Investigation of optimal separation condition in negative dielectrophoresis force based particle sorting platform

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ABSTRACT

We have proposed sorting platform based on the negative dielectrophoresis (n-DEP) force [1]. In the proposed sorting platform, separation efficiency (SE) is varied according to particle size and separation conditions (voltage and fluid flow rate). In this paper, therefore, we investigate optimal separation conditions regarding the gravitation, the hydrodynamic force and the n-DEP force acting on particles to achieve high SE in proposed sorting platform. The hydrodynamic force depends on the size of particle and fluid flow rate. The n-DEP force, on the other hand, depends on the size of particle and applied signal as well as the dielectric material properties of a particle [2]. Accordingly, based on the simulation and experimental studies, we investigated the optimal separation condition by comparing the n-DEP force with the hydrodynamic force. Conclusively, the particles are most effectively deflected under the condition of low voltage (5Vp-p with 30MHz) and flow rate of 5μL/min driven by gravitation and flow regulator.

Keywords: separation efficiency (SE), dielectrophoresis, hydrodynamic force, high throughput sorting.

1. INTRODUCTION

During last two decades, on the basis of the development of microfabrication technology, various applications for continuous separation have been reported [3]. One of these applications is the dielectrophoretic (DEP) platform [4]. This platform has advantages such as a no-labeling process, a fast process, and an easy interface. Nevertheless, a limitation exists in that the SE of particle based on the high voltages and high fluid flow rates could be affected by external pump and microchannel. The high voltages and high fluid flow rates, in case of bioparticles, can be a stress and, as a result, cause unavoidable damage such as cell lysis or rupture. Accordingly, in order to overcome these limitations, some researchers have tried to develop platform acting with relatively low conditions (voltage and flow rate) [5]. They were able to successfully demonstrate particle separation with relatively low conditions by combining DEP force and sedimentation as a gravitation-driven platform. We also proposed a sorting platform (Figure 2) using gravitation, hydrodynamic force and n-DEP force. In this platform, the flow in microchannel is derived by gravitation and is controlled by flow regulator. However, high SE under low conditions is still a fundamental issue to be solved. Therefore, we investigate an optimal separation condition regarding the gravitation, the hydrodynamic force and the n-DEP force acting on particles in the sorting platform since contribution of each force is the main parameter to determine SE. The hydrodynamic force depends on the size of particle and fluid flow rate. The n-DEP force, on the other hand, depends on the size of particle and applied signal as well as the dielectric material properties of a particle. Accordingly, based on the simulation and experimental studies with 10- and 25μm particles, we investigated most effective separation conditions such as magnitude and frequency of input voltage, and fluid flow rate of drain of water pool.

2. WORKING PRINCIPLE AND EXPERIMENT SETUP

2.1 Basic principle

In Figure 1, we illustrate basic principle for deflection of target particle in the sorting platform. In the microchannel,

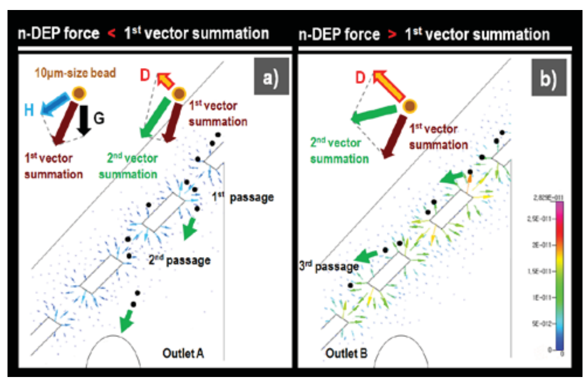

Figure 1. Basic principle of 10μm beads deflection in non-uniform electric field; Gravitation (G), Hydrodynamic force (H), Negative dielectrophoretic force (D). a) the n-DEP force is smaller than 1st vector sum (combination of hydrodynamic force and gravitation). b) the n-DEP force is bigger than 1st vector sum.

