광력을 이용한 입자 분리 장치

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Particle Separator using Radiation Force

Sang Bok Kim, Sang Youl Yoon, Sang Soo Kim and Hyung Jin Sung

Abstract

To improve the conventional optical chromatography, the continuous particle separator, the cross-type optical chromatography, is fabricated using micro-channel and fiber optics. A laser beam irradiates into the liquid solution containing particles in the perpendicular to the liquid flow direction. The different sized polystyrene latex micro-spheres, 2.0 μm ± 0.02 μm, 5.0 μm ± 0.05 μm, and 10.0 μm ± 0.09 μm diameter, are separated in cross-type optical chromatography. The separated particles are delivered to down stream in the micro-channel maintaining the retention distance continuously. The measured retention distances for different sized particles well agree with theoretical predictions.

Key Words : Radiation force (광력), Particle separator (입자 분리기)

1. Introduction

Since the first observation of the radiation forces on micro objects by Ashkin [1], they are successfully applied to many research fields [2-6]. The most well-known application of the radiation forces is the optical tweezers which is now widely used in biological cell manipulation [6]. Nowadays, the separation of particles or biological cells using radiation forces, termed optical chromatography, is considered vigorously [7-11]. The optical separation techniques based on optical tweezers were also researched [12, 13]. However, the separation time is much longer comparing to optical chromatography and required complicated experimental equipments.

In the conventional optical chromatography, the loosely focused laser beam propagating in the opposite direction to the liquid flow [7]. Particles in the liquid flow experience two opposite forces: fluid drag force and radiation force. Particles remain stationary point where the two opposite forces are equal. Since the drag and radiation forces depend on particle size, the particles can be separated in size order. Furthermore, the radiation forces depend on refractive index of particles as well as size, chemically different but uniformly sized particles also can be separated [9].

However, in the conventional optical chromatography, the separated particles remain stationary point and other procedures are required to further analysis of separated particles or biological cells. To improve the conventional optical chromatography, Kim *et al.* proposed cross-type optical chromatography theoretically [14]. In the cross-type optical chromatography, the loosely focused laser beam propagating in the perpendicular to the liquid flow in order to deliver separated particles to further analysis zone continuously.

In present study, the experimental verification of the cross-type optical chromatography was performed.

The cross-type optical chromatography was fabricated using micro-channel and fiber optics component. The retention behaviors of particles in the cross-type optical chromatography were recorded using CMOS camera and the measured retention distances of different sized particles were compared to theoretical predictions.

2. Theory

Based on the theoretical study for cross-type optical chromatography by Kim *et a.l*[14], the theoretical retention distance in the cross-type optical chromatography is introduced briefly. Kim *et al.* assumed a constant scattering force and assumed that the laser beam width is larger than particle size so that gradient force can be ignored [14-16]. The constant scattering force, in the Gaussian intensity profile, can be expressed as

$$F^{*} = \frac{n_0 P}{4c}\left(\frac{d_p}{\omega_0}\right)^2 Q^{*}\sqrt{\frac{\pi}{2}}\,\mathrm{erf}(\sqrt{2})\,. \tag{1}$$

where, n_0 is refractive index of medium, P is the power of laser beam, c is the speed of light in the free space, d_p is the radius of particle, ω_0 is the width of the laser beam, Q^* is constant value which depends on refractive indices of particle and medium, and erf denotes the error function.

As shown in Fig. 1, the particle dynamic equation can be written as

$$m_p\frac{\mathrm{d}^2 z}{\mathrm{d}t^2} + 3\pi\mu d_p\frac{\mathrm{d}z}{\mathrm{d}t} = F^{*}, \tag{2}$$

$$y = Ut \tag{3}$$

where, m_p is the particle mass, μ is the dynamic viscosity of the fluid, U is the uniform fluid velocity, and z, y are the particle positions in the z and y directions, respectively. Since the scattering force was assumed constant, the analytic expression of the retention distance can be obtained as

$$z = \frac{n_o P}{6\pi\mu U c}\frac{d_p}{\omega_0}Q^{*}\sqrt{\frac{\pi}{2}}\,\mathrm{erf}\left(\sqrt{2}\right) \tag{4}$$

In Eq. (4), the retention distance is proportional to particle diameter and there is no minimum size of particle to be separated, theoretically.

