Dielectrophoretic Microfluidic Device for Type-Based Separation of Microparticles: Viability Study

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***Abstract*— This study proposes a model of a microfluidic device that will separate Silicon dioxide microparticles and Polystyrene microparticles based on type through the method of dielectrophoresis. The device consists of a vertical layer of electrodes used as the separation section creating a non-uniform electric field. Our research shows that the Silicon dioxide microparticles are subjected to negative dielectrophoresis (nDEP) while the Polystyrene microparticles are subjected to positive dielectrophoresis (nDEP). This had lead to each experiencing opposing vertical displacements thereby achieving separation. It is observed from the model that operating and geometric parameters influence the performance of the microfluidic device.**

I. Introduction

Microfluidic devices are instruments that enable fluids to flow through channels that are less than 1 millimeter. These devices are important because they allow for the manipulation of liquids based on their physical and chemical properties. More specifically, microfluidic devices can separate mixtures, such as blood, into smaller, distinct components, such as circulating rare-blood cells and regular blood cells. To accomplish this separation, dielectrophoresis - which is when uncharged particles move as a result of a non-uniform electric field - is required. By adjusting the electrodes in the field, it is possible to attract or repel certain microparticles toward or away from these electrodes. A microfluidic device based on separation by type and size was proposed by Cetin and Li (8) in which a spatially varying electric field with electrodes placed at the beginning and end of a curved section separates the heterogeneous mixture of microparticles into two homogeneous samples by moving the pDEP and n-DEP microparticles to the inner and outer wall of the microchannel. In this article however, the microfluidic device proposed is one that employs insulator structures to create an electric field gradient.

II. Proposed Microfluidic Device

The proposed design of the microfluidic device, as depicted in figure 1, displays a Insulator Based DEP(iDEP) which incorporates the use of insulator structures within an microfluidic device to create an electric field gradients as opposed to using the shape and configuration of metal electrodes to create the non-uniform electric field.

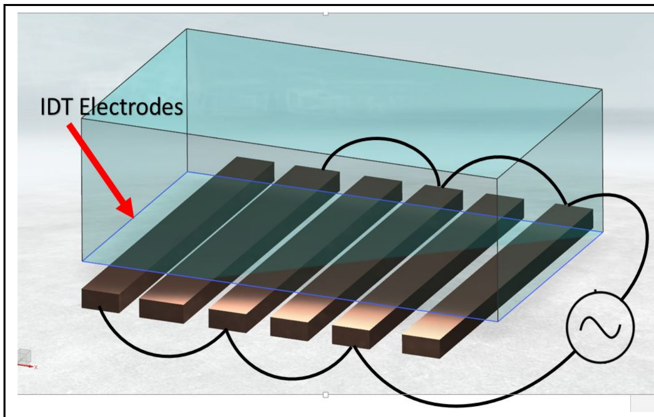

Fig 1: Proposed microfluidic device.

In iDEP, electrodes are placed on opposite ends of a microfluidic device in direct contact with the sample solution.

An array of insulator posts are placed in between the electrodes. This arrangement forces the electric field to move

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around the structures and creates a non-uniform electric field required for DEP.

In terms of the wiring design for our device, the wires are configured so that everything is connected to an A/C current. The wires are on both sides of the channel lying vertically flat on the surface. This design is implemented so that the positive and negative charges can be distributed evenly. The vertical composition is also a more efficient design because whether you cut the electron vertically, it will remain the same, except on the x and z axis.

