International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 8 (2018) pp. 6047-6051

Experimental Evaluation of Particle Separation Efficiency for Dielectrophoretic Flows Passing through a Microfluidic Device

Jae Heon Lee[1,a], Haider Ali[1,b], Kyung Won Kim[1,c], Gun Woo Noh[1,d], Moon Kyu Kwak[1,e], Jung Goo Hong[1,f] and Cheol Woo Park[1,g*]

[1]School of Mechanical Engineering, Kyungpook National University, 80 Daehakro, Bukgu, Daegu, 41566, Korea.

Abstract

Dielectrophoresis-based microfluidic device separates particles based on size and dielectric properties. The performance of a microfluidic device mainly depends on frequency of applied voltage, size of particles, and dielectric properties of particles and fluid. In this study, a microfluidic channel based on dielectrophoresis field-flow fractionation was developed for separating particles of different sizes. A low voltage (6 V) was applied to electrodes to separate the particles of three sizes (i.e., 2, 7, and 15 μm). This study evaluated the separation efficiency of the microfluidic device with the effects of different particle sizes and buffer flow rates. Results showed that the separation efficiency of the device was significantly reduced with the use of large particles (15 μm). A high buffer flow rate increased the movement of the particles in the device, thereby reducing the separation efficiency because of less dielectrophoresis force.

Keywords: Dielectrophoresis; Microfluidic Device; Particle; Electrode; Separation Efficiency

INTRODUCTION

Dielectrophoresis (DEP)-based microfluidic devices are widely used to separate particles and biological cells. A microfluidic device uses a non-uniform electric field to exert DEP force on the particles. DEP force separates the particles based on size. The magnitude and direction of DEP force depend on the frequency of applied voltage, size and shape of particles, and dielectric properties of particles and fluid [1].

DEP force is modeled using the Clausius–Mossotti (CM) factor, which incorporates the dielectric properties of the particles and fluid. DEP separation techniques are categorized as positive DEP (p-DEP) and negative DEP (n-DEP) based on the magnitude of the CM factor. p-DEP represents a positive value of the CM factor and particles move towards the electrodes of the microfluidic device. Similarly, n-DEP shows a negative value of the CM factor and particles move away from the electrodes. p-DEP technique efficiently separates particles or cells in suspended flows with low electrical conductivities but is less efficient for flows with high conductivities, such as blood [2, 3].

Separation of particles or biological cells using DEP-based microfluidic devices has attracted considerable research interest. Demierre et al. [4] developed a microfluidic device with two arrays of distant electrodes. This novel arrangement of electrodes generates two opposite DEP forces that help to focus and separate particles accurately by adjusting the electric potential and frequency [4]. Wakizaka et al. [5] proposed different electrode geometries (pin-plate and wire-wire) to improve the separation efficiency of DEP-based microfluidic devices. The separation efficiency of the microfluidic device with the wire-wire electrode is 1.7 times larger than that of the device with a pin-plate electrode [5]. Braschler et al. [6] developed an opacity-based DEP microfluidic device to separate viable and non-viable yeast cells. However, the opacity-based technique is suitable only for particle or cells with similar size and is not efficient for particles with different sizes [6].

Field-flow fractionation (FFF) is another technique applied to generate DEP force using low electrical voltage. FFF-based techniques separate particles based on their size. Therefore, FFF can replace opacity-based technique to generate DEP force in microfluidic sorting devices [7]. Piacentini et al. [8] used a DEP-FFF-based microfluidic device to separate only two types of blood cells. Unfortunately, experimental work on a DEP-FFF-based microfluidic device is limited. To date, such devices can only separate two types of particles or cells [8].

In the present study, a DEP-FFF-based microfluidic device was fabricated to separate particles of three different sizes for medical application. The microfluidic device adopted seven liquid electrodes with a low electrical voltage to generate DEP force. The microfluidic channel was made of polydimethylsiloxane (PDMS), and the device was fabricated using a bio-MEMS technology (photolithography).

The left side of the microfluidic device was called the injection section with the sample fluid and buffer fluid inlets. The right side of the device was called collection section with three different outlets for particles. An inverted-type microscope connected with a cooled-CCD camera was used to visualize the separation process and count the number of successfully separated particles at their respective outlets. Different particle sizes and buffer flow rates were applied to investigate their effects on the separation efficiency of the microfluidic device.

