유전-전기영동 기반 입자 편향에 관한 3차원 시뮬레이션 및 실험

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3-D Simulation and Experiment on Particle Deflection by Dielectrophoresis

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Abstract

We present full 3-D simulation of dielectrophoretic (DEP) deflection of particle trajectory in micro channel and compare the simulation results with experimental results. In simulation, the particle 3-D movements along x, y and z-axis are simulated precisely, and the streamlines of particles movements and the change of particle height are investigated experimentally. Therefore, the deflection performance is investigated on the designed and fabricated deflection microchip.

1. Introduction

Dielectrophoresis (DEP) has been widely used as a driving force to deflect particle movement trajectory in micro channel [1]. Various DEP based applications such as particle separation [2], sorting and focusing [3] are based on the deflection phenomena. Mostly, 2-D simulation has been used to see simple particle movement tendencies in micro channel in simulation study. However, 3-D simulation is required to estimate the particle movement more exactly. To satisfy the requirement, we need perform the simulation study in which real experimental situations are reflected to the simulation, and investigate the similarity between the simulation and the experiment. In this paper, we present a model simulation study to investigate the particle deflection movements in 3-D in experiment and in simulation.

2. Principle

DEP is the movement of electrically-neutral particle at non-homogeneous electric fields distribution. As shown in the DEP equation (1), the gradient of the square of electric fields determines the direction and the relative magnitude of DEP force, entirely.

$$\vec{F}_{DEP} = 2\pi r^3 \epsilon_m Re\left[\chi(\omega)\right] \overrightarrow{\nabla}|E|^2 \quad (1)$$

In this paper, 6.4-μm-diameter polystyrene particles are used. The CM-factor Re[χ(ω)] of the used particle is -0.475 (negative DEP) at 10 MHz (fixed). The relative permittivity of used water is 80. AC voltage is fixed to be peak-to-peak 20 V. Therefore, the DEP force is determined only by the gradient of the square of electric fields.

3. Design

Fig. 1 shows the layout of largely-spaced bar electrodes array to apply DEP force to particles. As shown in Fig. 1, particle goes near a side wall of channel at the entrance initially, and the particle is deflected step by step during passing through channel. In DEP deflection chip, it is necessary to make particles meet into the same streamline (focusing). This is a solution to realize high-throughput DEP deflection application.

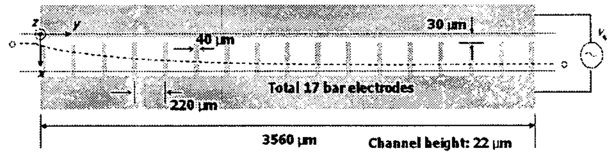


Fig. 1. Channel layout (top view).

There may exist a adequate range of particle initial positions to make the deflected particle streamlines almost the same ones. Particle deflection depends on liquid flow velocity as well as AC voltage magnitude. The slower the liquid velocity is, the more largely the particle is deflected. Liquid flow velocity is determined on the relation of $Q = \Delta P/R$ (Hagen-Poiseuille equation) [4]. The R is determined by channel dimension. The ΔP is controlled by the liquid level difference Δh between input and output of channel in this paper.

4. Simulation

In the dynamics of particle in a liquid, viscous drag by liquid mainly affects particle movement (Stokes drag force) [5]. A simple force equation is considered as equation (2), and then the equation (2) is redescribed as shown in equation (3).

$$\vec{F}_{DEP} + \vec{F}_{drag} + \vec{F}_g = 0 \quad (2)$$

$$\vec{F}_{DEP} + \vec{F}_g - 6\pi\eta r(\vec{v}_{particle} - \vec{v}_{fluid}) = 0 \quad (3)$$

Finally, a particle velocity is obtained as shown in equation (4).

$$\vec{v}_{particle} = \vec{v}_{fluid} + \frac{(\vec{F}_{DEP} + \vec{F}_g)}{6\pi\eta r} \quad (4)$$

