Fluido-Dynamic and Electromagnetic Characterization of 3D Carbon Dielectrophoresis with Finite Element Analysis

R. Martinez-Duarte[*], S. Cito[**], Esther Collado-Arredondo[***], S. O. Martinez[***] and M. Madou[*]

[*]Mechanical & Aerospace Engineering Department, University of California, Irvine, 4200 Engineering Gateway, Irvine, CA, 92617, USA, drmartnz@gmail.com
[**]Universitat Rovira i Virgili, Tarragona, Spain, salvatore.cito@gmail.com
[***]Tecnológico de Monterrey, Campus Monterrey, Monterrey, Mexico, smart@itesm.mx

ABSTRACT

The following work presents the fluido-dynamic and electromagnetic characterization of a 3D electrodes array to be used in high throughput and high efficiency Carbon Dielectrophoresis (CarbonDEP) applications such as filters, continuous particle enrichment and positioning of particle populations for analysis. CarbonDEP refers to the induction of Dielectrophoresis (DEP) by carbon surfaces. The final goal is, through an initial stage of modeling and analysis, to reduce idea-to-prototype time and cost of CarbonDEP devices to be applied in the health care field. Finite Element Analysis (FEA) is successfully conducted to model velocity and electric fields established by polarized high aspect ratio carbon cylinders, and its planar carbon connecting leads, immersed in a water-based medium. Results demonstrate correlation between a decreasing flow velocity gradient and an increasing electric field gradient toward electrodes' surfaces which is optimal for CarbonDEP applications. Simulation results are experimentally validated in the proposed applications.

Keywords: carbon, dielectrophoresis, c-mems, high flow rate, simulation.

1 INTRODUCTION

Even when the field of bioparticle separation has advanced significantly in recent years with the wide use of techniques such as Fluorescence-Activated Cell Sorting (FACS) or MACS (Magnetically-Actuated Cell Sorting) such techniques require the use of specific, and often expensive, tags to achieve high selectivity. An ideal solution would be a technology which eliminates the need of such tags while maintaining a high throughput separation process. We believe Dielectrophoresis (DEP), the induction of a force, F_{DEP}, on a polar particle immersed in a polar media by a non uniform AC or DC electric field, could be such solution. A huge advantage of DEP is the selection of the targeted particle, by inducing either an attractant or repellent F_{DEP} force to the nearest electrode surface, using only its intrinsic dielectric properties which are solely determined by the particle's individual phenotype such as its membrane morphology. Such advantage eliminates the need of specific tags linked to magnetic beads or fluorophores to discriminate targeted particle types potentially reducing the cost of each assay.

As an enhancement to current DEP devices, we propose the use of Carbon Dielectrophoresis (CarbonDEP). Carbon DEP refers to the use of carbon surfaces to induce DEP. Carbon surfaces offer better electrochemical and biocompatibility properties than other conductive materials [1] as well as lower costs. The use of volumetric (3D) structures allows higher throughput than traditional planar DEP devices [2] towards rates comparable to current separation techniques.

In the following work we present initial models and analysis of a proposed CarbonDEP array to characterize its advantages. The use of Finite Element Analysis is towards implementing a design and fabrication methodology leading to shorter development times of CarbonDEP applications in the health care field. In contrast to previous work where 3D electrodes arrays made out of a perfect conductor and immersed in DI water [3] or only simplified planar geometries in conductive media are simulated [4], we have modeled and analyzed both electric and flow velocity fields independently in an array of polarized carbon 3D electrodes and their 2D connection leads immersed in a water-based medium. Simulated geometry is a replica of physical device. Experimental validation and examples of applications are also described.

2 MATERIALS AND METHODS

Complete experimental device fabrication procedure is detailed elsewhere [2]. Briefly, a 5 X 29 array of carbon electrodes, and their connecting leads, is obtained through the C-MEMS technique [1]. CarbonDEP array features 60 µm high post electrodes with a diameter of 25 µm. The gap between electrodes in the axis parallel to the channel wall is 40 µm while it is 100 µm in the perpendicular one. A 500 µm wide, 65 µm high channel was then fabricated around the electrode array using SU-8 (MicroChem Corp.). Finally, the device was sealed and electrical connections were made. Channel features SU-8 on the four walls.