THEORETICAL APPROACH

DEP Force

DEP force separates particles based on size, and it depends on the frequency of applied voltage, size of the particles, and

dielectric properties of the particles and fluid. The present study used Equation (1) to model the time-averaged DEP force (F_{DEP}) on the spherical particles in the microfluidic device.

$$F_{DEP} = 2\pi\varepsilon_m r^3 Re[f_{CM}]\nabla[E_{RMS}]^2 \qquad (1)$$

where F_{DEP} represents DEP force (N), ε_m is the permittivity of the medium, r is the radius of the particles (m), $Re[f_{CM}]$ is the real part of the CM factor, and E_{RMS} is the root mean square of the electric field. f_{CM} is defined using the following equations:

$$f_{CM} = \frac{\varepsilon_p{}^* - \varepsilon_m{}^*}{\varepsilon_p{}^* + 2\varepsilon_m{}^*} \qquad (2)$$

$$\varepsilon^* = \varepsilon - \frac{j\sigma}{\omega} \qquad (3)$$

where ε^* is the complex permittivity, which includes the permittivity (ε) and the conductivity (σ) of the particles and the fluid; j is the imaginary unit, ω is the angular frequency of the electric field (rad/s), and $\varepsilon_p{}^*$ and $\varepsilon_m{}^*$ are complex permittivity of particles and fluid, respectively. An $f_{CM} > 0$ shows that particles move to the region with a strong electric field (towards electrodes) and is termed as p-DEP. By contrast, an $f_{CM} < 0$ suggests that particles move to the region with a weak electric field (away from electrodes) and is called as n-DEP.

Field-flow Fractionation

FFF is a technique in which particles are separated in a single liquid phase. FFF uses an external source to apply the electric field to the sample fluid in a narrow channel, perpendicular to the direction of the fluid flow. A laminar parabolic flow profile is developed at the entrance because of the high aspect ratio of the FFF flow channel (Figure 1). The flow velocity is maximum at the center of the channel and minimum near the channel walls. The particles change their positions and relative velocity in the FFF microfluidic channel based on their size or mass. The DEP force pushes the particles in the perpendicular direction, and the separation occurs because of the difference in the relative velocities of the particles. Figure 1 represents the FFF with p-DEP and n-DEP separation techniques.

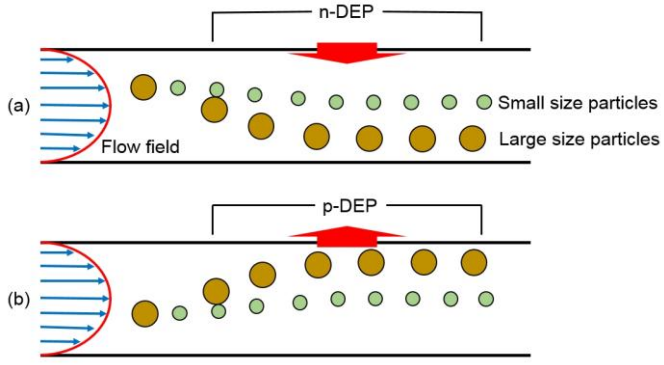


Figure 1. Field-flow fractionation with (a) n-DEP and (b) p-DEP techniques.

EXPERIMENTAL APPARATUS AND METHODS

Microchannel

The microfluidic device used in this study was fabricated using photolithography. The microchannel of the device was made of PDMS. The microfluidic device consisted of three different sections, namely, injection, separation, and collection sections (Figure 2). As shown in the figure, the left side of the microfluidic device represents the injection section, and it includes the sample solution and buffer inlets. The central region of the device is the separation section. The electrodes are present in the separation section, wherein particles are separated.

The right side of the device is the collection section and it includes three different outlets for particles. The particles are separated in the separation section and move to their respective outlets in the collection section. The total length of the microfluidic device is 870 µm. The width of the microfluidic channel is 40 µm. The angle between the *P1* outlet and electrode (θ_1) is 45°. The angle between the *P1* and *P2* outlets (θ_2) is 65°, and the angle between *P2* and *P3* outlets (θ_3) is 40°.

