Optical mobility in cross-type optical particle separation

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The optical mobilities of particles in a cross-type particle separation system were measured experimentally. Three particles were chosen to test the effects of optical mobility, namely, polystyrene latex, polymethylmethacrylate, and silica particles. The particles, which had the same optical mobility, showed identical behavior even though their sizes and refractive indices were very different. The optical mobility was validated by measuring the retention distance where each particle was deflected by the radiation force. © *2008 American Institute of Physics*.
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Development of micrototal analysis systems capable of separating biological cells or microsized particles is a topic of intense interest due to the potential applications of such systems in the fields of biology, immunology, and chemical analysis. Among the many approaches to particle separation examined to date,[1] the use of radiation forces has advantages such as its noncontact feature,[1] high accuracy,[2] and simple geometry.[3] Recently, simple optical particle separation methods, termed optical chromatography[4–8] (OC) and cross-type optical particle separation[9] (COPS), have been developed. In OC and COPS, the sample is irradiated with a loosely focused laser beam. Among the radiation forces acting on the particles in the sample, the scattering force, which acts in the direction of laser beam propagation, is dominant. Because a loosely focused laser beam is adopted in OC and COPS, radiation-induced damage to particles or biological cells is reduced, and many particles or cells can be separated in a single experiment.[4] In OC, the scattering force and fluid drag force act on the particle in opposite directions. In COPS, however, the scattering force acts in a direction perpendicular to the direction of fluid flow. This orthogonal arrangement of laser beam propagation and fluid flow in COPS means that this method can separate particles in a continuous manner.[9]

Since the radiation force depends on the size and refractive index of particles, the separation characteristics are also influenced by these two parameters.[10] In optical separation, not only different-sized particles but also optically different particles (i.e., those of uniform size but with different refractive indices) can be separated, although in a different manner. In previous studies, only one property—size[4,9] or the refractive index[5]—was considered to characterize optical particle separation. However, particle separation should be characterized in terms of optical mobility, which governs the behavior of a particle in optical particle separation.[10] This is relevant to the electophoretic[11] and magnetophoretic[12] mobilities in electrophoretic and magnetophoretic separation.

In the present study, the concept of optical mobility is derived and the effect of optical mobility on separation is validated experimentally in a COPS system. To see the effect of optical mobility, three particles with different optical mobilities are chosen, and the behavior of particles with the same optical mobility but different sizes and refractive indices is determined.

In COPS, the scattering force dominates because the width of the laser beam is much greater than the particle size. Although the scattering force varies as a function of the distance from the laser beam axis, a spatially averaged scattering force can be adopted.[13] Thus, the behavior of particles in COPS can be simplified as a particle in a constant force field. The spatially averaged scattering force on a spherical particle is expressed as[13]

$$F^* = \frac{n_0 P}{4c}\left(\frac{d_p}{\omega_0}\right)^2 K(m), \tag{1}$$

where n_0 is the refractive index of the medium, P is the incidence power of the laser, c is the speed of light in a vacuum, d_p is the particle diameter, and ω_0 is the waist radius of the laser beam. The dimensionless parameter $K(m)$ represents the conversion efficiency from the momentum change of photons to the scattering force[10] due to reflection and refraction at the interface between the medium and particle surface. The parameter $K(m)$ solely depends on the ratio of the refractive index of the particle to that of the medium m.

Due to the scattering force, particles in COPS are pushed in the direction of the laser beam, which is perpendicular to the direction of fluid flow. As a particle passes into the laser beam, its trajectory is deflected in the direction of laser beam propagation. After escaping the laser beam, the particle is continuously transported downstream due to the fluid flow without the scattering force pushing it in the direction of laser beam propagation (see Fig. 1). The change in the particle position in the direction of laser beam propagation, termed the retention distance, can be derived as[10,13]

$$z_r = \frac{n_0 P}{6\pi\mu U c}\frac{d_p}{\omega_0}K(m), \tag{2}$$

where μ is the dynamic viscosity of the medium and U is the velocity of the particle in the medium. A detailed derivation and theory can be found elsewhere.[10,13]

The retention distance expressed in Eq. (2) depends on the size and optical property $K(m)$ of the particle. Therefore, particles for which the quantity $d_pK(m)$ is the same will have the same retention distances. Previous studies focused solely on either differences in the particle size or differences in the optical properties of particles. However, as described above,

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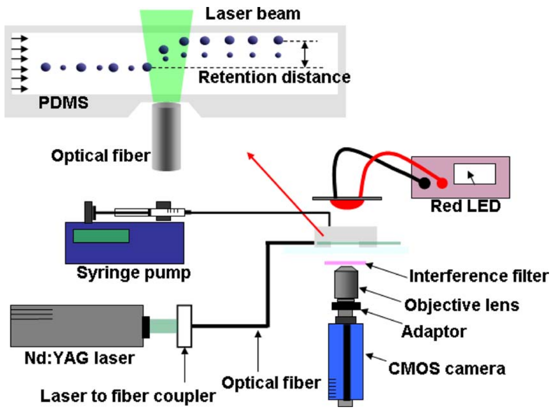

FIG. 1. (Color online) Schematic of the experimental setup.