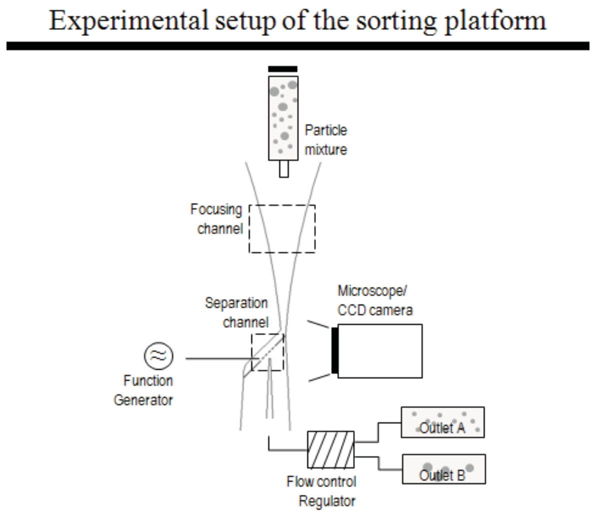

Figure 2. The configuration of Experimental setup. The sorting platform is placed before a CCD scope and the electrode array is connected to the function generator. The flow rate during the separation is controlled by flow control regulator.

the movement of target particle is affected by Gravitation(G), Hydrodynamic force(H) and negative Dielectrophoresis force(D). In particular, n-DEP force generated from inclined cantilever electrode(CE) array plays a key role to control deflection in the proposed system. The magnitude of n-DEP force is changed according to applied voltage and frequency, the sizes of target particles and dielectric property of both target particle and medium. In case the maginitude of the first vector summation (combination of hydrodynamic force and gravitation) is larger than that of n-DEP force, migration of target particle is governed by 1st vector summation. As a result, target cells move down to outlet A through 1st and 2nd passage between electrodes. In case the n-DEP force is bigger than 1st vector summation(Fig 1-b), migration of target particles is governed by n-DEP force. Therefore, cells deflected on the CE array and move to outlet B.

2.2 Experimental setup

The system consists of function generator and flow regulator to control n-DEP force and hydrodynamic force respectively. We have controlled the magnitude of n-DEP force using the function generator connected to CE array. In the microchannel, the magnitude of the hydrodynamic force based on the flow rate is detemined by flow regulator. During separation, movement of particles in the vicinity of inclined CE arrays is observed by a CCD scope(INF-500, Moritex, Japan).

2.3 Theory

In order to seek optimal separation condition, it is essential to investigate the magnitude of force acting on a particle. For simplified analysis, we considered coordinates system in microchannel to be 2-dimensional in the x-y plane. The time-averaged DEP force is given by