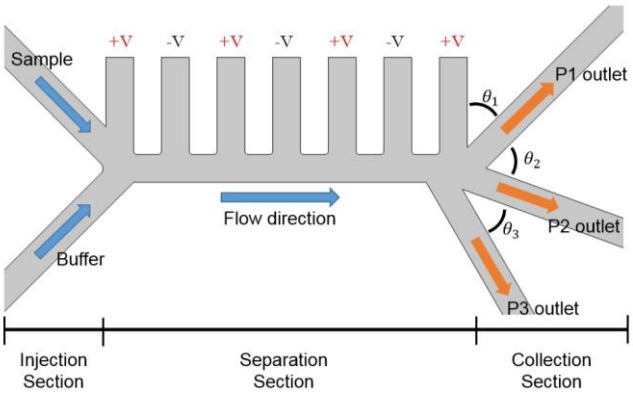
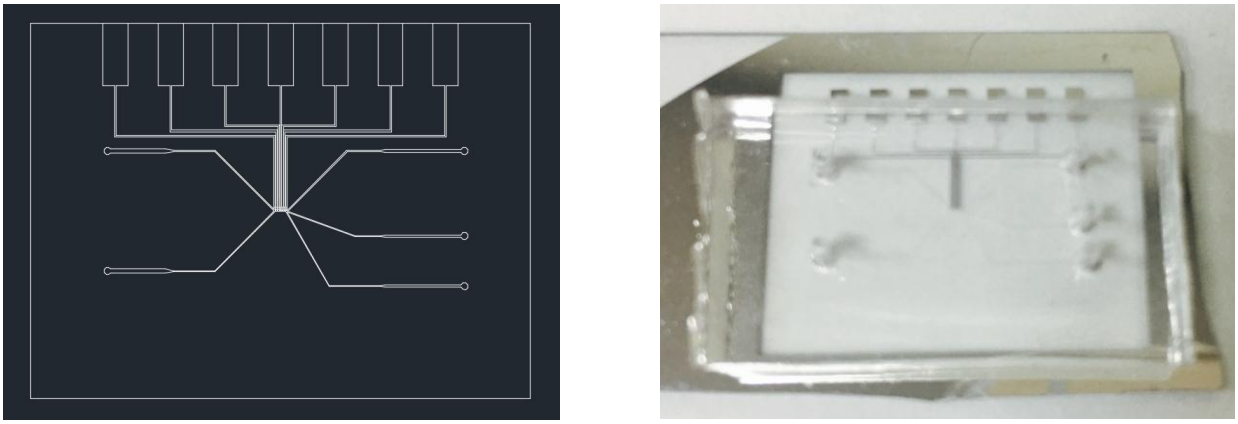


Figure 2. Schematic of the DE-FFF-based microfluidic device

Electrode

Liquid electrodes were used to generate DEP force in the microfluidic channel. Liquid electrodes are less prone to metal degradation because of their surface area. The liquid electrodes were connected to large metal electrodes, which allowed the operation of n-DEP with variable frequencies. The seven electrodes received a voltage of 6 V, but successive electrodes had opposite charge. The electrodes were rectangular (2500 µm long and 1000 µm high). A smooth connection existed between electrodes and external electrical supply (Figure 3). To achieve perfect mating of the microfluidic channel and electrodes, 60 µm thick metal electrodes were used. This thickness of metal electrodes allowed correct alignment of both electrodes during the oxygen-plasma bonding process.



(a) **(b)**

Figure 3a. Mask design with connected electrode and microchannel for the lithography and **(b)** microchannel model made with PDMS deposited aluminum electrode on the Pyrex glass

Particle Separation

This study used particles of three different sizes (diameter): 2 μm (red fluorescent 1% solids polymer microspheres of *ThermoScientific*®), 7 μm (red fluorescent model 36-2B 18% CV of *DukeScientific* Corporation), and 15 μm (*fluostar* fluorescence microspheres *rhodamine B* of *EBM* Corporation). The particles were fluorescent and therefore can be visualized inside the microchannel using a CCD camera. Voltage was supplied to electrodes using a source meter (*Keithley* 2440). The inlets of sample solution and buffer were connected to a syringe pump using tubes. The syringe pump (*Legato* 200, *KDScientific* Corporation) used in the experiment enabled the random choice of flow rates of the sample solution and buffer.

