NUMERICAL MODEL FOR MICROPARTICLE AND LYMPHOCYTE MOTIONS IN DIELECTROPHORETIC MANIPULATION DEVICE

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ABSTRACT

This paper describes the development of numerical model and scheme that can accurately solve the particle/cell motion dynamics in microchannels considering the physics of the AC electric field, dielectrophoresis (DEP) force, electrothermal flow, and hydrodynamic forces in three-dimensional form. This numerical model can be used to aid the designing of the microchip particularly intended for cell manipulation and separation. To demonstrate the performance of the model, a particle/cell manipulation device using semicircle electrode and microchannel flows was designed and evaluated experimentally.

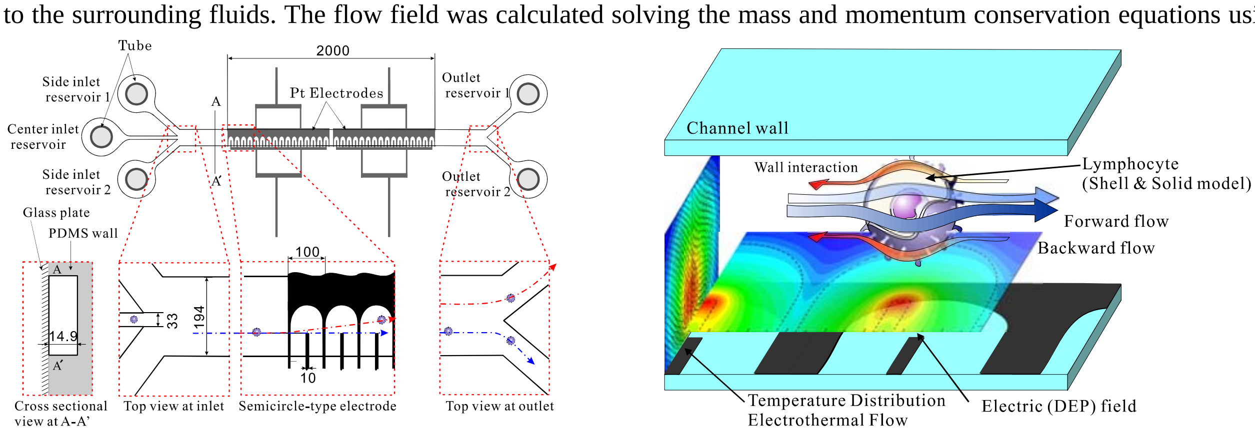
KEYWORDS: Numerical simulation, Cell manipulation, Dielectrophoresis, Microparticle, Lymphocyte

INTRODUCTION

Cell manipulation and separation technology using DEP force and microchannels has been keenly investigated in the past decade providing various types of electrodes and channels [1,2]. However, the manipulation performance has not sufficiently reached the level for practical use in terms of manipulation speed and accuracy. One of the practical issues in developing the devices is the absence of a simulation model that can predict the cell motion and phenomena accurately. The numerical model originally coded in this study considers not only the AC electric field, shell model of the cell and DEP force applied to the cell or particle, but also the flow/particle conjugate problem including the three-dimensional interaction between the solid particle and flow. Further, the influence of the electrothermal flow appearing in the microchannel attributed to the Joule heating is considered in the simulation. Based on the authors' knowledge, such a detail and accurate scheme has not been provided yet, and it will largely contribute to the fields of micro fluidic devices, electrochemistry and medicine. In this study, the numerical scheme was used to design a manipulation device shown in Fig. 1 (a), paying attention particularly on the pattern of the electric fields that can provide stable and effective particle motion. In the manipulation area, comb shape electrodes attached to the channel bottom wall and aligned in the streamwise direction were basically considered to generate a negative DEP force on the particles and move them apart from the straight comb electrodes.

NUMERICAL

The numerical model mainly consists of two parts: the electric field and DEP force for the particle or lymphocyte, and fluids and particle motions. The electric field was calculated using a commercially available software COMSOL multiphysics. The DEP force F_{dep} was then evaluated from the electric field considering the Clausius-Mossotti function of a spherical particle. In this case, the lymphocyte was modeled as a sphere with uniform electric properties which were calculated on the basis of a multi shell model described in reference [3]. Once the F_{dep} was obtained, the equation of fluid and particle motions were calculated. A particle with finite diameter was considered in this study, where the interaction between the particle and fluid was solved using the Immersed Boundary method [4]. Namely, the force applied to the particle surface by the flow shear stress and pressure was considered in the equation of motion, while the particle momentum is then transferred and applied to the surrounding fluids. The flow field was calculated solving the mass and momentum conservation equations using



(a) particle/cell manipulation device *(b) numerical model*

Figure 1: Schematic diagram of (a) the electrodes and microchannel in the particle/cell manipulation device (the dimensions are in μm) (b) three-dimensional numerical model applied to solve lymphocyte motion in the device.

