Effect of Electric Field Distortion on Particle-Particle Interaction under DEP

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Abstract: Particles in a non-uniform electric field will move under dielectrophoretic (DEP) forces. Recently we have seen a lot of activities on using DEP forces to manipulate tiny particles and cells. While the theory on DEP provides a convenient way to predict the direction of the DEP forces, which served well as the basis for particle separation and cell sorting, it does not give much information on particle-particle interaction and particle alignment. For example, in our experiments of manipulating polystyrene beads using DEP we observed some interesting alignment phenomena that cannot be explained by the current DEP theory. Moreover, others have used DEP to form patterns of different cells on a chip to imitate the structure of tissues.[1] To obtain better understanding of the underlying DEP mechanisms we developed a new method to quantify the DEP forces and use it to explain particle-particle interaction and particle alignment patterns.

Keywords: electric field distortion, pearl-chain alignment, particle-particle interaction

1.Introduction

Experiments are conducted by dispensing polystyrene beads in DI water on top of parallel electrodes and examining the formed alignment patterns. Frustrated with the inability of using the conventional DEP formulas to explain our experimentally observed phenomena, we developed 3D COMSOL models to elucidate the underlying driving forces the particles experience. In particular, we aim to determine the DEP forces exerted on particles. We hypothesized that the volumetric domains of the particles, which possess different dielectric properties than the surrounding media, will distort the electric field and alter the resulting DEP forces. Thus the size and location of a particle and the distance between two particles will all have certain effects on the resulting DEP forces. In the model a spherical particle is placed in a liquid (DI water) chamber above the electrodes as shown in Figure 1.

2. Governing Equations

Conventionally, the DEP force is calculated by using [2]

$$F = 2\pi a^3 \varepsilon_0 \varepsilon_m Re(f\_cm) \nabla E_{rms}^2 \qquad (1)$$

where

$$Re(f\_cm) = \frac{\omega^2(\varepsilon_p - \varepsilon_m)(\varepsilon_p + 2\varepsilon_m) + (\sigma_p - \sigma_m)(\sigma_p + 2\sigma_m)}{\omega^2(\varepsilon_p + 2\varepsilon_m)^2 + (\sigma_p + 2\sigma_m)^2}$$

This formula assumes that the electrical field, E, will not be affected by the presence of a particle, no matter what the actual size (a) and the dielectric property (ε_p) of the particle are. To counter for the size, it just multiplies the volume of the particle. Moreover, the only component that considers the dielectric property of the particle is the Clausius-Mossotti factor (f_cm). So in a general sense the formula provides a good qualitative guide in predicting the DEP forces, but it is not adequate to provide precise and quantitative evaluation of the DEP forces.

For most sorting applications, this may not be an issue. But for using DEP forces for patterning and alignment purposes, as well as for potential sensing applications, a better understanding of the dependence of the DEP force on the physical and material properties of the particle is necessary. Therefore, we performed this work to counter for the influence of the volumetric domains of the particles on the distortion of electrical field.

We begin by going back the basics to treat a particle as a group of point dipoles. The force density on point dipole is calculated

$$f = (P \cdot \nabla)E \qquad (2)$$

where P is the polarization of the particle. By integrating this force density over the volumetric domain of the particle we obtain the expression for the DEP force as

$$F = \frac{\varepsilon_p - \varepsilon_m}{\varepsilon_p + 2\varepsilon_m} \varepsilon_0 \int (P \cdot \nabla) E dV \quad (3)$$

The following simulation results are all based on this new formula.