The geometry implemented for simulations is based on the experimental device. Given the symmetry of the

CarbonDEP array, its length was reduced from 5 X 29 to 5 X 5 to reduce computational power requirements.

2.1 Electromagnetic Analysis

Electromagnetic simulation was conducted using COMSOL v3.3 (COMSOL) running in a Workstation having Solaris 9 (Sun Microsystems) as operating system (OS). Processor used was a Sun Blade 1500 @ 1 GHz. 2 GB of RAM and up to 5 GB of Virtual Memory were at hand.

Analysis is completed by separately meshing connecting leads and carbon posts using Triangular 2D meshes and implementing coupling through identity boundary conditions. Carbon structures were considered to have an equal resistivity at all points of 1.07×10^{-4} W-m [4]. Electrodes are assumed to be in contact with a water medium of conductivity equal to 2 mS/m. Excitation voltage was 4 V_{pp}. Boundary conditions are those of an insulator in all channel walls and in channel regions furthest away from electrode array.

2.2 Fluido-dynamic Analysis

Fluido-dynamic simulation was conducted using Fluent 8.3 (ANSYS, Inc.).

Analysis is done by applying a 3D model and numerically solving the Navier-Stokes equation in a structured grid using an absolute velocity formulation with a relaxation factor of 0.3 for the pressure, density Body forces and momentum variables. Problem has been solved in steady condition as a fully developed flow assuming a Newtonian flow with water as a fluid. Boundary conditions are those of No-slip imposed on the channel walls and carbon posts' surface. A 3D pressure-based laminar approach has been considered with a mass-flow channel inlet of 1.6×10^{-7} kg/s and an outflow boundary condition at the outlet. Such condition assumes a zero normal gradient for all flow variables except pressure. Velocity and pressure have been coupled using the standard SIMPLE model that uses a relationship between velocity and pressure corrections to enforce mass conservation and to obtain the pressure field. For the numerical discretization, a second order upwind scheme has been used.

3 RESULTS

3.1 Electromagnetic

Isometric views of the Electric field distribution at 10 µm from the channel floor (Fig. 1 A) and at 60 µm (Fig 1 B) are shown together with a detailed top view of the 30 µm cross section of the array (Fig. 1 C). As expected, at 10 µm one can discern a fairly strong electric field gradient induced by the connection leads. At 60 µm, top of the channel, the electric field gradient induced by the leads completely vanquishes and the one generated by the carbon posts predominates. Fig. 2 is a X-Z cross section at point A on Fig. 1C clearly showing how the effect of the leads diminishes as distance from the channel floor increases.