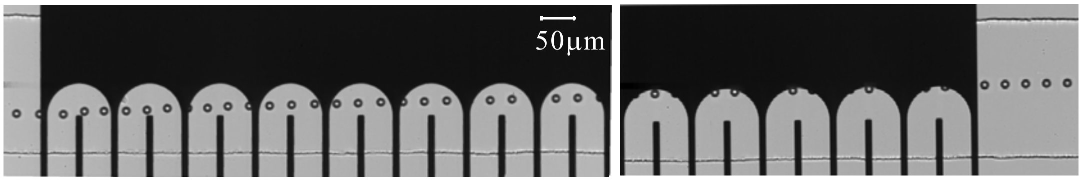


Figure 2: Trajectory of the micro polystyrene particles manipulated by the DEP force.

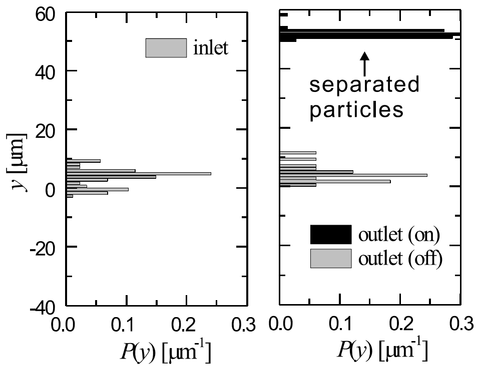


Figure 3: Probability density function at the inlet and outlet positions.

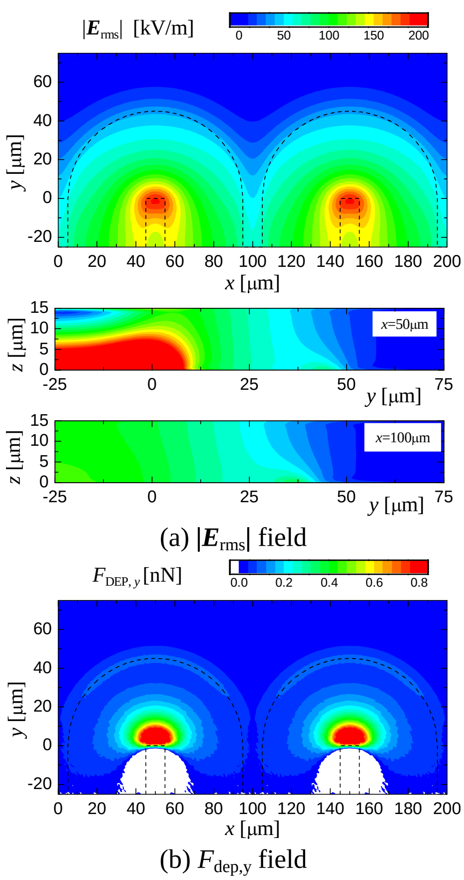


Figure 4: (a) Electric field intensity $|\boldsymbol{E}_{rms}|$ and (b) spanwise dielectrophoresis force $F_{DEP,y}$ distributions on x-y plane at z=7.5μm.

finite volume method and SIMPLE algorism. Further, the energy conservation equation in the channel was solved considering the Joule heating of the electric field in order to calculate the temperature field. The resulting electrothermal flow was then simulated by applied an external force based on the temperature distribution to the momentum equation of the flow field [5]. These computations were carried out in a computational domain presenting a single periodic unit of the manipulation (electrode) area.

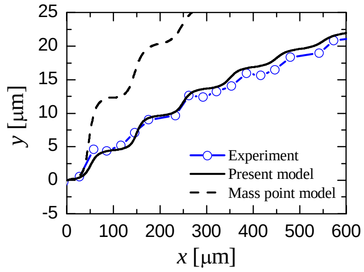
EXPERIMENTAL

As shown in Fig. 1(a), the device has three flow inlets by which a sheath flow is generated and the spanwise position of the particle entering the electrode area is controlled precisely. In the downstream region of the manipulation area, the channel is bifurcated where the particles are normally guided to one side while the specific particles are selected to flow to the other side by activating the dielectrophoretic force. Platinum electrodes were sputtered and patterned on the glass plate onto which the PDMS channel was attached. The motion of the particles was measured using a microscope and high-speed digital video camera, and the particle/cell positions and velocities were measured from the recorded images. Experiment was carried out for polystyrene microparticles (Thermofisher scientific; 4212A) and lymphocyte (ATCC; CRL-2570) suspended in PBS solution using the micro manipulation devise shown in Fig. 1 (a). AC voltage of $19V_{p\text{-}p}$ and 10MHz was applied to the electrodes. The total flow rate in the main channel was 1.2μL/min.