The flow rates of the sample solution and buffer were set at 1 and 5 μl/min, respectively. The velocities of the sample solution and buffer inside the microchannel were 150 and 850 μm/s, respectively. The buffer velocities were varied from 850 μm/s to 1400 μm/s to determine the effect on the separation efficiency of the microfluidic device. To focus the particles towards the electrodes, the flow speed of buffer solution was higher than that of the sample solution. This approach needed a small magnitude DEP force to separate the particles. An inverted microscope was used connected with a cooled-CCD camera (s*ensicam, PCO.*) with a 1600×1200 pixels resolution and 30 frames/second capture capability. The images were taken at approximately 30 ms interval to count the number of particles at the injection section and collection section. Then, the particle separation efficiency of the device was computed based on the calculated number of particles at the injection section and collection section.

RESULTS AND DISCUSSION

Figure 4 presents the separation efficiency of the microfluidic device for different particle sizes. Results were obtained using the electrical voltage of 6 V, sample solution flow rate of 150 μm/s, and buffer flow velocity of 850 μm/s. The separation efficiencies for the 2, 7, and 15 μm particles were 47%, 45%, and 40%, respectively. DEP force depended on particle size, and affected small particles more than large particles. The separation efficiency of the 2 μm particles was high because of the significant effect of DEP force. Similarly, the 15 μm particles experienced small DEP force and thus less number of particles reached the *P3* outlet. The separation efficiency can be increased by increasing the electrical voltage. Thus, a high separation efficiency of microfluidic deice can be achieved by using small particles.

Figure 5 shows the separation efficiency of different particles for various buffer flow rates. Results were obtained using an electrical voltage of 6 V and sample solution flow rate of 150 μm/s. The separation efficiency of the 2 μm particles decreased by approximately 4.5% with the increase of buffer flow velocity from 900 μm/s to 1000 μm/s. A 7% decrease in the separation efficiency was observed when the buffer speed increased from 1000 μm/s to 1200 μm/s. Similarly, a decrease of approximately 6.5% and 4.5% in the separation efficiency was recorded for the 7 μm particles when the buffer velocity increased from 900 μm/s to 1200 μm/s, respectively.

The decrease in the separation efficiency reached to 8.75% and 7.1% for the 15 μm particles when the buffer velocity was increased. An increase in the buffer flow velocity also increased particle motion in the microfluidic channel. The particles moving at a high buffer velocity do not adequately experience DEP force, thereby reducing the number of separated particle at the respective collection outlets. These results suggested that a low buffer rate was suitable for achieving efficient particles separation in the microfluidic device.