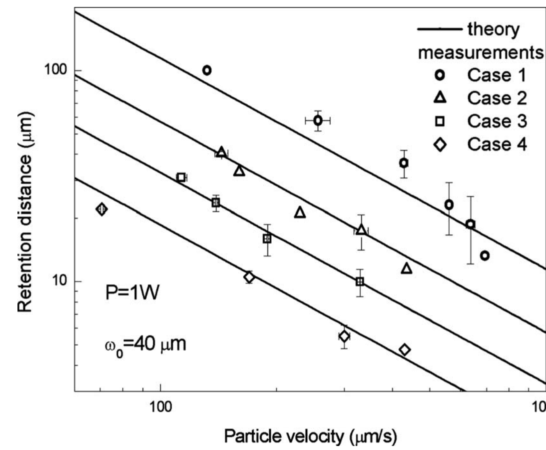

FIG. 2. Comparison of measured retention distances with predicted ones.

the mixed properties of particles should be accounted for when characterizing optical particle separation. To characterize optical particle separation, the concept of optical mobility must be invoked.[10] The optical mobility can be derived following an approach similar to that used for other mobilities such as the electrophoretic mobility[11] and magnetophoretic mobility.[12] Since the scattering force is proportional to the photon momentum flux in the laser beam, $n_0P/(c\omega_0^2)$, the optical mobility Z_{opt} can be expressed as

$$Z_{\mathrm{opt}} = \frac{F^*}{3\pi\mu d_p}\frac{c\omega_0^2}{n_0P} = K(m)\frac{d_p}{12\pi\mu}. \tag{3}$$

The second term in Eq. (3) is obtained by substituting the scattering force F^* in Eq. (1) into the first term. The optical mobility has units of $\mathrm{m^4/W\,s^2}$. Using the definition of the optical mobility, the retention distance of a particle in COPS can be rewritten as[10]

$$z_r = Z_{\mathrm{opt}}\frac{2n_0P}{cU\omega_0}. \tag{4}$$

To verify the optical mobility, a COPS system was fabricated. The system consisted of a polydimethylsiloxane (PDMS) microchannel and a Nd:YAG laser operating at 532 nm. The PDMS microchannel was fabricated via conventional soft lithography and had a width of 210 μm and a height of 100 μm. The microchannel had a Y-branched inlet to control the inlet position of particles in a flow cell. The laser beam was delivered into the microchannel using an optical fiber (MMJ-3I-IRVIS-50/125, NA=0.22, Oz Optics) and a laser to fiber coupler (HPUC-23–532, Oz Optics) as shown in Fig. 1. The laser beam power was in the range of 0.5–1 W. Images were collected using a complementary metal-oxide semiconductor (CMOS) camera (PCO, 1200 hs), which was combined with microscopic objective lens via a cubic adaptor. Because scattered light from the laser blurs the images, an interference filter (F10–632.8–4-2.00, CVI Optics) was used to remove such light, and a red light-emitting diode was adopted as a light source for the CMOS camera. Particles were suspended in water and injected in the microchannel using a 1 ml gastight syringe (81230, Hamilton), a syringe pump (220, KD Scientific), and a polytetrafluoroethylene tube. The characteristics of the particles used in the experiments are summarized in Table I.

First, particles with different optical mobilities were considered (cases 1–4 in Table I): 10.00 ± 0.09 and 5.00 ± 0.05 μm diameter polystyrene latex (PSL) (Duke Scientific Corp.), 4.90 ± 0.35 μm diameter polymethylmethacrylate (PMMA) (Magsphere, Inc.), and 4.80 ± 0.42 μm diameter silica particles (Bangs Laboratory). The refractive indices of the PSL, PMMA, and silica particles were 1.59, 1.49, and 1.43, respectively. During the experiment, the power and waist radius of the laser beam were kept constant at 1 W and 40 μm, respectively. Because the waist radius of the laser beam is much larger than the particle size, the gradient force can be neglected.[13,14] The maximum variation in the retention distance due to the size variation in particles is less than 20% for the particle velocity ranges employed. Under the experimental conditions used, the retention distances of the different particles do not overlap; hence, the size variation effect can be neglected. Three particles (cases 2–4) have almost the same size but quite different optical mobilities. From Eq. (3), the optical mobilities of the PSL, PMMA, and silica particles are 25.8×10^{-6}, 14.5×10^{-6}, and 8.03×10^{-6} $\mathrm{m^4/W\,s^2}$, respectively. Figure 2 shows a comparison of the theoretical predictions of Eq. (4)

TABLE I. Properties of particles.