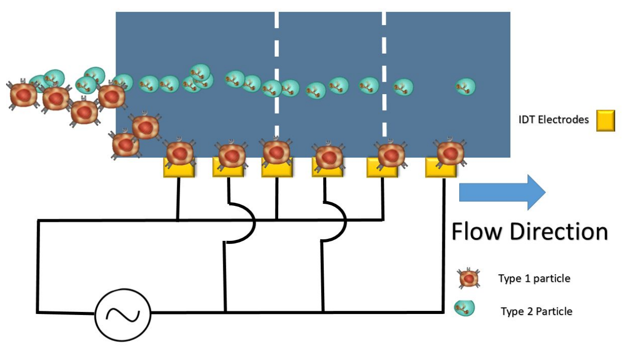

Fig 2: Schematic of the working of the proposed microfluidic device

In the separation section, the microparticles are subjected to either p-DEP or n-DEP. If the microparticle is subjected to pDEP, then it will be pushed farther away from the IDT electrodes of the separation section. On the other hand, if the incoming microparticle is subjected to p-DEP then it will be drawn closer to the IDT electrodes, sticking to the electrodes on the bottom on the boundary as shown in the figure. Thus by simultaneously generating p-DEP and n-DEP, it is possible to separate the heterogeneous mixture of microparticles, at the inlet of the microfluidic device, into two homogeneous mixtures. The n-DEP experienced by microparticle in the separation section needs to be strong for pushing the microparticle onto the bottom surface of the channel. The p-DEP experienced by the microparticle in the separation section is strong to draw near to the IDT electrode. The operating frequency in the separation section is chosen appropriately to subject certain microparticles to p-DEP and the remaining microparticles to n-DEP. The choice of operating frequency depends on the type of microparticles handled in the microfluidic device.In our case, we would need to figure out the optimal frequency to separate endothelial cells appropriately. To further visualize, Fig. 2 provides an illustration of the anticipated flow for the microparticles.

III. Theoretical Model

The motion of a dielectric microparticle through a microchannel can be tracked by Newton's second law of motion (1) where the total external force on the particle is equal to the product of the particles mass and acceleration.

$$\sum F_{ext} = m_p \frac{d^2 X_p}{dt^2} \quad (1)$$

The equation above (1) uses $\boldsymbol{F}_{ext}$ (N) , m_p (kg), and X_p (m) as the external force, mass, and displacement of the microparticle respectively. Placing the microparticles in a non-uniform electric field adds a dielectrophoretic force contributes to the motion of the microparticle through the channel (2).

$$F_{DEP} = 2\pi\varepsilon_m r_p^3 Re(f_{CM}) \nabla E^2 \quad (2)$$

$$f_{CM} = \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*} \quad (3)$$

$$\varepsilon^* = \varepsilon - \frac{\sigma}{\omega} j \text{ and } \sigma_p = \frac{2k_p}{r_p}$$

The F_{DEP} equation (2) has multiple components where ε_m is the absolute permittivity of the medium, r_p is the radius of the microparticle, σ_p (S/m) is the conductivity, and f_{CM} is the Clausius-Mossotti factor. The f_{CM} represents the frequency that stands for a positive or negative DEP force. For this equation, we will only be concerned with the real component of fcm represented by $Re(f_{CM})$.

Drag force is another factor that must be accounted for in the second law equation. Drag force can be calculated by multiplying the difference between the instantaneous velocities of the medium ($\boldsymbol{U}_m$) and the microparticle ($\boldsymbol{V}_p$) by the viscosity of the medium and the radius of the microparticle (4)[10]..

$$F_d = 6\pi\mu_m r_p (U_m - V_p) \quad (4)$$

Before we start doing calculations, we can start to simply our equation. Based on our design of our channel, we can see that there is no variation along the width of the channel. This allows us to eliminate the calculation of the z-component and make our problem 2-dimensional.Following the same trend of simplifying calculations, we can also determine that there is no variation in the flow of the medium along the y-direction. This eliminates the Um term in our drag force equation along the y-component [10].

$$U_m = \left[\frac{\left(\frac{48Qm}{\pi^3 WH}\right)\left[\sum_{i=1,3,5} \left(\frac{(-1)(}{i^3}\right) cos\,[i] \left\{1 - \frac{cosh\,[[i]]}{cosh\left(\frac{i\pi H}{2W}\right)}\right\}\right]}{\left[1 - \sum_{i=1,3,5} \frac{tanh\left(\frac{i\pi H}{2W}\right)}{i^5}\right]} \; 0 \right] \quad (5)$$

For our second law equation to be complete, we have a couple more forces to account for in the y-component. When the particle travels along the medium, it experiences a buoyancy force (6) as it floating in the medium. This force works against the natural force of gravity (7) as the particle moves through the channel[10].

$$F_b = \rho_m V_p g \quad (6)$$

$$F_g = \rho_p V_p g \quad (7)$$

ρ_m (kg/m^3) stands for the density of suspension medium and ρ_p (kg/m^3) stands for the density of the microparticle. V_p (m^3) represents the volume of the microparticle. Lastly, the acceleration due to gravity is expressed by g (m/s^2).