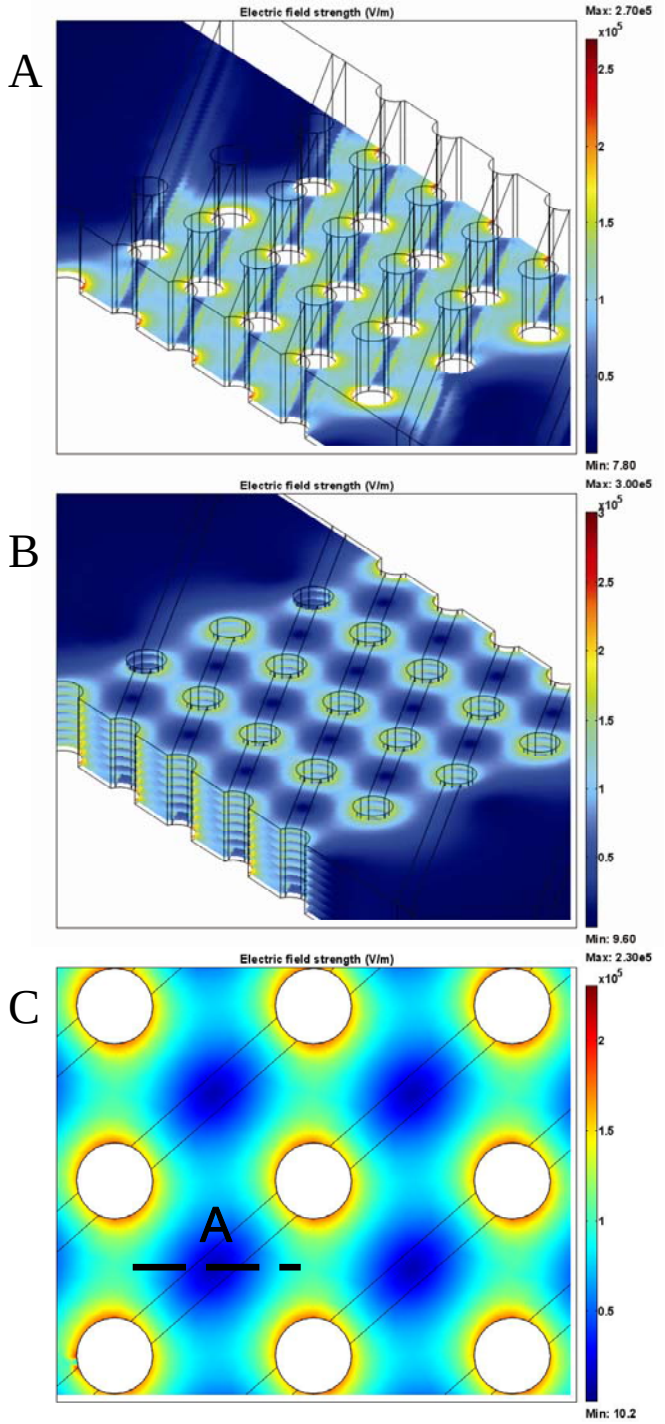

Fig 1. Electric field distribution in a Carbon electrode array contained in a SU-8 channel at 10 µm from channel bottom (A), at 60 µm (B) and top view of 30 µm cross section (C). Excitation Voltage of 4 V_{pp} with medium conductivity of 2mS/m.

NSTI-Nanotech 2008, www.nsti.org, ISBN 978-1-4200-8505-1 Vol. 3

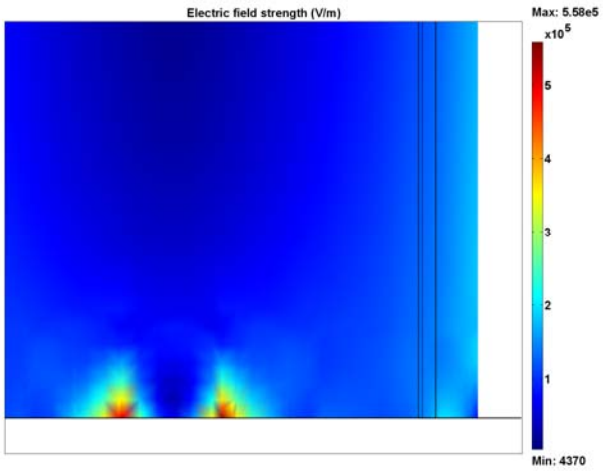

Fig. 2. X – Z cross section on electric field distribution in a Carbon electrode array. Note how the electric field gradient induced by connection leads in channel bottom quickly vanishes at around 20 µm from channel floor.

3.2 Fluido-dynamic

3D Flow velocity field is shown in Fig. 3 A. X-Y, X-Z and Y-Z cross sections are shown in Fig. 3 B, C and D respectively. Analysis clearly shows a 3D parabolic flow profile with highest velocities in between electrodes in the plane perpendicular to channel wall (Fig. B and D).

4 DISCUSSION

Following DEP theory, it is known how particles exhibiting Positive DEP at a given frequency are attracted to high electric field gradient areas while particles exhibiting Negative DEP get repelled to more stable low electric field gradient areas. Based on such principles one designs an electrode array to induce desired electric field distributions optimized for specific applications.

