ELECTROKINETICS OF MICROPARTICLES USING AC DIELECTROPHORESIS

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ABSTRACT

Meso-scale (approximately 10 μm to 1000 μm) systems have a variety of applications, including use in medical and biological fields, automotives, and space technology. An electro-kinetic device for manipulating and moving biological micro-particles is the focus of this paper. Rectilinear motion of the particles is caused by using traveling wave dielectrophoresis. The theory behind dielectrophoresis (DC and AC), design, forces, fabrication methods, and results, are discussed.

1. INTRODUCTION

Many types of devices have been created to move biological micro-particles, which include bacteria, viruses, animal cells, and plant cells. The electro-kinetic device attempts to move, manipulate, rotate, or separate different sized and different types of particles by using electric fields. An electro-kinetic device for manipulating and moving biological micro-particles is the focus of this paper. When the particle involved is neutral, the controlling force in these manipulations is called dielectrophoresis. Either DC or AC electric fields can be used to create dielectrophoretic forces. Traveling wave dielectrophoresis, which uses AC signals, will be used in our device.

The technology of electro-kinetic devices has the greatest potential in the medical and biological fields. If these micro-particles can be moved and separated, depending on size, conductivity, and electric field properties, then cells and other microorganisms can be moved and separated as well. The sizes of some biological particles are given in Table 1. The scale used in the discussion is the cellular scale, which is considered larger than 1 μm.

Possible applications of meso-scale systems include separation of cancer cells from blood cells, separation and controlled movement of bacteria, and separation of viruses from cells [1].

Table 1: Biological Particle Size

Small molecules	1 nm
Viruses	10-100 nm
Bacteria	1 μm
Animal cells	10 μm
Plant cells	100 μm

The benefit of the electro-kinetic device is that it is designed to control movement, but has no moving parts. The device designed is intended to provide a good base to enhance electro-kinetic devices as research continues. The initial results from testing will be used to make corrections to the frequency, electric field, and physical design of the device.

2. DIELECTROPHORESIS

2.1 Using DC

The controlled motion of the micro-particles is created using dielectrophoresis, a term first used in 1978 by Herbert A. Pohl [2]. When a neutral particle is placed in the presence of a DC electric field, polarization is created in the particle. Polarization causes the positive nuclei of the particle to move toward the negative electric field and the negative electrons toward the positive electric field. If the electric field is uniform, the forces from this polarization are cancelled out, and the particle remains in a central location between the electrodes. If the forces are non-uniform, motion occurs.

Polarization also occurs in the medium in which the particles are suspended (distilled water, in this experiment). The outcome depends on how polarized the micro-particles are compared to the medium. If the micro-particle is more polarizable than the medium, then the particle will move toward the areas of higher electric field, while the medium moves toward the areas of minimum electric field. This is called positive dielectrophoresis. In contrast, if the medium is more polarizable than the micro-particle, the particle moves away from areas of high electric field. This is negative dielectrophoresis. Figure 1 shows positive and negative dielectrophoresis.

