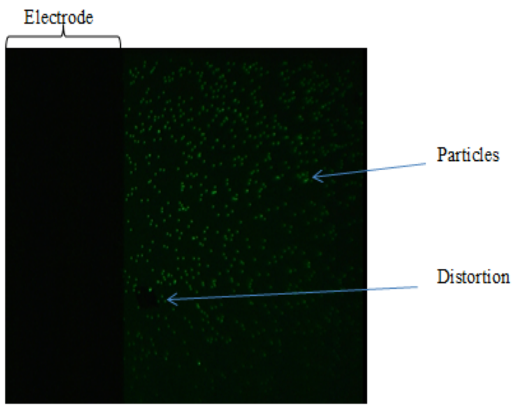


Figure 1. (a) Moving particles in KCl solution

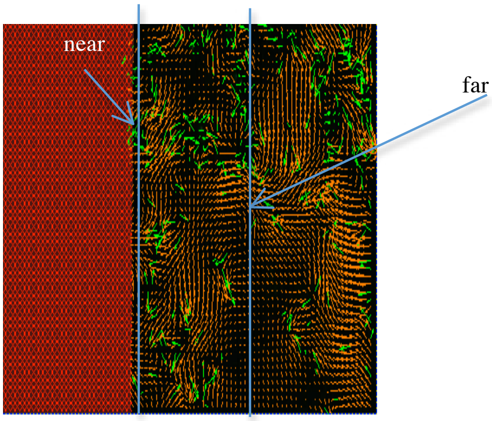


Figure 1. (b) Particles movement near mid and far from electrode

Figure 1a shows the basic layout of one frame. It was picked randomly from 350 frames. There are selected lines on Figure 1b to show the behaviour of particles near the electrode and far from the electrode. The movement (behaviour) of particles are represented by the arrows; as the bigger the arrow means the more electrical field its possessed and cause the particles to move further. The selected line near electrode was chosen to be 5 µm and the far selected line from electrode is chosen to be 35 µm. Identifying the line near and far from the electrode will provide consistency along the simulation. In the above experiment, the particles are the latex beads with all the same size of 2 µm in diameter. The electrode is located on the left hand side and the right hand side of the ROI. The particles are very active within electrode vicinity as compared to the particles in the middle region, which tend to approach zero. The middle region has less electrical field strength. Thus, the concentration of particles is observed lesser at the centre and increase when they get closer to the electrode as shown in Figure 2.

Figure 2 implies that, as the particles get closer to the electrode, they have been exposed to higher electrical field strength near the electrode hence obtain greater velocity. This behaviour is increasing in frequency as shown and discussed in the following section.

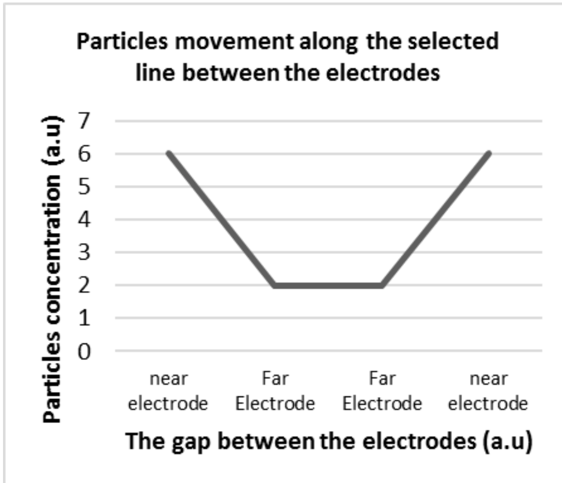


Figure 2. The behaviour of particles movement along the line

RESULT AND DISCUSSION

The electric field strength generated by the parallel array of interdigitated microelectrodes produces sufficient dielectrophoretic forces to manipulate colloidal particles and macromolecules in microflows (Thielicke, 2014). As the electroosmotic velocity is proportional to the applied electric field strength and DEP force is proportional to the gradient in the electric field strength, it is instructive to look at the components of the electric field strength to gain a better intuition into the forces acting on target particles/species.