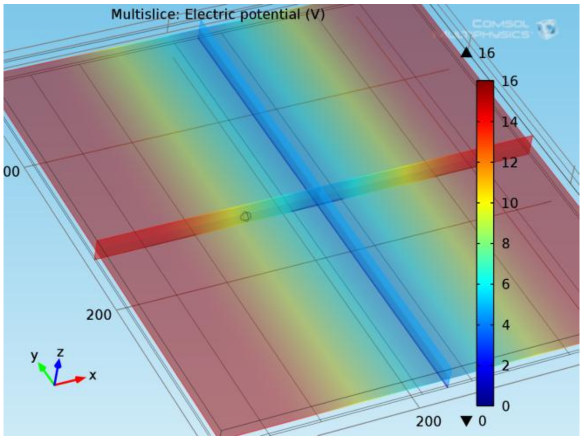


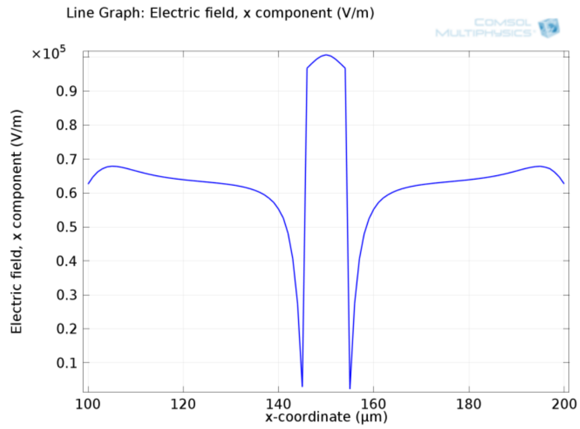
Figure 1. COMSOL model for elucidating the influence of particle volumetric domain on the distortion of electrical field

3. Modeling Results

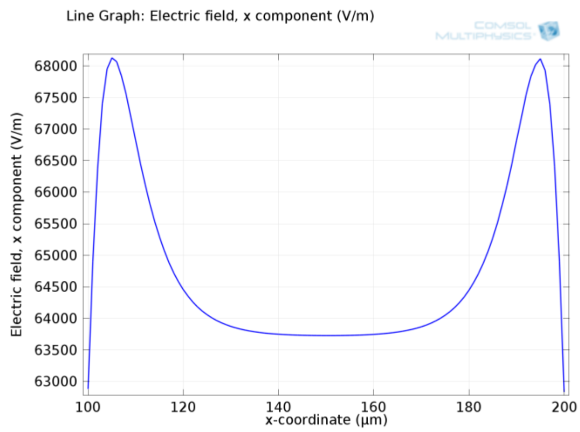
We will present and discuss the obtained results with two focused subjects: 1) electric field distortion, and 2) particle-particle interaction.

3.1 Electric Field Distortion Effect

Figure 2(a) plots the x-component of the induced electric field along a line that is perpendicular to the electrodes passing through the center of the particle (a = 5nm) sitting in the middle of the gap. Figure 2(b) shows the corresponding result when the presence of the particle domain is ignored. Clearly, the electrical field surrounding the particle is distorted drastically. This distortion is due to the presence of the particle having a different conductivity and permittivity from the surrounding medium. This fact suggests that ignoring such distortion may lead to inaccurate quantification of the generated DEP forces.



(a)



(b)

Figure 2. (a) Influence of the presence of a particle on the electric field is significant as compared with (b) when the presence of the particle is ignored.

3.2 Particle-Particle Interaction

When multiple particles are placed close to one another, the dipoles induced by electric field of one particle will interact with those of others. [3, 4, 5] Whether the interaction will result in an attractive or repelling force depends on the orientations of the dipoles. When two particles were placed along the x-direction, which is perpendicular to the electrode orientation, we found (Figure 3) that as the distance between the particles (center to center distance) increases from 10 um (the two particles are in contact) to 40 um, the x-component electric field exhibits a transition from having overlapped peaks to having two distinct individual peaks, indicating the diminishing interaction between dipoles as the particle-to-particle distance increases.

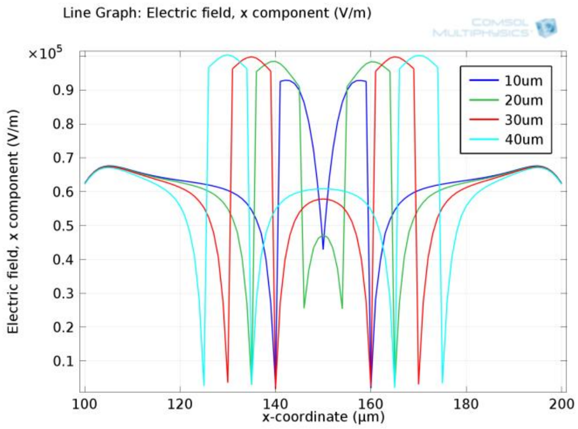


Figure 3. Influence of distance between particles on distortion of electric field