Expressing the left-hand side of (1) in terms of all forces encountered by the microparticle results in the preceding equation [10].

$$\sum F_{ext} = F_b - F_g - F_d + F_{DEP} \tag{8}$$

Our second law equation is now complete (8). The calculation along the x-component has less variables as the buoyancy force and gravity is equal to 0 in that direction. However, the equation along the y-component in represented in the equation below. The next equation (9) takes a step further and substitutes the remaining terms for equation component of the second law equation.

$$[\frac{d^2X_p}{dt^2}\ \frac{d^2Y_p}{dt^2}] = \rho_m V_p[0\ g] - \rho_p V_p[0\ g] - 6\pi\mu_m r_p[U_{m,x} - \frac{dx}{dt}\ \ - \frac{dy}{dt}\ ] + 2\pi\varepsilon_m r_p^3 Re(f_{CM})[\nabla {E_x}^2\ \nabla {E_y}^2\ ]$$
(9)

In order to solve (9) it is important to know the electric field. Electric field inside the microchannel needs to be solved prior to solving (9). The electric potential inside the microchannel is dictated by (10). Once the electric potential inside the microchannel is available, the electric field inside the same microchannel can be determined using (11).

$$(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2})V = 0 \tag{10}$$

$$E_x\vec{i} + E_y\vec{j} + E_z\vec{k} = -(\frac{\partial V}{\partial x}\vec{i} + \frac{\partial V}{\partial y}\vec{j} + \frac{\partial V}{\partial z}\vec{k}) \tag{11}$$

Where V (V) is the electric potential inside the microchannel. Solution of electric potential and calculation of electric field, using (11) and DEP forces, using (2) are not determined over the entire microchannel but rather just inside a single repeating unit and then the information mapped onto the entire microchannel. This approach is less taxing in terms of computational resources and faster. The repeating units are provided in Fig. 3 and Fig. 4 along with the associated boundary conditions. Fig. 3 is the repeating unit of the focusing section while Fig. 4 is the repeating unit of the separation section.

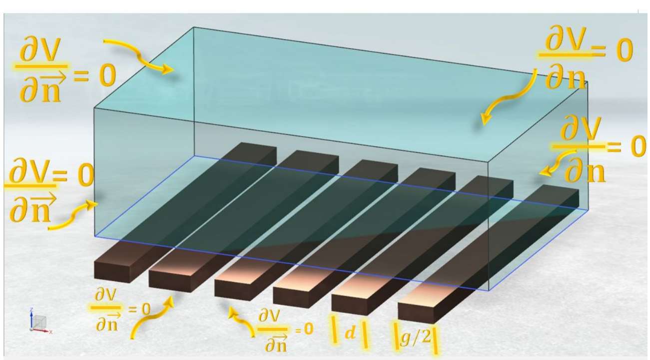

Fig 3: Repeating unit with boundary conditions

Following our long second law equation, we see that the only unknown terms left is the electric field. Since the z-component is eliminated, we can use the finite difference method to solve equation (10) and (11). Solving these equations will provide us with the electric field and allows us to use the repeating unit, Fig. 3, to finally track the movement of the particle throughout the channel.

IV. Results and Discussions

Fig. 4 shows the contour graph depicting the height and voltage of the electric field at various points throughout the channel. It can be noticed that as expected, the electric field decreases with increase in height in both the sections. We were able to capture the discrepancies with the microfluidic device in terms of separating the microparticles by either Silicon dioxide or Polystyrene. This has given us the assurance that

the proposed microfluidic device can achieve separation of microparticles based on type. When electrodes of the type shown in Fig. 1 are employed, each electrode needs to be powered individually which in turn

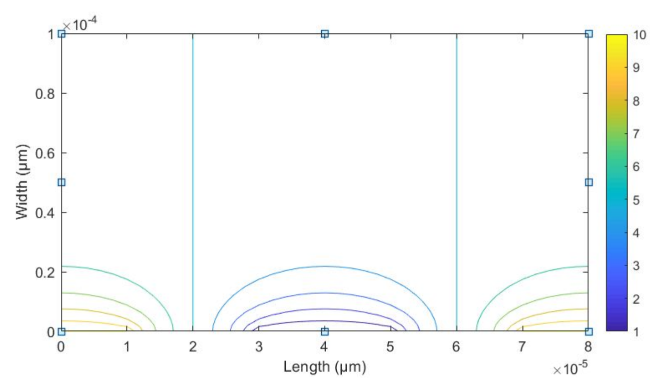

Fig 4: Voltage of electric field (V/m) at various points in the fluid channel.

limits the number of electrode pairs possible within the dimensions of a microfluidic device. Ten electrode pairs are accommodated within a typical microfluidic device and thus used in this study.