In this section, the observation was made on how the electroosmotic behaviour is reacting. It is based on different frequencies applied under voltage 2Vpp. Several results have been generated to serve the objective and this result was generated from the developed MATLAB

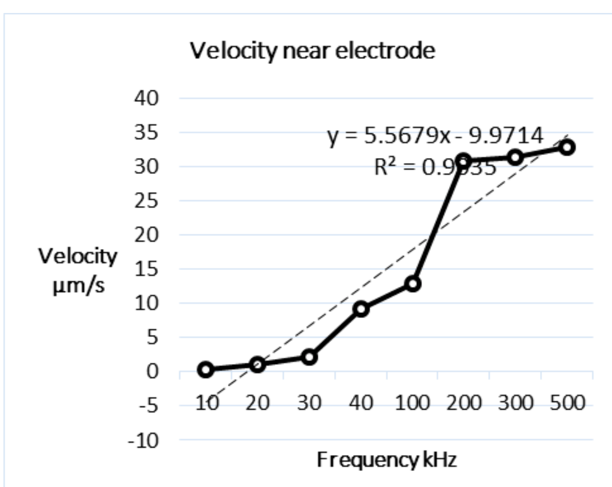


Figure 3. Velocity vs frequency near microelectrode

program. The data were collected for all videos with the same parameters as before. Figure 3 shows the velocity profile of particles taken vertically near the microelectrode. The dot lines represent the profile as the frequency increased.

Figure 3 shows that as the frequency increases, the velocity increases as well. The activity near the microelectrode is higher as compared with the one further away from the microelectrode. This is due to the fact that, as the particles are near the microelectrode, the electrical field is higher and the DEP force is present. It causes the particles move under certain velocity where ACEO is also present. Near the electrode, the velocity of particles increase and become hyper active as compared to the particles far away from the electrode as shown in Figure 4.

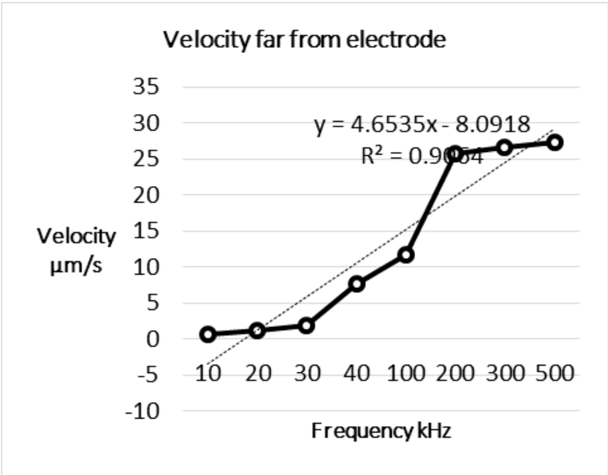
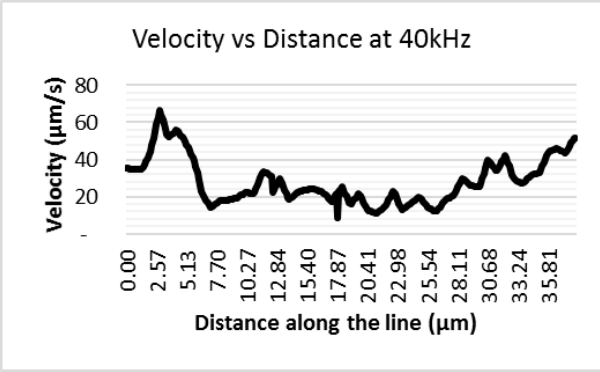


Figure 4. Velocity vs frequency far from microelectrode

Figure 4 shows the velocity of particles under the effect of DEP and ACEO far from microelectrode is lower as compared to their velocity shown in Figure 3. The result shows that as the DEP and ACEO present with the frequency increases, the particles will move under clear velocity. Whenever the particles travel away from the electrode, although the frequency is increased, the particles velocity will still decrease respectively due to weak DEP and ACEO further away from the electrode and this is proven by Clausius-Mossotti factor (Jones, 1995; Tabeling, 2005; Thomas B. J., 1995). Besides that, to further study the electroosmotic of latex particle, another analysis was carried out to fulfil the finding and the following graphs was generated. The graph in Figure 5a shows the velocity of latex particles at 40kHz. The velocity has been observed and measured along the selected line shown in Figure 5b.