Important is to note how the electric field gradient increases towards the electrode surfaces'. Furthermore, thanks to the different electrode arrangement in the X and Y axis, higher electric field gradients coincide with lower velocity magnitude areas. Such correlation proves to be optimal for DEP trapping since F_{DEP} is at its maximum where velocity magnitude is at its minimum. Such distribution also restricts the trapping of desired particles, and the subsequent particle cluster, to areas that would minimally disturb the path lines and maintain the laminar flow.

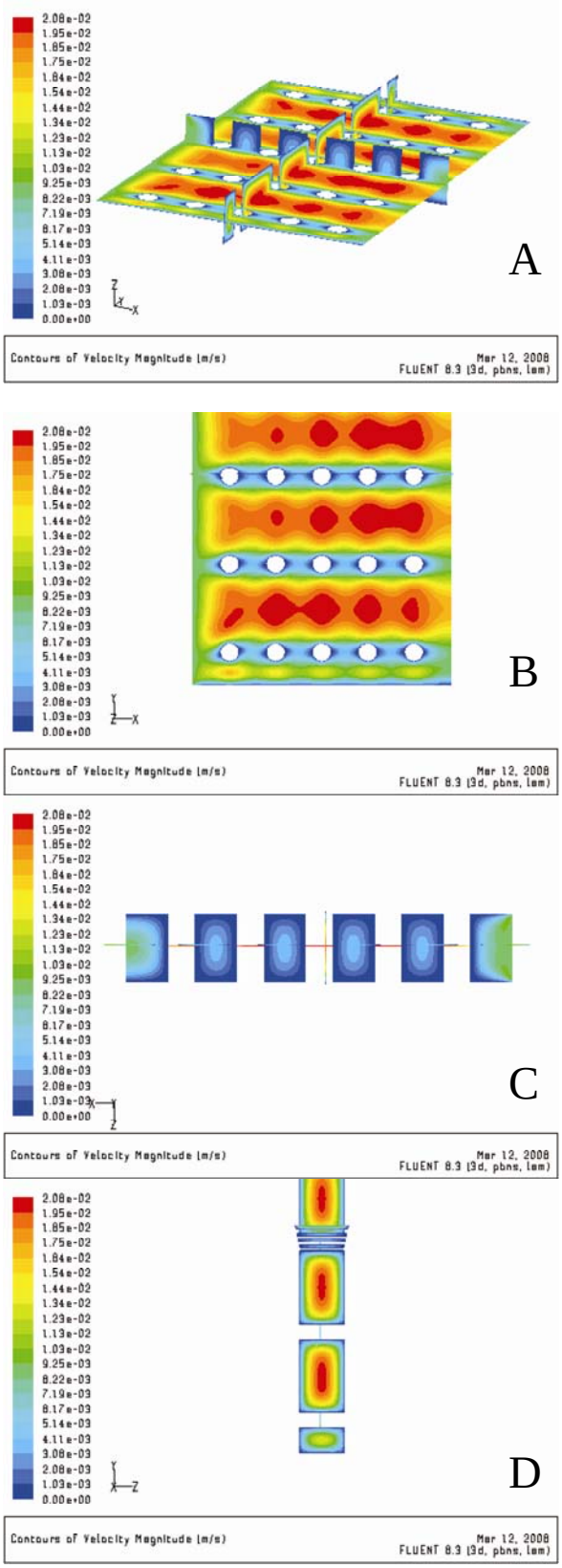

Fig. 3. Simulation results showing the flow velocity field in a Carbon electrode array for a 10 µl/min flow. 3D model (A), X – Y (B), X – Z (C) and Y –Z (D) cross sections.

5 EXPERIMENTAL VALIDATION AND APPLICATIONS

Fig. 4 shows the trapping of yeast against a 10 µl/min flow flowing from the left. It can be clearly seen how yeast is trapped in those areas predicted by the electromagnetic analysis.