3. Experiments

Figure 1 shows the schematics of the cross-type optical chromatography and the experimental set-up. The micro-channel was fabricated conventional soft lithography and channel width and height are 210 μm and 100 μm, respectively. The Nd-YAG CW laser operating at 532 nm wavelength was used to exert radiation force and the laser beam was delivered into the micro-channel through optical fiber (MMJ-3l-IRVIS-50/125, Oz optics). Using the CMOS camera (pco. 1200hs), objective lens (20 X), and mirror, the inverted microscope was set up as shown in fig. 1. To obtain clear images of particle trajectories, the scattered light from the Nd-YAG laser was prevented by interference filter (F10-632.8-4-2.00, CVI optics) and red led was used as light source for image capture. The flow system consisted of 1 mL gas-tight syringe (81320, Hamilton), a syringe pump (pump 11, Harvard apparatus) and PTFE tube.

Different sized micro-spheres were used: 2.0 μm ± 0.02 μm, 5.0 μm ± 0.05 μm, and 10.0 μm ± 0.09 μm diameter polystyrene latex (PSL, Duke Scientific Corp.). The refractive index of PSL particles are 1.59. PSL particles were suspended in water and introduced into the mico-channel.

4. Results and discussion

In the experiments, the flow velocity was 250 μm/s and measured laser power and radius of the laser beam width were 1 W and 40 μm, respectively. Since the radius of