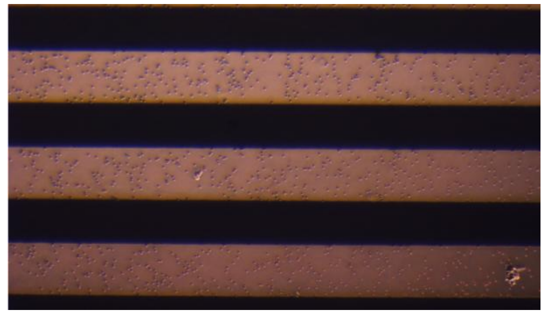
4. Pearl-Chain Formation

4.1 Interaction Forces Between Two Particles

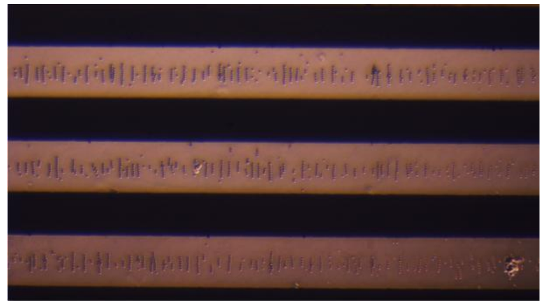
In our experiment with polystyrene beads (a=5um), we noted that beads formed pearl chains when the applied potential reaches a certain critical value. Figure 4(a) shows the bead distribution pattern when no electrical potential is applied, and figure 4(b) shows the bead alignment when a potential of 15V at 200 KHz is applied where the beads form pearl chains and align near the center gap region with some distances separating the chains.

To elucidate the cause for such a pearl-chain formation, we apply our method to examine particle-particle interaction with two particles, one placed at the center gap of the electrodes and the other at a distance along the x-axis, or in a direction perpendicular to the electrodes. Figure 5 shows that the attractive force exerted on the middle particle decreases as the other particle moves further away, an indication of weakening particle-particle interaction.

When placing the second particle along a direction parallel to electrodes, we found that the repelling force decreases as the distance increases as shown in Figure 6. This repelling force becomes negligible when distance reaches a certain value (e.g., 30 um in this case). This fact suggests that neighboring chains of beads would repeal each other to push the neighbors away until a certain distance is reached. The predicted distance value based on the COMSOL model is consistent with our experimental results.



(a)



(b)

Figure 4. Beads alignment no potential(a) and at 15V, 200KHz (b)

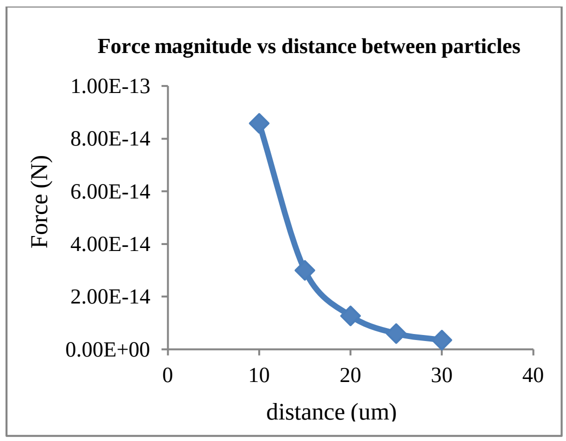


Figure 5. Beads get attracted in perpendicular direction

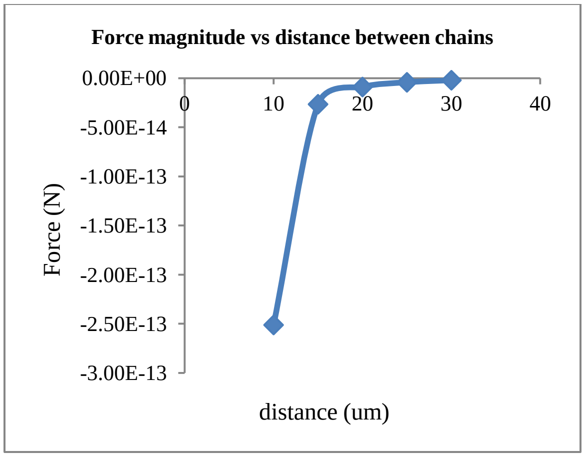
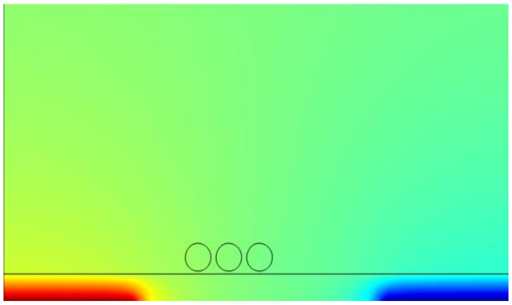