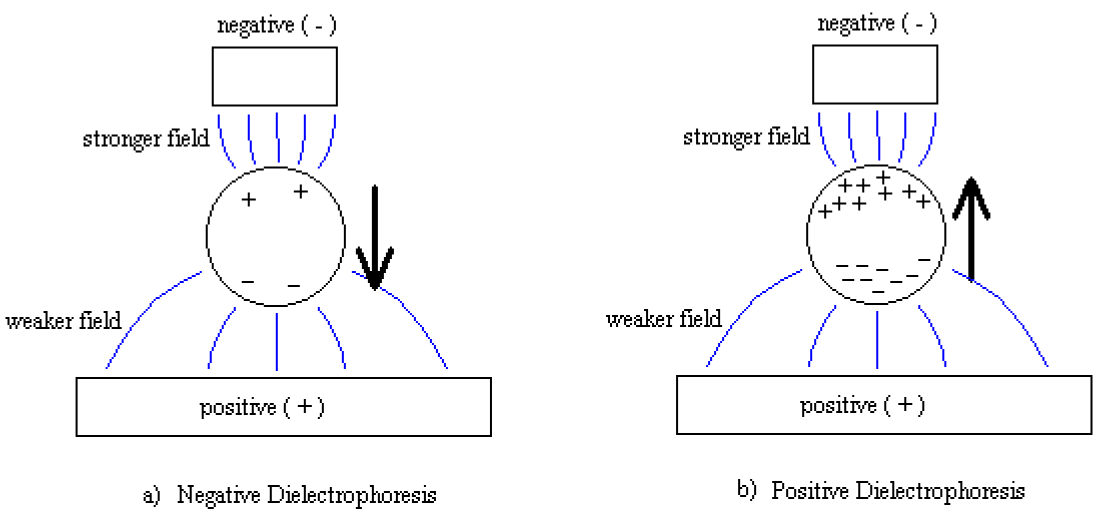

Figure 1. Non-uniform electric fields. The field at the top is stronger in both diagrams. a) Particle is less polarizable than medium, so it moves toward the weaker electric field. b) Particle is more polarizable than medium, so it moves toward the stronger field. The arrows in the figure show the direction of the motion of the particle. The particles of the medium move in the opposite direction of the particle.

2.2 Traveling Wave – Using AC

The same principles that were explained above for DC electric fields can be used in AC electric fields. AC signals are more complex than DC signals, and therefore have more variability in controlling the motion of particles. Frequency and phase are two very useful properties of the signal. The frequency, along with the amplitude of the voltage of the AC signal, directly controls the polarizability of the particles. A specific frequency can also be used to achieve particle selectivity. A frequency of 200 kHz may create the right polarization to move one particle but not another. The difference of polarization between the medium and the particle is significant as well, since it can cause either positive or negative dielectrophoresis. The phase, another important characteristic of the signal, has the benefit of causing non-uniform electric fields that form a traveling wave.

A traveling wave is made when different electrodes are lined up, and have phase-shifted AC signals going through them. The actual traveling wave describes the way in which the electric field moves over the electrodes, and is the inspiration behind the device described in this paper. If four electrodes are lined up so that each is 90° phase-shifted from the last, then each electrode will hit its peak voltage at a different time, and non-uniform electric fields will be created. The principles behind this are very similar to those that move a 3-phase AC motor, in that a dipole moves with the changing electric field. The difference is that the electrodes are arranged in a plane instead of a circle. Figure 2 shows a basic diagram of the device that will be used to create traveling wave dielectrophoresis.

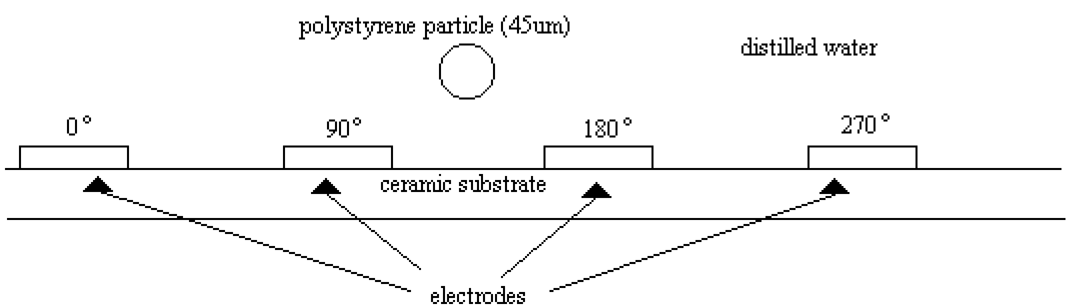

Figure 2. Side view of traveling wave device described in this paper.

2.3 Physics of Electro-kinetics

Many particles are in a solution of distilled water that sits on top of the substrate and electrodes. For simplicity, only one particle will be examined here. We will assume that the properties of the electric field, micro-particle, and medium cause *positive* dielectrophoresis to occur. There are electric fields around the particle because AC signals are running through the electrodes below the particle. These fields induce polarization and create a force in the particle. The particle will move toward the area where the highest electric field amplitude occurs because of the dielectrophoretic force.

At t=1, the AC signals are at a different position, which changes the electric field around the particle. The micro-particle is now in a non-uniform electric field. Since positive dielectrophoresis was assumed above, the particle moves toward the area of high electric field.

At t=2, the particle is now drawn to the new area of highest electric field. This process continues to cause a dielectrophoretic force on the particle. Because each electrode is out of phase by 90° from the previous one, the particle moves from the inside of the coil toward the edges of the device along with the traveling electric field.

3. OTHER FORCES

Many other forces contribute to the motion of the micro-particle besides traveling wave dielectrophoresis. These forces, depending on their magnitude, may cause the particle to move in undesired patterns, or cause the particle to be stationary. They include sedimentation forces, Brownian forces, Coulomb forces, hydrodynamic forces, and electro-thermal forces. The device is designed to make the traveling wave force predominant, while minimizing the other undesirable forces.