Figure 5(a) indicates that the velocity of latex particles was high near the microelectrode and kept decreases until it reaches a very small value approximately 8 µm/s, where there is minimal electrical field presented. It starts to increase again up to 70 µm/s as it approaches the other microelectrode. The analysis was taken for frequencies varying from 10kHz up to 500kHz. It is noticed that, as the frequency is low, the particles behave unstably and in almost in circular motion e.g. moving forward and backward (oscillation) as the sufficient electrical field did not reach to start the electroosmotic of the latex particle.



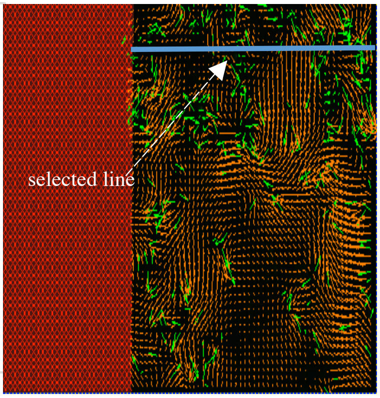


Figure 5. (a) Velocity vs distance at 40kHz

Figure 5. (b) Selected line used in Figure 5a & Figure 6

However, the starting frequency whereby the latex started to stop oscillating and generated proper velocity (of ACEO) was at 40kHz. The 40kHz was chosen after trying lower frequencies such as 10, 20, 30, and 40kHz. The 40kHz seems to give a better steady state and less circular motion and as the frequencies increased further the particles tend to response better until it reach steady state movement. Once the steady motion is reached, the particles motion is observed at even higher frequency i.e. 500kHz. The graph on Figure 6 shows the electroosmotic flow velocity of latex particle at 500kHz.

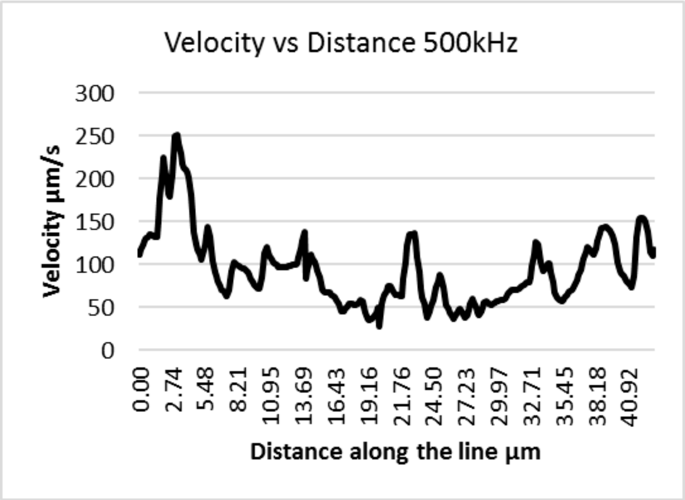


Figure 6. Velocity vs distance at 500kHz

The graph of Figure 6 shows the average particles electroosmotic velocity is increased up to 250 µm/s at 500kHz as compared to 70 µm/s at 40kHz. This is due to higher frequency and higher electrical field under DEP and ACEO effects (Chen et al., 2014; Feshbach, 1953). The comparison is made between Figure 5 and Figure 6. It is shown that, after increasing the frequency, the particles tend to gain more velocity under the effect of DEP and ACEO. The parameters such as the latex particles size, electrolyte, PIV software environment, the location of the velocity measured are not changed at all processing frequencies.

CONCLUSION

The study of AC electrokinetic forces, dielectrophoresis (DEP) and AC electroosmotic (ACEO), becoming the proven techniques for manipulating particles in microfluidic systems. The effect of electrical field on the moving particles of latex is studied using PIV, to test the velocity of particles movement at varying frequencies from 10k to 500kHz. The work has shown that, at lower frequency, latex particles are unstable and generating circular motion (oscillation). As the frequency increase, the particles start to stabilize and get higher velocity (higher electric field strength and force applied). This study could benefit the researchers for useful particles and fluid manipulation in term of particles behaviour at certain electrical properties environment. Further studies can be done by expanding the range of potential systems such as varying the voltage supplied and electric fields strength. Those parameters can be used to manipulate further the particle behaviour near and far from the microelectrodes in the microfluidic system. Besides that, by varying the electrolyte to Sodium hydroxide, NaOH (e.g. used for microfluidic mixer) and Potassium hydroxide, KOH (e.g. used for fungal cultures in microfluidic) (Persar, 2009; Saini, 2016) can also be promising study in the future.

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