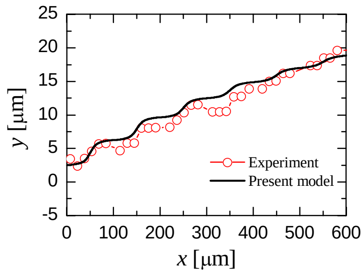
RESULTS and DISCUSSION

Several types of comb shape electrodes were investigated in advance of the experiment employing the present numerical scheme. Among these, the semicircle type electrode shown in Fig. 1 showed a good performance in the meanings of providing large and stable DEP force on the particles for manipulation. The experimental results are shown here to demonstrate the performances. Figure 2 shows the photographs of the polystyrene particle passing the manipulation area. The probability density function (PDF) distributions measured at the inlet and outlet are shown in Fig. 3. As shown in Fig. 2, the particle is effectively driven in the spanwise direction due to the DEP force. The PDF distributions show that the particles led to the electrode tip at the inlet of the manipulation area by the sheath flow are manipulated and separated to the opposite side at the outlet successfully and accurately.

Figure 4 shows the numerical results of the electric field $|\boldsymbol{E}_{rms}|$ distributions, and the spanwise component of the DEP force that works on the particle, $F_{DEP,\,y}$. Since the semicircle shape electrode encircles the other straight electrode, $|\boldsymbol{E}_{rms}|$ gradually deceases toward the semicircle electrode side. As a result, $F_{DEP,\,y}$ shows a positive value in the overall area located between the electrodes. This leads to a stable cell manipulation that was not obtained in other electrode shapes additionally tested in the simulation and experiment.

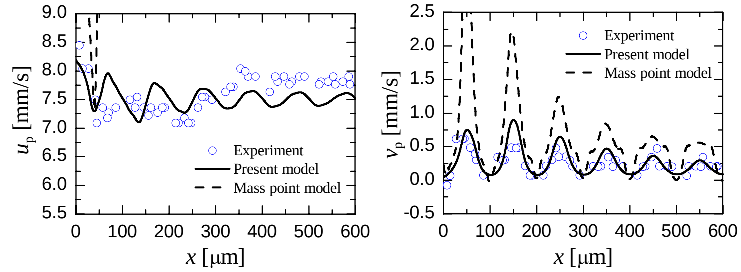


(a) polystyrene particle

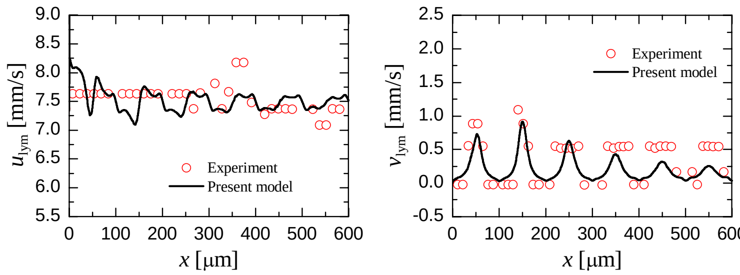


(b) lymphocytes

Figure 5: Trajectories of the polystyrene particle and lymphocytes.



(a) polystyrene particle



(b) lymphocytes

Figure 6: Instantaneous streamwise and spanwise velocity distributions of polystyrene particles and lymphocytes.

Figure 5 shows the experimental and numerical results of the trajectories projected on the x–y plane in the cases of the particle and lymphocyte motions. Figure 6 shows the streamwise and spanwise velocities, u_p and v_p, of both cases. To demonstrate the accuracy of the present scheme, the numerical results applying the model that assumes the particle as a mass point and neglecting the influence of the particle on the flow are also depicted in the figure.

Focusing on the pattern of the trajectories and the velocity distributions, the particle moves in the spanwise direction in a staircase pattern with a large displacement observed in the area close to the electrode tip. This agrees well with the feature of the $F_{DEP,\,y}$ distribution shown in Fig. 4 (b). Comparing the numerical and experimental results, the calculation using the mass point model over-predicts the velocity and the spanwise position of the particle. This is mainly attributed to the lack of consideration on the particle-fluid interaction that markedly influence the flow field and resulting particle behavior. Therefore, in the case of the calculation employing the present numerical scheme, an excellent agreement is achieved for the trajectories and velocities in both cases of polystyrene particle and lymphocyte. The calculation predicts the motions even at the positions of the electrode tip showing that the influence of the 3D distribution of the $F_{DEP,\,y}$ field and the resulting behavior of the particle and cells observed in a 3D form can be simulated accurately.

CONCLUSION

A numerical scheme that considers the electric field, DEP force, flow field, fluid-particle interaction, and the electrothermal flow was developed in this study in order to accurately predict the particle and lymphocyte motions in the manipulation device using the DEP force. On the basis of the numerical results, a semicircle shape electrode was designed and was evaluated experimentally showing a high and stable performance. Furthermore, an excellent correspondence between the numerical and experimental results was obtained showing the validity of the numerical scheme.

ACKNOWLEDGEMENTS

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