Fig. 5 depicts the plot of the Polystyrene particle at select voltages & flow rates. This was done to show the variations on the response of our calculations. Fig. 6 depicts this same variation but on the Silicon dioxide particle. For both microparticle types, Silicon dioxide and Polystyrene, the they follow our anticipated results. Polystyrene follows the pDEP path as it is attracted to the electrodes. Silicon dioxide follows the nDEP path as it is pushed away from the electrodes. Through the success of the microfluidic channel, it allows for the non-uniformity to come into use. With the horizontal placement of the electrodes and vertical motion of the fluid, the non-uniform electric field can attract the desired type while repelling the alternative type.

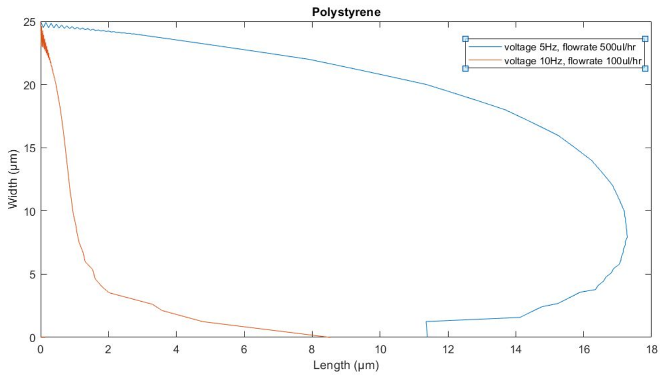

Fig. 5: Plot graph of Polystyrene at 2 distinct voltages and flow rates. This shows the effect of the variation on the plot.

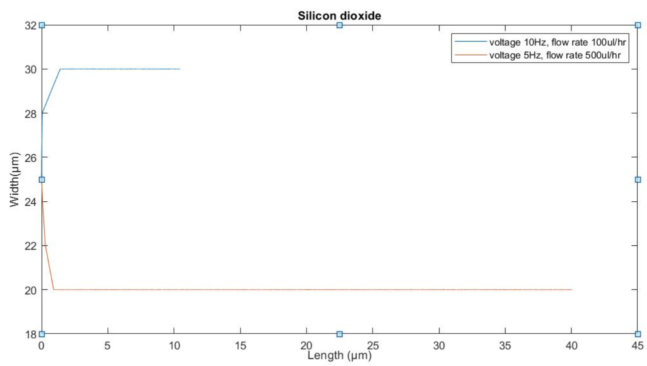

Fig. 6: Plot graph of the Silicon dioxide particle at 2 distinct voltages and flow rates. This shows the effect of the variation on the plot.

In the case of our channel shown in Fig. 1 and Fig. 2, the width and height both equal to 50 μm and employing ten electrode pairs in the focusing and separation sections. The applied potential for the microfluidic device is 10 V_{pp} while the operating frequency of the focusing is section is 1E5 Hz. Our operating frequency in radians per second is equated to

$$w = N(2\pi) \tag{14}$$

The flowrate is maintained at 100 μl/h and the initial vertical position is 25E-6 m.

V. Conclusion

The viability of a microfluidic device for separating microparticles based on size and type using the dielectrophoresis method is studied in this article using a mathematical model. The microfluidic device consists of lateral electrodes along the full length of the channel. This layout ensures that all microparticles are subjected to same or equal voltage in DEP non-uniform electric field when they are flowing through the channel. The microparticles are subjected to the force from the electric field along with buoyancy force, DRAG force and the force due to gravity. Contingent upon the properties of the microparticles, the microfluidic channel allows for the achievement of separation of the particles and the response to those having different lateral displacements thereby achieve separation. It is observed from the model that operating and geometric parameters influence the performance of the microfluidic device. This study was primarily focused at proving the possibility of the proposed design of microfluidic device for purposes of type-based separation. Future work is dedicated towards a detailed analysis of the influence of operating and geometric parameters of the microfluidic device as well as experimental validation of the model.

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