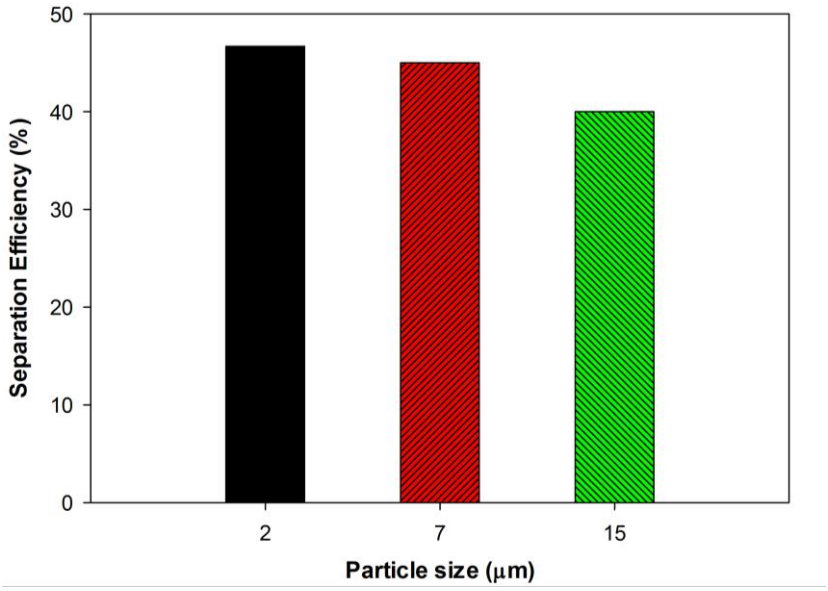


Figure 4. Separation efficiency of device with the effect of the particles size

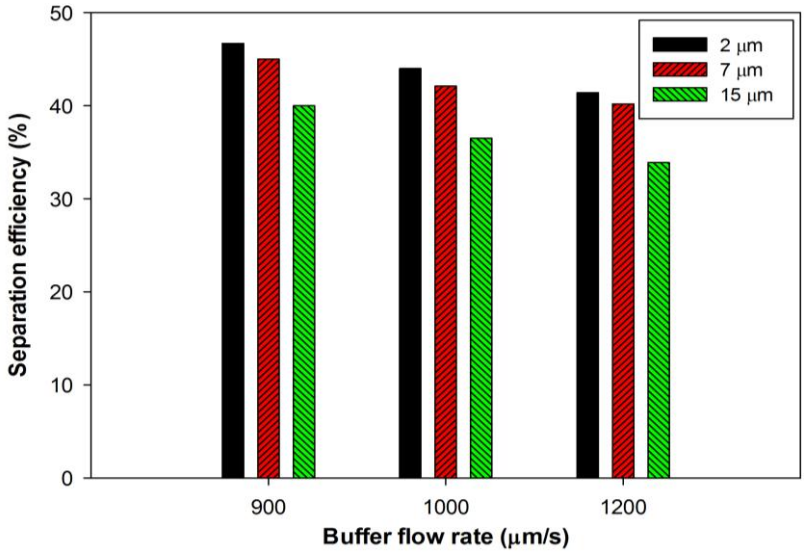


Figure 5. Separation efficiency of device with the effect of the buffer flow rates

CONCLUSION

A DEP-FFF-based microfluidic device was developed to separate particles of three different sizes. The microfluidic device consisted of two injection inlets for the sample solution and buffer and three collection outlets for different particles. Liquid electrodes with a low electrical voltage were used to generate DEP force in the device. The separation efficiency of the device was calculated as the ratio of the number of particles at injection section to the number of particles at the collection section. The separation efficiency of the microfluidic device was computed for different particle sizes and buffer flow rates. Results showed a high separation efficiency of the microfluidic device for small particles. Particles with considerable size experience less DEP force, thereby decreasing the separation efficiency. An increase in buffer flow velocity increased the motion of particles in the device, thus reducing their contact with DEP force. Therefore, the separation efficiency decreased with the increase in buffer velocity. The separation efficiency of the microfluidic device can be increased by applying low buffer flow rates and appropriate electrical voltage.

ACKNOWLEDGMENT

This study was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2017R1A2B2005515), and a grant from the Priority Research Centers Program through the NRF, as funded by the MEST (No. 2010-0020089).

REFERENCES

[1] A. Lenshof, T. Laurell, Continuous separation of cells and particles in microfluidic systems," Chem. Soc. Rev., 39 (2010) 1203.

[2] B. Çetin, D. Li, Dielectrophoresis in microfluidics technology, Electrophoresis, 32 (2011) 2410–2427.

[3] B. H. Lapizco-Encinas, B. A. Simmons, E. B. Cummings, Y. Fintschenko, Dielectrophoretic concentration and separation of live and dead bacteria in an array of insulators, Anal. Chem., 76 (2004) 1571–1579.

[4] N. Demierre, T. Braschler, R. Muller, P. Renaud, Focusing and continuous separation of cells in a microfluidic device using lateral dielectrophoresis, Sens. Actuators, B, 132 (2008) 388–396.

[5] Y. Wakizaka, M. Hakoda, N. Shiragami, Effect of electrode geometry on dielectrophoretic separation of cells, Biochem. Eng. J., 20 (2004) 13–19.

[6] T. Braschler, N. Demierre, E. Nascimento, T. Silva, A. G. Oliva, P. Renaud, Continuous separation of cells by balanced dielectrophoretic forces at multiple frequencies, Lab Chip, 8 (2008) 280–286.

[7] B. Mathew, A. Alazzam, M. Abutayeh, A. Gawanmeh, S. Khashan, Modeling the trajectory of microparticles subjected to dielectrophoresis in a microfluidic device for field flow fractionation, Chem. Eng. Sci., 138 (2015) 266–280.

[8] N. Piacentini, G. Mernier, R. Tornay, P. Renaud, Separation of platelets from other blood cells in continuous-flow by dielectrophoresis field-flow-fractionation, Biomicrofluidics, 5 (2011) 034122.