The equation (4) can be rearranged using three unit vectors again as shown in equation (5). The change of particle position is made based on the equation (5).

$$\vec{v}_{particle} \doteq \vec{a}_x\left(\frac{F_{DEP\_x}}{6\pi\eta r}\right) + \vec{a}_y\left(\frac{F_{DEP\_y}}{6\pi\eta r} + v_{fluid\_y}\right) + \vec{a}_z\left(\frac{F_{DEP\_z} + F_{g\_z}}{6\pi\eta r}\right) \quad (5)$$

Since the rightward three vector terms are mutually independent, each displacement along three axes of a particle is described as shown in equation (6), (7) and (8), respectively. Since liquid is almost laminar in micro channel, the liquid flow velocity v_{fluid} is a function of x and z, as shown in the equation (7).

$$\Delta x = \Delta t \frac{F_{DEP\_x}(x, y, z)}{6\pi\eta r} \quad (6)$$

$$\Delta y = \Delta t\left(\frac{F_{DEP\_y}(x,y,z)}{6\pi\eta r} + v_{fluid\_y}(x,z)\right) \quad (7)$$

$$\Delta z = \Delta t\left(\frac{F_{DEP\_z}(x,y,z)}{6\pi\eta r} + v_{g\_z}\right) \quad (8)$$

Each DEP force along x, y and z-axis is a function of x, y and z. The liquid velocity has a parabolic shape of distribution. We know Δh in experimental setup. After the channel pressure drop ΔP is calculated, and then the value is used as a simulation input value. Finally, the velocity $v_{fluid}(x,z)$ is obtained from commercial simulation tool - CFD-ACE. New position is made by previous position plus new increment, as shown in equation (9), (10) and (11).

$$x_{n+1} = x + \Delta x \quad (9) \qquad y_{n+1} = y + \Delta x \quad (10) \qquad z_{n+1} = z + \Delta z \quad (11)$$

Fig. 2 presents the particle displacements described with vectors.

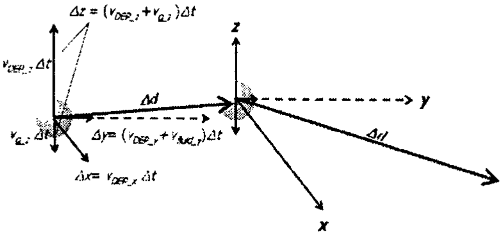


Fig. 2. Particle displacement described by numerical calculation. During particle moves, DEP force and fluid velocity change continuously. $\Delta d = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$

Fig. 3 shows the log scale distribution of the x-direction DEP force (main deflection force) at z = 3 μm. In Fig. 3, white-colored regions are the places in which the directions of DEP force along x-axis are negative. Particle can be deflected in $-x$ direction in the regions. The $-x$ direction DEP force regions exist within x = 30 μm entirely

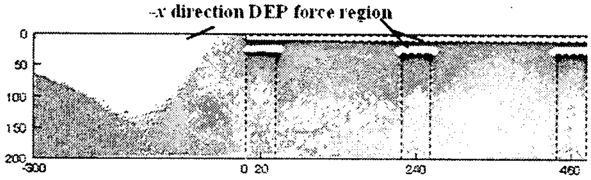
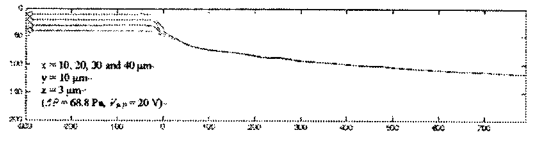
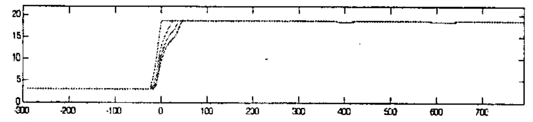


Fig. 3. Distribution of x-direction DEP force magnitudes - $\mathrm{Log}_{10}\ F_{DEP\_x}$ at channel height 3 μm.