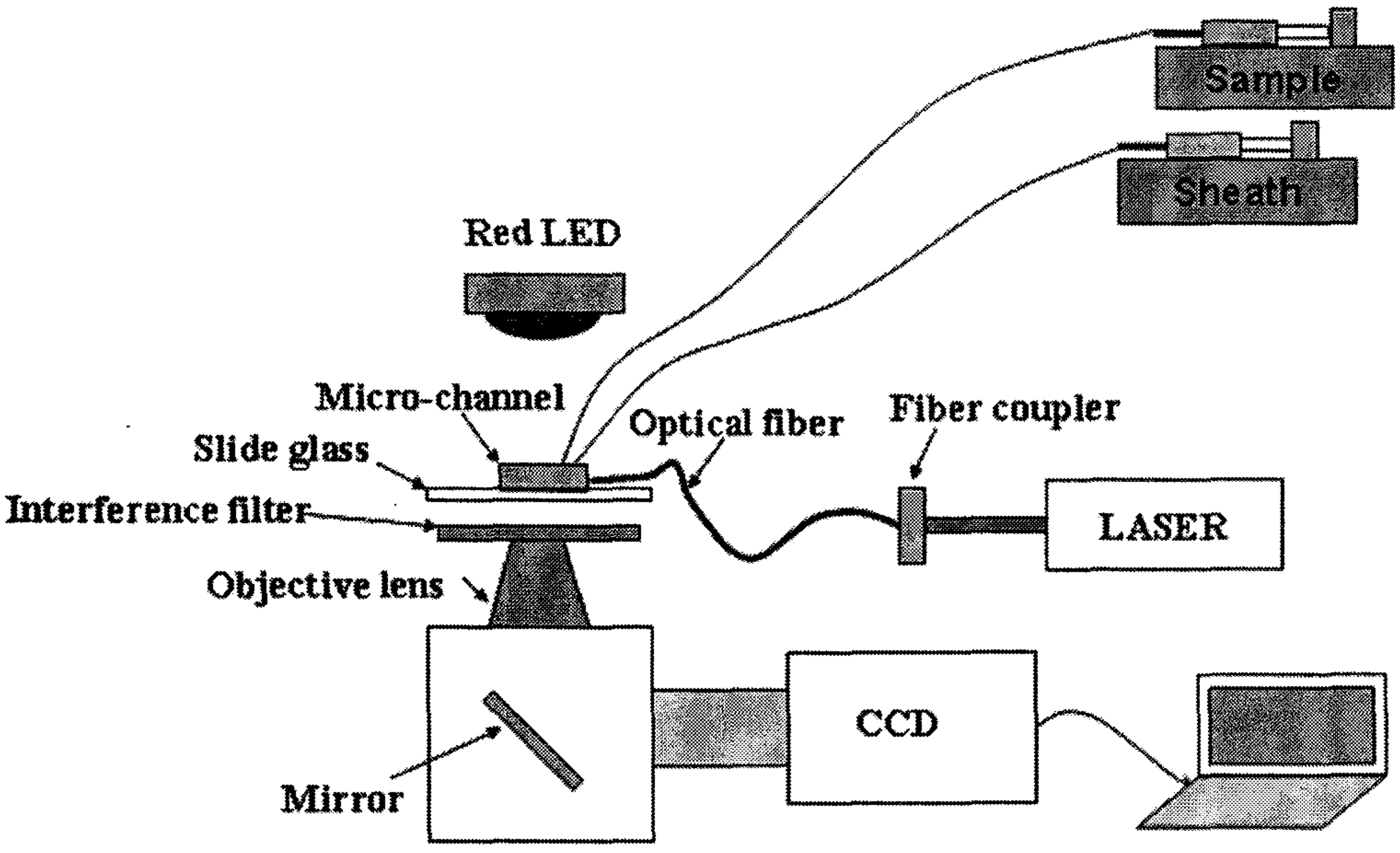

Fig. 1. Schematic diagram of experimental set-up

the laser beam width is larger than particle sizes, the assumptions used in derivation of the theoretical retention distance are satisfied. Figure 2 shows the snap shot of the trajectories of the particles. Particles are deviated from their initial position as passing through the laser beam. As shown in fig. 2, the retention behavior of the particles is observed. Initially, particles go down stream with straight trajectories and deviate in the laser beam then escape the laser beam maintaining the retention distance. The lager particles, the larger deviations were occurred. These observations well agree with theoretical prediction in Eq. (4).