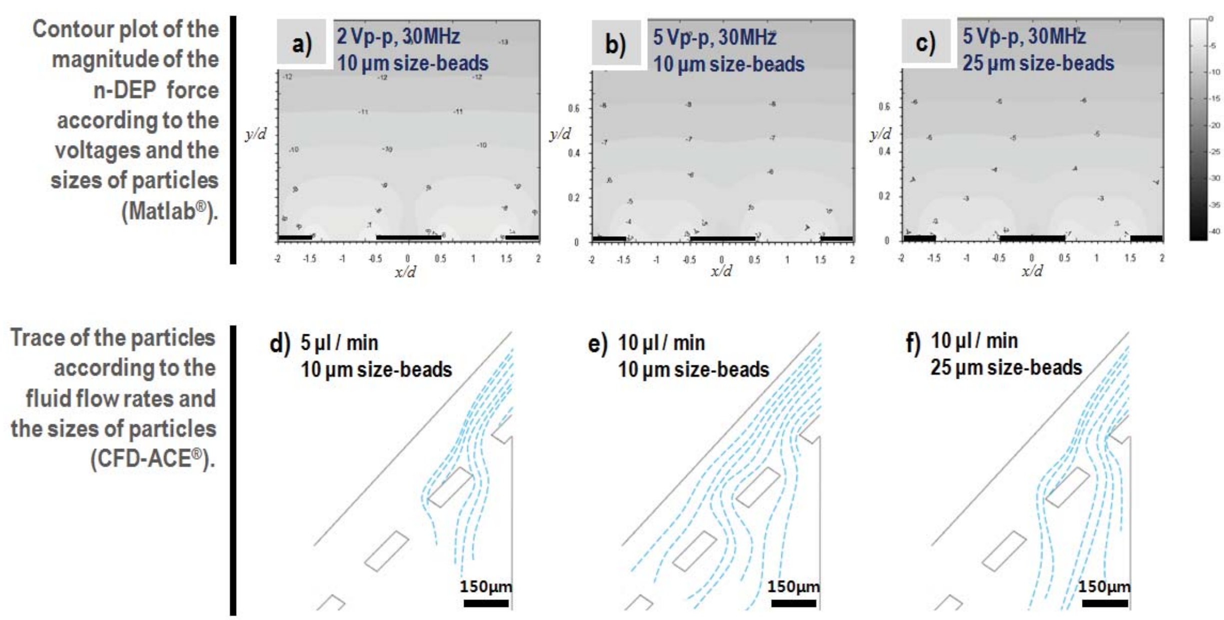

Figure 3. Numerical results with commercial code (MATLAB® and CFD-ACE®) ; a) Contour plot of the magnitude of the n-DEP force according to the applied voltages and the sizes of particles. b) Trace of the particles according to the fluid flow rates and the sizes of particles.

$$F\,DEP = \frac{1}{4} v\mathrm{Re}[\alpha]\nabla(E_x^2 + E_y^2) \quad (1)$$

$$\nabla(E_x^2 + E_y^2) = 2u_x(E_x E_{x,x} + E_y E_{y,x}) + 2u_y(E_x E_{y,x} + E_y E_{y,y}) \quad (2)$$

$$E_{x,x}(x,y) = \frac{\partial E_x}{\partial x} = -\frac{\partial E_y}{\partial y} = -E_{y,y}(x,y)$$
$$= \frac{2V_0 \sinh\hat{y}}{d^2}\left[\frac{\cos\hat{x}}{\cosh 2\hat{y} - \cos 2\hat{x}} + \frac{\sin\hat{x}}{\cosh 2\hat{y} + \cos 2\hat{x}}\right]$$
$$E_{x,y}(x,y) = \frac{\partial E_x}{\partial y} = \frac{\partial E_y}{\partial x} = E_{y,x}(x,y)$$
$$= \frac{2V_0 \cosh\hat{y}}{d^2}\left[\frac{\cos\hat{x}}{\cosh 2\hat{y} + \cos 2\hat{x}} - \frac{\sin\hat{x}}{\cosh 2\hat{y} - \cos 2\hat{x}}\right] \quad (3)$$

where v is the volume of the particle, $\nabla(E_x^2 + E_y^2)$ is square of electric field gradient, and $Re[\alpha]$ is the real value of the Clausius-Mossotti factor depending on the change of frequency and dielectric properties (permittivity and conductivity) of both particle and medium [6].

In case of hydrodynamic force, we have assumed that Reynolds number is very small ($Re<0.1$). Therefore, hydrodynamic force in the microchannel can be approximated with Stokes drag force. For steady flow, hydrodynamic force in microchannel is given by

$$F_{HD} = 6\pi\mu(V_f - V_p)r \quad (4)$$

, where μ is the viscosity of the fluid, r is the radius of the particle, V_f is the velocity of the fluid, and V_p is the velocity of the particle [7].

Based on the theories of n-DEP force (Equation 1 ~ 3) and hydrodynamic force (Equation 4), numerical study using computational code of MATLAB® and commercial codes of CFD-ACE® has been carried out to obtain the magnitude of n-DEP force and the movement of target particles in the vicinity of inclined CE array respectively.