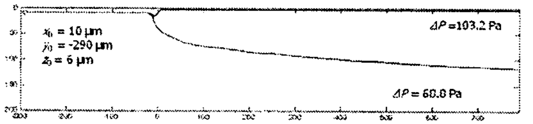
Fig. 4 shows the simulated basic particle movements. In simulation it is assumed that the particles go between x = 0 and x = 40 μm at the entrance of channel.



(a) Trajectories of particles with different initial positions



(b) Side view of (a)



(c) Two different particle deflections

Fig. 4. Basic particle trajectories indicating focusing efficiency (a), particle uprising (b) and two directions of particle deflection (c).

Although the particles have different initial positions, they meet into the same path as soon as they are deflected as shown in Fig. 4 (a). Fig. 4 (b) indicates the side view of Fig. 4 (a). Especially in Fig. 4 (a), it is described that the particles go near bottom. The z-direction DEP force is also large, and the particles uprise in an instant and go near channel top side. In most deflection time, the uprisen state continues. As shown in Fig. 4 (c), it is simulated that the particle can be deflected in two possible directions due to the effect of $-x$ direction DEP force as can be expected from the DEP force distribution in Fig. 3.

5. Experimental results

Fig. 5 shows a overlapped capture image of deflected particles at the entrance of channel. Pressure drop is 68.8 Pa. Peak-to-peak voltage is 20 V. As shown in Fig. 5, the two particles in Part A are deflected in $-x$ direction, and the three particles in Part B are deflected in $+x$ direction. The two directions of deflection were predicted in simulation already. Fig. 5 also verifies the simulation result of Fig. 4 (a). The particles starting at different initial positions in Part B meet into almost the same movement path as soon as they are deflected.

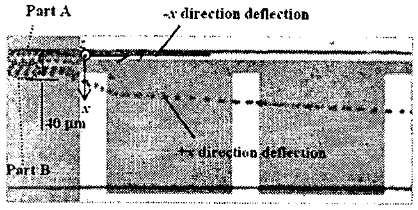
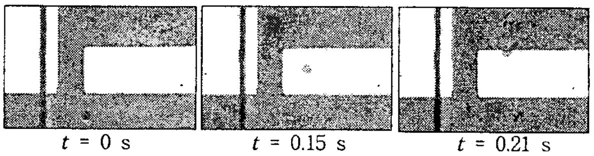


Fig. 5. Overlapped capture image of deflected particles. Deflection direction depends on initial position of particles. Initial positions of particles are within 40 μm.

The microscopic images of Fig. 6 verifies the predicted particle's z-direction uprising, indirectly. Microscope is focused on bottom electrode in Fig. 6. Particle goes near bottom before deflected in t = 0 s and so the observed particle image is clear. As soon as the particle is deflected, the particle is levitated by strong z-direction DEP force.



t = 0 s t = 0.15 s t = 0.21 s

Fig. 6. Experimental confirmation of the particle uprising during deflection at the entrance of channel. Microscope is focused on bottom electrode.

In t = 0.21s, the particle image becomes out of focus and blurred largely. The uprisen state continues until the particle reaches the exit of channel in the same manner to the simulation result.

6. Conclusions

Particles deflection movements by DEP are simulated in 3-D and the simulated results are confirmed experimentally. Here, The simulation preestimate some specific working characteristics of the designed microchip such as generic deflection trajectories (generic motion styles along x, y and z-axis), deflection direction and focusing efficiency in full 3-D, and the similarity between the simulation and the experiment is verified. This simulation study shows that the designed micro electrode and fluidic channel can be used as a nicely working DEP-based particle deflection microchip. It is expected that the proposed simulation method can be used as a pre-estimation tool for deflection microchip design.

Acknowledgement

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