The sedimentation forces result from gravity pulling down on the particles. Gravity is actually very useful in controlling the particle's vertical position. Brownian forces are caused by smaller particles bumping into the particles being observed. Since the size of our particle is 45 μm diameter, the Brownian forces should be close to negligible for the experiment. The large size of the particle is an advantage in this case. Coulomb forces, though, probably will not be negligible. Coulomb forces are caused by the charges and polarization of each particle--the electrical interaction of the particles with each other. At certain frequencies, these Coulomb forces may dominate and make the dielectrophoretic force useless. Hydrodynamic forces are also involved in the motion of the particles. When the particles are being forced one way, a counter drag force is acting, stemming from the viscosity of the medium. For distilled water at 20° C, the dynamic viscosity is $1.0 * 10^{-3}$ Pa*s. The last force mentioned is electro-thermal force. A large power density exists around the electrodes, which can cause the temperature of the distilled water medium to rise. The increase depends on the strength of the electric field, and the frequency. When certain sections of the fluid medium have different temperatures, natural convection occurs. The fluid flow causes undesirable forces on the particle. Electro-thermal forces can be considered negligible if the correct frequency is used in the device.

4. PROCESS / DESIGN

4.1 Device Specifications

The general design of the electro-kinetic device was selected to create rectilinear, or straight line, motion. The idea came from an article titled "Micro-Belt Conveyor of Latex Micro-spheres" [3]. The device designed here (shown in Figure 3) is about 10 times larger than the device in the article, but is intended to create the same type of results.

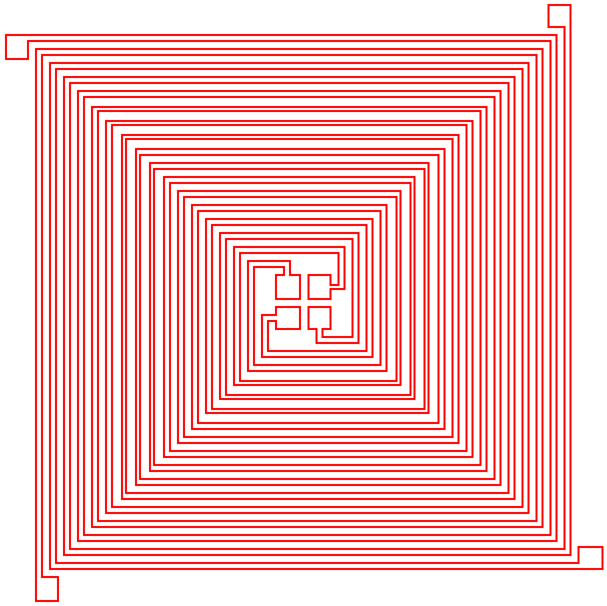

Figure 3. Top view of device design (made on AutoCAD).

Gold conductor thickness is approximately 2 mils (.002“). The conductor lines are all 5 mils wide (.005“), and the spaces are 7 mils wide (.007“). At each end of the conductor square-spiral lines there is a contact pad that is 9 mil (.009“) square. The working area is a square with 450 mil (.450“) sides. The entire device is contained on a 1“ by 1“ piece of fired ceramic substrate. Figure 3 shows a top view of the device.

4.2 Fabrication

The basic design of the electro-kinetic device is four individual square spirals intertwined with each other (shown above). Two ideas were considered for fabricating the shaped device, both of which use Low Temperature Co-fired Ceramic (LTCC) processes at the University of Pennsylvania. See [4] for more information on LTCC processes.

4.2.1 Stencil Process

The first process considered involves using a screen-printing instrument to print the conductive paste onto a piece of DuPont’s 951 ceramic tape. The screen is cut with a laser. The problem with this process is that the laser used to cut the stencils is not effective for cutting very small features. The line width was scaled up from 2 mils to 5 mils for this reason. The conductive paste is applied using a print machine that has a squeegee mechanism. After conductive paste is applied, the whole device is fired, with the firing profile shown in Figure 4, to sinter the paste.