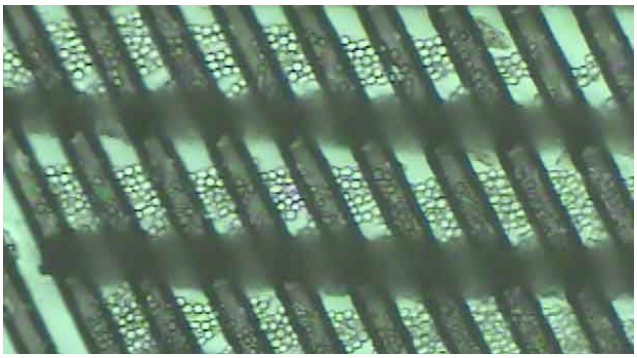

Fig. 4. Yeast trapped in high electric field gradient areas in a CarbonDEP array as predicted by electromagnetic analysis (Fig. 1 A and B). Optical Image focused on channel bottom (compare to Fig. 1A). Dark lines represent tightly trapped yeast which are out of focus (Compare to Fig. 1B).

5.1 Filter

Fig. 5 shows the filtering of viable yeast, by DEP trapping to carbon electrode surface, from non viable yeast at a 10 µl/min flow. Experimental details and Filter efficiencies for different flow rates are described elsewhere [ ]. The correlation of a decreasing flow velocity gradient and an increasing electric field gradient towards electrode surface improves viable yeast trapping.

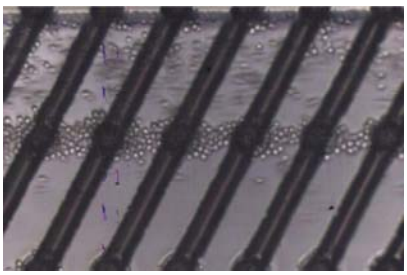

Fig. 5. Viable yeast filtered from Non viable yeast against a 10 µl/min flow using a polarized CarbonDEP array at 5 MHz and 10 V_{pp}. Medium conductivity of 51 mS/m.

5.2 Continuous Enrichment

Fig. 6 shows the continuous enrichment of viable yeast by Positive Dielectrophoresis Focusing. The principle works when the hydrodynamic force overcomes the DEP trapping force. Since laminar flow is established in the channel and path lines have been shown to be minimally disturbed by our array geometry, viable yeast flushes away contained in those flow lines co-linear with the polarized electrode rows. Such principle allows continuous separation at higher flow rates than those achieved when implementing separation by trapping, such as in a filter, but requires more complicated geometries for enriched population retrieval.

Fig. 6. Continuous enrichment of viable yeast at 20 µl/min with a polarized CarbonDEP array at 1 MHz and 10 V_{pp}. Medium conductivity of 51 mS/m.

6 CONCLUSIONS

We have demonstrated how our 3D CarbonDEP array 1) achieves higher throughput by inducing positive and negative DEP regions in the bulk of the channel and not only in the vicinity of channel walls as in the case of 2D DEP systems, 2) induces an increasing electric field magnitude gradient towards the electrodes' surfaces, 3) establishes a decreasing flow velocity gradient towards the electrodes' surfaces, 4) establishes an optimal correlation between a decreasing flow velocity gradient and increasing electric field gradient toward electrodes' surfaces and 5) do not create physical traps by minimally disturbing the flow path lines. Furthermore we demonstrate such advantages in the detailed applications.

ACKNOWLEDGEMENTS

This work was supported in part by the University of California Institute for Mexico and the United States (UC MEXUS), award number UCM- 40117 .

REFERENCES

[1] C. Wang, et al, Journal of Microelectromechanical Systems, **14**, 2, 348, 2005.
[2] R. Martinez-Duarte, et al, Proceedings of the 11th International Conference in Miniaturized Systems for Health and Life Systems: microTAS 2007, Paris, France, **1**, 828, 2007.
[3] B.Y. Park, M.J. Madou, Electrophoresis, **26,** 3745, 2005.
[4] B.Y. Park, M. Madou, Journal of the Electrochemical Society, **152**, 12, J136, 2005.