Modeling of Dielectrophoresis for Handling Bioparticles in Microdevices

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ABSTRACT

Dielectrophoresis can be used to trap and position bioparticles such as biological cells efficiently and successfully in BioMEMS devices. This paper presents a computational model to simulate this process. In particular, the model will solve for electric potential distribution, bioparticle movement in a Lagrangian frame, Joule heating, and medium flow due to electrothermal effects. As an illustration, the model was used to simulate a cell trapping process in a three-dimensional chamber.

Keywords: dielectrophoresis, Joule heating, cell traps, electrothermal effects

NOMENCLATURE

C_D	drag coefficient
$\mathbf{E}$	electric field intensity
$\mathbf{f}$	force due to electrothermal effect
$\mathbf{F}_{DEP}$	dielectrophoretic force
K	medium thermal conductivity
m_p	particle mass
P	pressure
r_p	particle radius
$\mathbf{U}$	velocity of suspending medium
$\mathbf{V}$	particle velocity
$\mathbf{X}$	particle location

Greek Symbols

ϵ	medium permittivity
ϵ^*	complex medium permittivity
ϵ_p^*	complex particle permittivity
μ	dynamic viscosity of medium
ω	angular frequency of electric field
ϕ	electric potential
ρ	medium density
σ	electric conductivity

1 INTRODUCTION

Dielectrophoresis (DEP) means the creation of forces on polarizable particles and the resulting movement of them in a nonuniform electric field (usually AC electric fields)[1-2]. Dielectrophoretic forces can be used as a mechanism in various BioMEMS devices for characterization, handling, and manipulation of microscale and nanoscale bioparticles including sorting, trapping, and separating of cells, viruses, bacteria, and DNA etc.[3-8]. For example, compared to traditional laboratory experiments, manipulating an individual cell or a group of cells in various BioMEMS devices based on dielectrophoretic force allows scientists to obtain new kinds of biological information, leading to new insights into how cells work. Therefore, dielectrophoresis, as well as MEMS devices based on it for operation, plays more and more important roles in the study of biology and medical sciences and it has a broad range of applications in drug discovery, diagnostics, and cell therapy. Developing a computer model to simulate a dielectrophoresis process is not only important and useful for design of new DEP devices for bioscience applications, but also for optimal operation of them. Motivated by these facts, a model for particle dielectrophoresis is developed and presented in this paper.

As mentioned above, the dielectrophoretic force is utilized in various BioMEMS devices for handling bioparticles. The magnitude and direction of DEP forces depend on the frequency of the AC electric field, conductivity and permittivity of both particles and the medium where particles are suspended, and the gradient of electric field. The gradient of electric field is dependent on the geometry and numbers of microelectrodes used. In addition, the strong electric fields adopted in dielectrophoresis generate a large power density (**Joule or Ohmic heating**) in the suspending medium. Due to high nonuniformity of electric field thereby power density, a temperature gradient yields, which results in gradients of conductivity and permittivity. The former produces a free volume charge and a Coulomb force while the latter creates a dielectric force. These two forces cause medium flow, called **electrothermal effect**, and give rise to an effect of dielectrophoresis of bioparticles[9]. In present work, a comprehensive model is developed. In addition to the calculation of electric field and dielectrophoretic force on bioparticles, Joule heating and electrothermal effects are also included in the model. In the following section, the related governing equations and numerical methods are described. To demonstrate the application of the developed model, a

three-dimensional cell culture chamber is simulated and the results are presented in a separate section. Finally, the paper is ended by a brief conclusion.

2 GOVERNING EQUATIONS AND NUMERICAL METHODS

Flow of a suspending medium is described by the following incompressible mass and momentum conservation equations (The vector variables are represented in bold face in this paper.)