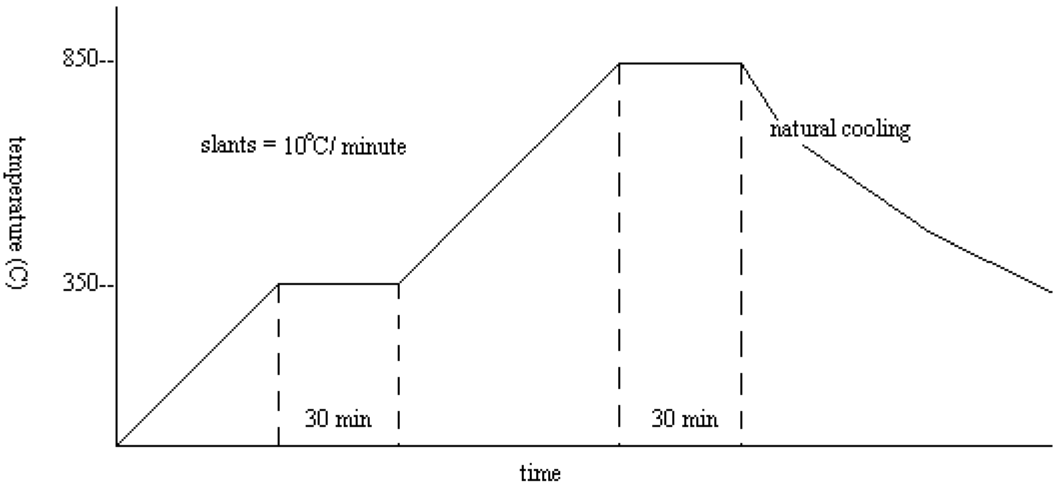

Figure 4. Diagram of heating process used to harden ceramic tape and conductor paste from soft state to its sintered state.

4.2.2 Fodel Process

The second process involves a DuPont photo-imageable material called Fodel. The first step is to make a negative of the design on a photo mask. The Fodel, which is UV light sensitive material, is spread and dried in a layer on top of a piece of ceramic tape. When the Fodel is exposed to UV light and developed, the areas illuminated disappear, while the areas that are protected from the UV light remain. The advantage of using this method is that it can produce thinner lines than screen-printing. The specifications for Fodel state that lines of 40-50 μm thicknesses can be created with accuracy.

4.3 Four AC Signals

The four signals were made by taking a regular AC signal from a function generator and using a custom-made circuit to split this signal into four phase-shifted signals. Each signal is 90° advanced from the last. The four signals are then connected, using probes (10-20 μm tip), to each of the four coils on the device. The grounds were connected to the other end of each signal. The circuit diagram is shown in the Appendix.

In general, higher frequencies lead to negative dielectrophoresis, while lower frequencies result in positive dielectrophoresis [1]. For this reason, low frequencies of 90 kHz and 170 kHz were used in the experiment. Positive dielectrophoresis is more favorable for the traveling wave effect that we are using. If negative dielectrophoresis was examined, then the particles could possibly be confined at areas of lowest electric field and would not move at all with the traveling wave.

The AC signal designed had an amplitude of 5 V. If this does not create a large enough electric field to move the particles, a larger voltage may be needed. The calculated peak electric field magnitude for the device is $2.1 * 10^4$ V/m. The other way to make the electric field larger would be to make the device smaller, but because of fabrication limits this is probably not reasonable.

5. PROPERTIES OF MICROPARTICLE / MEDIUM

The properties listed below, as well as other constant and experimental properties, will be used in the future to compute "order of magnitude" force calculations.

Properties of micro-particle:
material: polystyrene (latex)
diameter: 45 μm (approximately 2 mil)
density: 1.04-1.07 g/cm^3
permittivity: 2-2.8
conductivity: 1 * 10^{-13} / ohm*m
color: no dye

Properties of medium:
material: distilled (DI) water
density: 1 g/cm^3
relative medium permittivity: 80
dynamic viscosity at 20^{o} C: 1.0 * 10^{-3} Pa*s
color: transparent

Other constants:
free-space permittivity: 8.854 * 10^{-12}

The gravitational force is the only calculation that has been completed. The equation is given as [3]:

$$Fg = (4/3)(\pi)(r^3)(d_2-d_1)(g) \qquad (1)$$

where r is the particle radius, d_2 is the particle density, d_1 is the medium density, and g = 9.81 m/s^2. The calculated gravitational force is 1.50 * 10^{-10} N.

6. EXPERIMENTAL RESULTS

As of the deadline of this paper, few experimental results had been observed because the device was not completed. Another student, Shizhi Qian, was working on DC dielectrophoresis at the University of Pennsylvania, and his work was observed. The attempt was to move the 45 μm polystyrene particles in a channel using DC electric fields. The channel had an alternating alignment of electrodes: one at a high DC potential, the next grounded, etc. The particles were observed using a microscope to see if any motion occurred. These trials were unsuccessful.