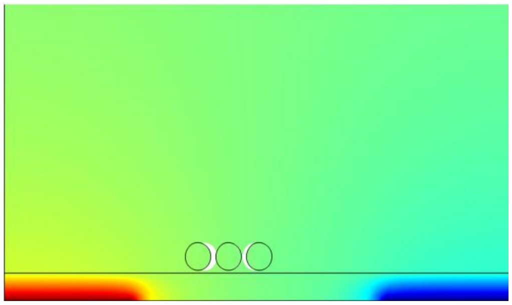
Figure 6. Chains repel each other along electrode orientation

4.2 Three-Particle Chain

To simulate the pearl chain formation process, we performed 2D modeling in a moving mesh study. Two cases are studied: In the first case, one particle is placed at the center gap and two other particles on the left side of the center particle (figure 7a). In the second case, one particle is placed at the center gap but two other particles on both sides of the center particle (figure 8a). Figures 7b and 8b show the positions of these particles after 12s of particle-particle interaction. Both results show that particles are pushed close together, indicating the tendency of forming pearl chains of particles in the center gap regions along a direction that is parallel to the electrical field line. The DEP forces along with the distortion of electric fields by the neighboring particles generate a driving force to move the particles closer together in a line that is parallel to the overall electric field.

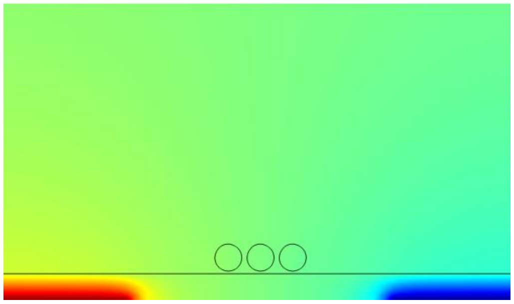


(a)

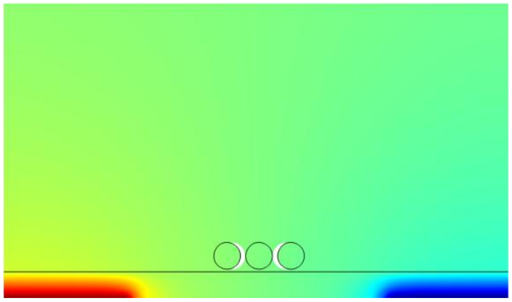


(b)

Figure 7. Movement of 10um particles on one side of center particle in forming a pearl-chain



(a)



(b)

Figure 8. Movement of 10um particles on both sides of center particle in forming a pearl-chain

5. Conclusion

Electric field distortion is the result of different permittivity between the particle and surrounding medium. Our new method to calculate DEP force utilizes an integral over the whole volume of the particle such that the effects of particle size, shape and its location are inherently considered in the resulting electric field. This is not the case when using the conventional DEP formula. Moreover, our modeling results prove to be valid in explaining our experimental observations.

6. Reference

1. Ho, C.-T., Lin, R.-Z., Chang, W.-Y., Chang, H.-Y., & Liu, C.-H. Rapid heterogeneous liver-cell on-chip patterning via the enhanced field-induced dielectrophoresis trap. Lab on a chip, 6(6), 724–34. (2006)

2. Wang, X-B., Huang, Y., Becker, F. F., & Gascoyne, P. R. C. A unified theory of dielectrophoresis and travelling wave dielectrophoresis. J. Phys. D: Appl. Phys., 27,1571. (1994)

3. Sancho, M., Martínez, G., Muñoz, S., Sebastián, J. L., & Pethig, R. Interaction between cells in dielectrophoresis and electrorotation experiments. Biomicrofluidics, 4(2), 1–12. (2010)

4. Washizu, M., & Jones, T. B. . Dielectrophoretic interaction of two spherical particles calculated by equivalent multipole-moment method. IEEE Transactions on Industry Applications, 32(2), 233–242. (1996)

5. Techaumnat, B., Eua-arporn, B., & Takuma, T. Calculation of electric field and dielectrophoretic force on spherical particles in chain. Journal of Applied Physics, 95(3), 1586. (2004).

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