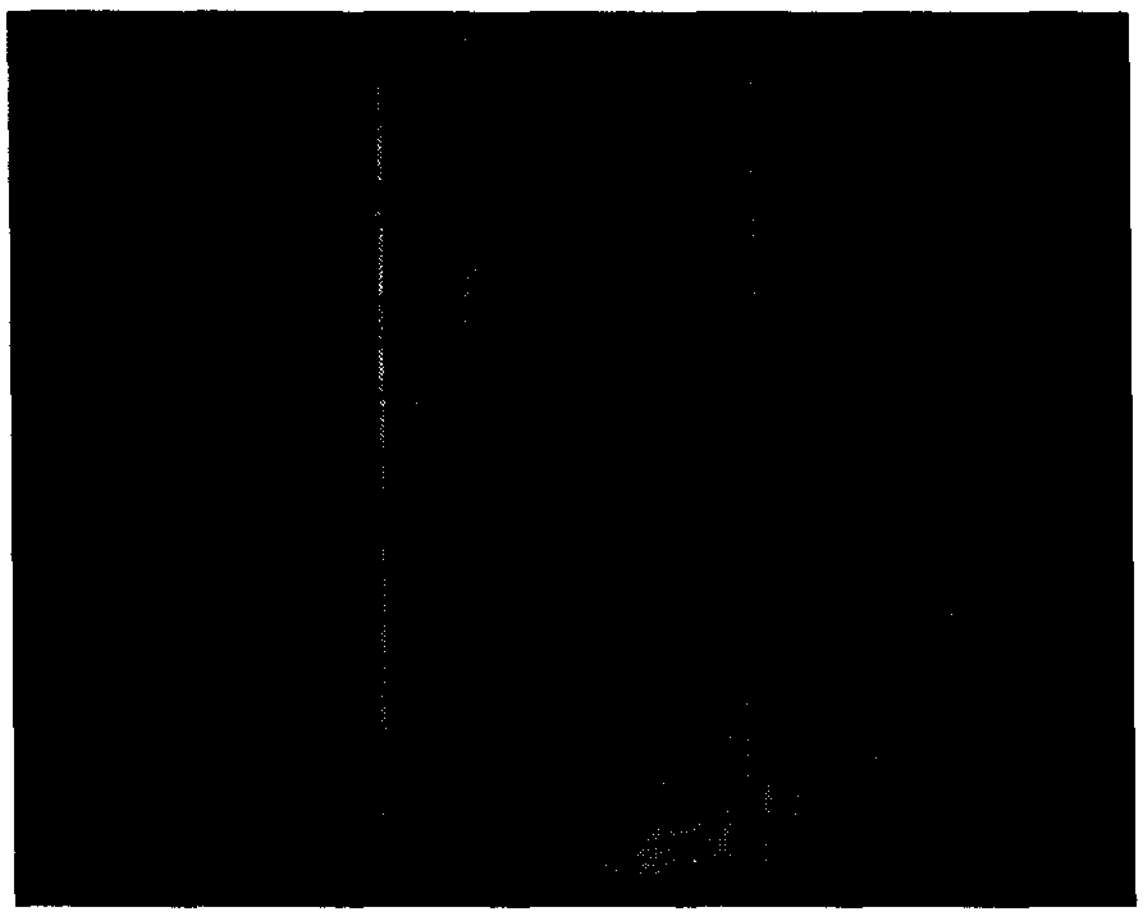

Fig. 2. Particle trajectories in the separator.

The measured retention distances of particle sizes, 2 μm, 5 μm, and 10 μm in diameter were 10 ± 1.3 μm, 26 ± 4.7 μm, and 58 ± 6.4 μm, respectively. The retention distances of the different particle sizes are linearly proportional to the particle sizes approximately. This linear proportionality between particle sizes and retention distances is consistence with the theoretical predictions derived in Eq. (4). Figure 3 shows the comparison between experimental measurements and theoretical predictions of the retention distance of the different particle sizes.

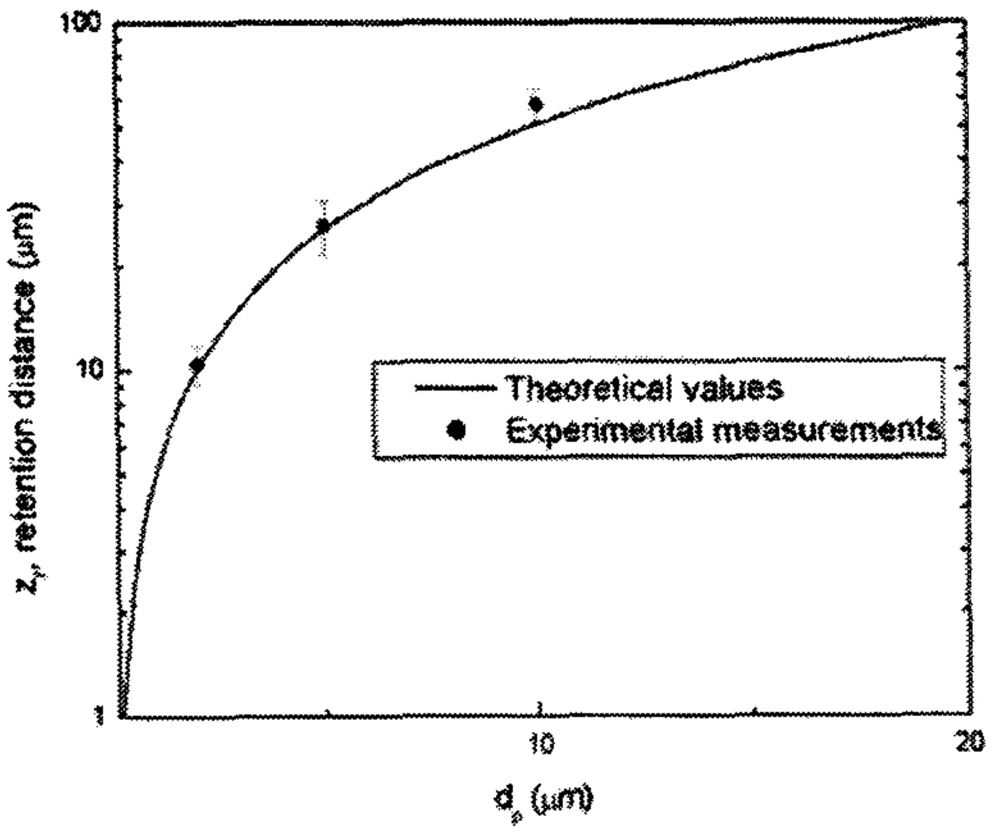

Fig. 3. Comparison between theoretical prediction and measured retention distance.

5. Conclusion

The experimental verification of the cross-type optical chromatography was performed firstly. The retention behavior was observed and the measured retention distances of different particle sizes well agreed with theoretical predictions.

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