$$\nabla \cdot \mathbf{U} = 0 \tag{1}$$

$$\rho \left[\frac{\partial \mathbf{U}}{\partial t} + \mathbf{U}(\nabla \cdot \mathbf{U}) \right] = -\nabla P + \mu \nabla^2 \mathbf{U} + \mathbf{f} \tag{2}$$

where the force created due to aforementioned electrothermal effects can be calculated by

$$\mathbf{f} = -0.5 \left(\frac{\nabla \sigma}{\sigma} - \frac{\nabla \epsilon}{\epsilon} \right) \cdot \mathbf{E} \frac{\epsilon \mathbf{E}}{1 + (\omega \sigma / \epsilon)^2} - 0.25 E^2 \nabla \epsilon \tag{3}$$

with gradients of σ and ϵ determined in terms of temperature distribution[9]. Temperature distribution due to Joule heating is solved from

$$K \nabla^2 T + \sigma E^2 = 0 \tag{4}$$

while movement of bioparticles due to dielectrophoresis is given by

$$m_p \frac{d\mathbf{V}}{dt} = -\frac{1}{2} \pi r_p^2 \rho C_D |\mathbf{V} - \mathbf{U}| (\mathbf{V} - \mathbf{U}) + \mathbf{F}_{DEP} \tag{5}$$

$$\frac{d\mathbf{X}}{dt} = \mathbf{V} \tag{6}$$

with the dielectrophoretic force imposed on a bioparticle calculated by

$$\mathbf{F}_{DEP} = 2\pi \epsilon r_p^3 \Re \left[\frac{\epsilon_p^*(\omega) - \epsilon^*(\omega)}{\epsilon_p^*(\omega) + 2\epsilon^*(\omega)} \right] \nabla E^2 \tag{7}$$

where $\Re$ represents the real part of a complex number[2]. Electric potential is derived by solving

$$\nabla^2 \phi = 0 \tag{8}$$

followed by the calculation of the electric field distribution using

$$\mathbf{E} = -\nabla \phi \tag{9}$$

The model presented here is implemented in ***FLOW-3D***®—a general purpose commercial CFD code. In particular,equations (1-4) and (8-9) are discretized in a set of fixed Eulerian grids or control volumes. Handling of a complicated computational domain is performed using a fraction- area- volume- obstacle- representation (FAVOR™) method[10]. The movement of bioparticles are tracked by solving Eqns.(5-6) in a Lagrangian frame. Detailed numerical methods adopted to solve for these governing equations can be found in [11].