	Particle size mean ± SD (μm)	Material	Relative refractive index m	Optical mobility Z_{opt} ($\mathrm{m^4/W\,s^2}$)
Case 1[a]	10.00 ± 0.09	PSL	1.20	51.6×10^{-6}
Case 2[a]	5.00 ± 0.05	PSL	1.20	25.8×10^{-6}
Case 3[a]	4.90 ± 0.35	PMMA	1.12	14.5×10^{-6}
Case 4[a]	4.80 ± 0.42	Silica	1.08	8.03×10^{-6}
Case 5[b]	4.90 ± 0.05	PMMA	1.12	14.5×10^{-6}
Case 6[b]	2.50 ± 0.025	PSL	1.20	12.9×10^{-6}

[a]P=1 W.
[b]P=0.55 W.

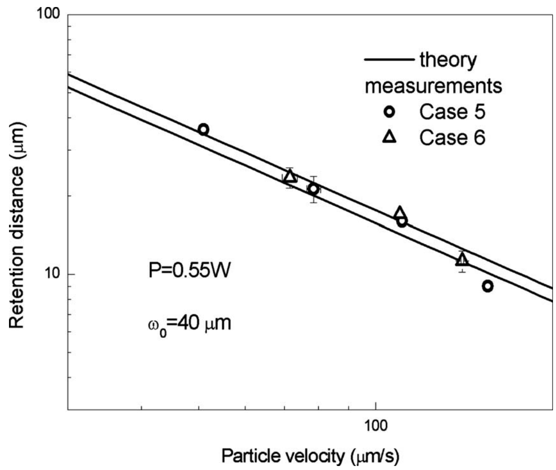

FIG. 3. Retention distances of particles with different sizes and refractive indices but similar optical mobilities (cases 5 and 6).

with the experimentally measured retention distances for various particle velocities. As seen in Fig. 2, distinct particles with different optical mobilities are completely separated, and the measured retention distances are in good agreement with theoretical predictions. The present results obtained for three particles of equivalent size but with different refractive indices are similar to the refractive-index-driven separations of colloidal particles in the OC performed by Hart and Terray.[5]

Second, two distinct particles with different sizes and refractive indices but almost the same optical mobility are considered. To accomplish this experiment, 4.90 ± 0.35 μm diameter PMMA (case 5) and 2.50 ± 0.025 μm diameter PSL (case 6) particles were used, and the power and waist radius of the laser beam were kept constant at 0.55 W and 40 μm, respectively. In cases 5 and 6, the power of laser beam and the flow velocity both decrease. Thus, the effect of scattering force on the retention behavior is almost the same since the retention distance depends on P/U as described in Eq. (4). Although these PMMA and PSL particles have very different sizes and refractive indices, their optical mobilities are similar, namely, 14.5×10^{-6} and 12.9×10^{-6}, respectively. Theoretically, the difference in retention distance between these two particles is predicted to be less than 5 μm, which is almost equivalent to the diameter of the PMMA particle. Figure 3 shows the measured and predicted retention distances of these two particles. As shown in Fig. 3, the retention distances of PMMA and PSL are almost the same, even though their sizes and refractive indices are completely different. Snapshots of the trajectories of the two particles, shown in Fig. 4, reveal that the PSL particle moves along a similar trajectory to the PMMA particle, even though the latter particle is twice the size of the former. These findings demonstrate that particles with the same optical mobility cannot be distinguished despite distinct differences in size and refractive index. Only spherical-shaped particles were considered in the present study. However, most of particles, such as biological cells, have irregular shapes. This irregularity of particle's morphology can have influence on fluid drag and radiation forces.[6] More studies are needed to evaluate the effect of particle's morphology quantitatively.

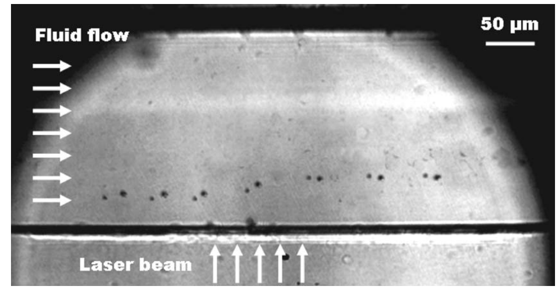

FIG. 4. Snapshots of two particles with different sizes and refractive indices but similar optical mobilities (cases 5 and 6). Particle velocity was 150 μm/s. The power and waist radius of the laser beam were maintained constant at 0.55 W and 40 μm, respectively.

In the present study, the importance of the optical mobility of particles subjected to optical particle separation has been investigated using the COPS system. Although the experiments were performed using COPS, the present analysis can be applied to any optical separation method. The results indicate that the optical mobility of a particle governs its behavior in optical particle separation systems, just as electrophoretic and magnetophoretic mobilities determine particle behavior in electrophoretic and magnetophoretic particle separation, respectively. Given the diverse sizes and chemical compositions of cells and polymer beads, it is essential to separate them based on the optical mobility.

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