3. RESULTS AND DISCUSSION

For numerical study, the assumption and variables have been introduced. Firstly, for simplified analysis in the micro-channel, we have considered the coordinate for migration to be 2-dimensional. Secondly, width of electrode and the distance between electrodes are 150μm. Finally, the conductivity and relative permittivity of the polystyrene bead are 2×10^{-4} S/m and 2.25 respectively, and the conductivity and relative permittivity of the medium are 0.01 S/m and 80 respectively.

To investigate the magnitude of n-DEP force in the vicinity of inclined CE array, MATLAB® was employed. Fig 3 (a), (b), (c) show a contour plot of the magnitude of n-DEP force according to the voltages and the sizes of particles. As in Equation (1), simulation result shows that n-DEP force is increased as input voltage and size of particle increase.

Through simulation study using CFD-ACE®, migration of particles according to sizes of particles and flow rate of drain are obtained as in Fig 3 (d), (e), (f). As a result of the simulation, the hydrodynamic force becomes more dominant over gravitation as particle size is smaller and flow rate is bigger. Conclusively, the particles move along the CE array due to superior hydrodynamic force. On the contrary, gravitation is more dominant over hydrodynamic force as particle size is bigger and flow rate is smaller. The simulation result at flow rate of 5μL/min demonstrates particles settled down through the 1st and 2nd passage between electrodes.

Based on the data through simulation, we have carried out a performance test in the proposed platform with 10μm beads. The deflection rate of target particles is measured under various voltages, frequencies and flow rates of drain.

The results of both simulation and performance test are presented in Figure 4 to demonstrate the deflection rate of the target particles according to input voltage. Since the small bubbles on electrodes disturb the effect of the n-DEP force, some error between simulation and performance test exist. Despite of some error, the deflection rate curve of performance test (solid line) is very similar shape with that of simulation (dashed line).

We could found that the optimal separation condition (low voltage of 5Vp-p with 30MHz and low fluid flow rate of 5μL/min) is appropriate to deflect the 10μm beads in the proposed sorting platform. Under this condition, 95 percent of 10μm beads deflected on the inclined CE array and moved to outlet B. Conclusively, through the numerical study of migration of target particles and performance test with 10μm beads, we confirm the optimal separation

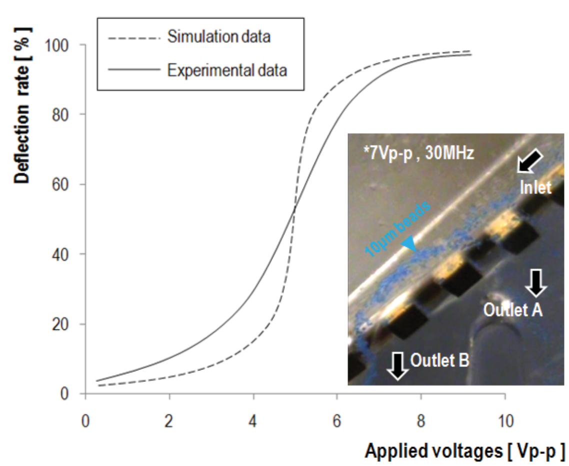

Figure 4. Deflection rate of 10μm-size beads according to applied voltage in the sorting platform.

condition in the proposed sorting platform.

4. SUMMARY

In order to improve the SE of proposed sorting platform, we have researched the optimal separation condition through simulation and performance test. The migration of target particles has been simulated under various voltages, flow rates and sizes of target particle. Then, performance test was carried out to verify feasibility of simulation result. The proposed sorting platform based on the n-DEP force can deflect the 10μm beads with 95% of SE under condition (low voltage of 5Vp-p with 30MHz and low fluid flow rate of 5μL/min). Conclusively, we successfully obtain the optimal separation condition using numerical and experimental studies.

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