Figure 1: Cell culture chamber geometry

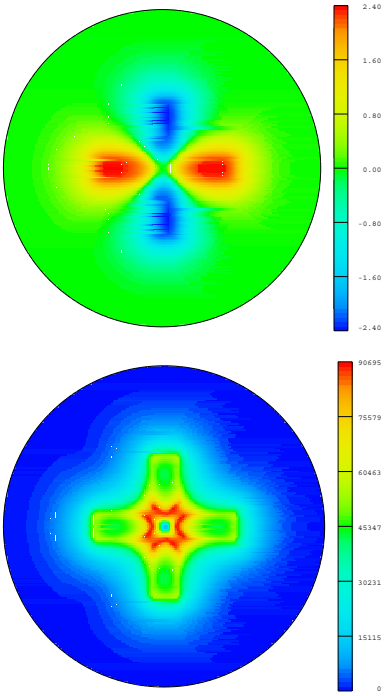

Figure 2: Top: electric potential; Bottom: electric field strength

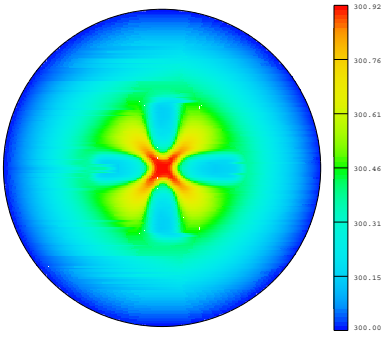

Figure 3: Temperature distribution

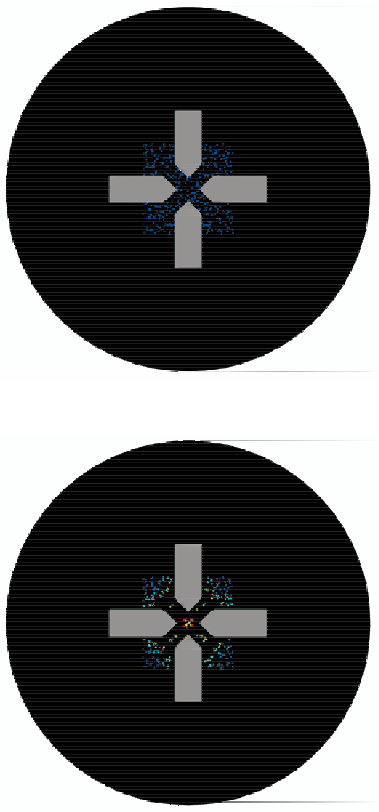

Figure 4: Particle distribution at two different times

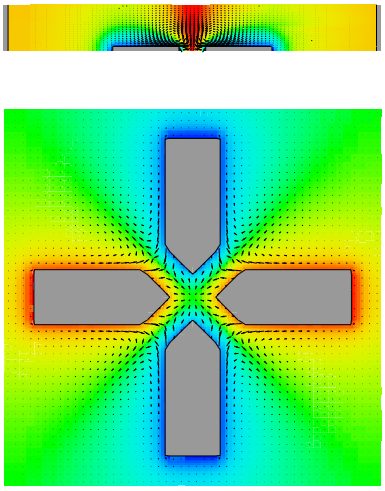

Figure 5: Velocity distribution

3 NUMERICAL RESULTS

To demonstrate the application of the presented model, a cell culture process in a three-dimensional chamber is simulated. The chamber geometry is displayed in Fig.1 with a chamber diameter equal to 800 μm and a depth equal to 100 μm. Also shown in the same figure are four microscale electrodes deposited on the bottom of the chamber which provide the electric potential. Experimental studies of cell trapping in this kind of device was performed by Heida et al.[6-8]. The viscosity, density, permittivity, and electric conductivity of suspending medium used in the simulation are $8.55\times10^{-4}\ N\cdot s/m^2$, 1000 kg/m^3, $6.95\times10^{-6}\ C^2/Jm$, and 0.1 Sm^{-1}, respectively. The value of $\Re$ appearing in Eqn.(7) can be obtained from the related handbook based on the angular frequency ω for a specific medium-particle pair. In the simulation presented here, a value of -0.1 was used.

Cell culture operation involves particle movement (cell trapping) due to dielectrophoresis, Joule heating created by a strong electric field and electrothermal effects corresponding to Joule heating. The model presented here captures all these physical processes. The top of Fig.2 shows electric potential distribution created by four microscale electrodes on a cross section 5 μm above the chamber bottom. The magnitude of the rms (root mean square) value of electric potential on the electrode surface is 3 volts. The electric field strength distribution at the same cross section is plotted in the bottom of Fig.2. As expected, strong electric field strength was observed near the edges of electrodes. In particular, a "potential energy well" in the center of the chamber, with minimum electric field strength at its center, is formed where some cells are trapped. To see the trapping, particle distribution at beginning of the operation (top) and at a later time (bottom) are displayed in Fig.4. Even though it is not possible to make a qualitative comparison between numerical predictions and corresponding experimental measurements due to the lack of detailed information on experimental conditions, a quantitative comparison with the experiments performed by Heida et al.[6-8] indicates that particle distribution derived from the present model is consistent with the experimental observation. Due to the high electric field and sensitivity of bioparticles on temperature, Joule heating may be significant. The temperature distribution due to Joule heating is provided in Fig.3. About a 1K temperature increase was observed. Medium flow around the "potential energy well" due to electrothermal effects are illustrated in Fig.5 with the top figure representing flow in a vertical cross section passing through the middle of chamber and the bottom figure representing flow on a horizontal cross section immediately above the chamber bottom. It can be seen that medium flow could affect cell trapping depending

on the operation conditions.

Here, we provide some results to illustrate the application of the presented model. For the design of a BioMEMS device, engineers need to know how to determine the number of microelectrodes and their geometry. For the use of these devices, it will be useful to know how to control different physical processes involved and get optimal operation. To this end, the present model will be useful for both design and operation of the related BioMEMS devices.

4 CONCLUSION

A computational model was developed and implemented in ***FLOW-3D***®—a general purpose commercial CFD code—to solve for electric potential distribution, Joule heating, and medium flow created by electrothermal effects. Numerical results derived from the simulation of cell trapping in a three-dimensional chamber demonstrated that the present model could be useful for the design and operation of the related BioMEMS devices.

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