Future testing will be done with the electro-kinetic device described in this paper. The 45 μm particles will be added to a solution of distilled water and placed on top of the device.

The first trial will use the four 5V AC signals at 90 kHz, and any movement will be observed using a microscope. The second trial will use four 5V AC signals at 170 kHz.

When optimal motion of the particles occurs as seen through the microscope, a camera will be used to give a better representation of this data. Also, written descriptions of the data will be made.

7. CONCLUSION

The unsuccessful trials of Qian's work suggest that my device may also be unsuccessful at first. In his work, a range of 5 - 20V amplitude was used to try to move the 45 μm particles using DC dielectrophoresis. The unfavorable findings were probably the result of the other forces acting on the particles besides dielectrophoresis. For this reason, I will try to compute "order of magnitude" calculations in the future. Determining the expected velocity of the particle will be a large advantage. Also, using a digital circuit to create AC signals may be a benefit, since it is easier to change amplitude and frequency.

The basic theory and design work have been completed, leaving the testing and adjustment stages ahead. The future design steps are listed below for this project:

- Decide on fabrication method: either print screen or Fodel
- Fabricate the device using the lab at the University of Pennsylvania
- Work on and complete calculations of "order of magnitude" calculations
- Test the device using 90 kHz and 170 kHz (5V) AC signals
- Create circuitry for different frequency and amplitude for AC signals
- Re-test the electro-kinetic device

Overall, the research done so far suggests that the project will lead to positive end results. The goal of this project will be accomplished when rectilinear motion of micro-particles is accomplished in a controlled manner by using the electro-kinetic device. Cellular particles can then be tested to determine if the device can be transferred effectively to biological uses.

8. ACKNOWLEDGMENTS

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9. REFERENCES

1. A. Ramos, H. Morgan, N.G. Green, A. Castellanos, AC Electrokinetics: A Review of Forces in Microelectrode Structures, *Journal of Physics: D.* **31** (1998) 2338-2353.

2. H.A. Pohl, *Dielectrophoresis: The Behavior of Neutral Matter in Non-uniform Electric Fields,* Cambridge; New York: Cambridge University Press, 1978.

3. M.F. Fernandez, J.E. Duarte, J. Samitier, Micro-belt Conveyor of Latex Microspheres. SBMicro 2000 – 17^{th} Symposium on Microelectronics Technology and Devices, Conf., 2000.

4. M.R. Gongora-Rubio, P. Espinoza-Vallejos, L. Sola-Laguna, J.J. Santiago-Aviles, Overview of Low Temperature Co-fired Ceramics Tape Technology for Meso-system Technology (MsST), *Sensors and Actuators A: Physical*, vol. **89**, Issue 3 (2001), pp. 222-241.

A.D. Goater, J.P.H Burt., R. Pethig, A Combined Traveling Wave Dielectrophoresis and Electrorotation Device: Applied to the Concentration and Viability Determination of Cryptosporidium, *Journal of Physics: D*, **30** (1997) L65-L69.

DuPont®, http://www.dupont.com/mcm/product/fodel.html, Accessed June 2002.

M. Hughes, AC Electrokinetics: Applications for Nanotechnology, Draft for the Seventh Foresight Conference on Molecular Nanotechnology, University of Surrey, Biomedical Engineering Group, European Institute of Health and Medical Sciences, 1999.

N.G. Green, H. Morgan, Dielectrophoretic Investigations of Sub-micrometre Latex Spheres, *Journal of Physics: D*, **30** (1997) 2626-2633.

N.G. Green, H. Morgan, Dielectrophoretic Separation of Nano-particles, *Journal of Physics: D*, **30** (1997) L41-4.

T. Muller, et al., Trapping of Micrometre and Sub-micrometre Particles by High Frequency Electric Fields and Hydrodynamic Forces, *Journal of Physics: D*, **29** (1996) 340-9.

X-B Wang, Y. Huang, J.P.H. Burt, G.H. Markx, R. Pethig, Selective Dielectrophoretic Confinement of Bioparticles in Potential Energy Wells, *Journal of Physics: D*, **26** (1993) 1278-85.

APPENDIX

Basic circuit diagram for creating four 90° phase-shifted AC signals.

INPUT: 5V amplitude, 90 kHz frequency sine wave
OUTPUT: 4 - 5V amplitude, 90 kHz frequency sine waves