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INVESTIGATION ON THE LASER TRAPPING MECHANISM OF LIGHT-ABSORBING PARTICLES IN AIR

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Abstract

We report on the micron-sized light-absorbing particle trapping in two configurations (horizontal and vertical), in order to elucidate the laser trapping mechanism based on the photophoretic force. The result shows that there are two types of photophoretic forces: $F_{\Delta\alpha}$ and $F_{\Delta T}$ forces on the laser irradiating particle. Furthermore, the forces and moments exerting the particles in various traps were analyzed. It was found that the $F_{\Delta\alpha}$ force due to the thermal accommodation difference among the irregular particles helps the irregular particles to be balanced more easily and of higher trapping efficiency and stability.

1 Introduction

Optical tweezers is a kind of technology for trapping and manipulating of the nano- and micro-objects using a highly focused laser beam [1]. As for the light-absorbing particles, the photophoretic force is 10^3-10^5 times stronger than the radiation pressure [2], and hence it can overcome the gravity and Brownian motion and realize the all-optical operation of the absorbing particles in air. Optical trapping based on photophoretic force plays an important role in operating the airborne particles, and it makes the in-situ study of the single aerosol particle possible [3].

Although optical trapping based on photophoretic force has already been widely used, there are still some controversies about the trapping mechanism. Some researchers claim that the direction of the photophoretic force can only be positive or negative [4, 5]. The other studies [6] demonstrating that the light-absorbing particles are subjected to two kinds of photophoretic forces, which overcome the gravity together and capture the particle in air.

In order to confirm the trapping mechanism of the particles in single-laser traps in air, we designed two trapping systems (horizontal and vertical) using Gaussian and hollow laser beam to study the trapping efficiency and stability of both regular and irregular light-absorbing particles. By comparing the trapping efficiency and stability, we determined the trapping mechanism of regular and irregular particles.

2 Experiments and results

Figure 1 shows the optical trapping used in this work. The laser source is a continuous-wave laser of 532 nm. Two types of trapping laser were used. One trapping laser was Gaussian shape. And the other one was the hollow laser beam with a doughnut shape, which was generated using the spatial cross-phase modulation method [7]. The trapping laser was focused by an f = 30 mm lens into the cuvette to trap the particles. During experiments, the dry particles were injected into the cuvette by a burette. The trapped particles were observed by a CMOS. Two types of particles were tested in this work. One type were the irregular graphite particles with the average diameter of 3 μm or so. The other type were the home-made carbon micro-spheres with the average diameter of 2.8 μm. The particle was trapped on the optical axis.

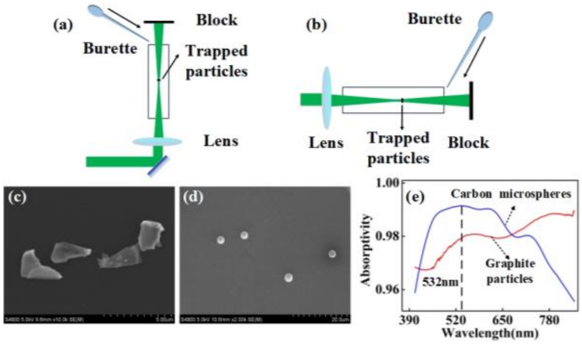

Figure 1 *(a) Scheme of the vertical trapping configuration; (b) Scheme of the horizontal trapping configuration; (c) The SEM image of the irregular graphite; (d) The SEM image of the carbon microspheres; (e) The infrared absorption spectre of the graphite particles and carbon microspheres.*

We firstly employed the vertical trapping configuration to trap the regular and irregular particles. As shown in Fig. 2, the trapping position variation of particles (the regular particles and irregular particles) using Gaussian beam and hollow beam as the trapping beam respectively. It is seen that trapping with hollow beam is of higher stability than Gaussian beam. Besides, the trapping stability of irregular particles and the regular particles are roughly the same in the same trap.

Secondly, we found neither the Gaussian beam nor the hollow beam was able to capture the regular particles in the horizontal configuration. By contrast, the irregular particles were easily trapped using either the Gaussian beam or the hollow beam. From Fig. 3, we can clearly see that the particle in the hollow beam trap moves with much smaller range compared with that in Gaussian trap, indicating that trapping with hollow beam is of much higher stability. Comparing with the results in Fig. 2, we can also see that the vertical trapping is of higher stability than the horizontal configuration.

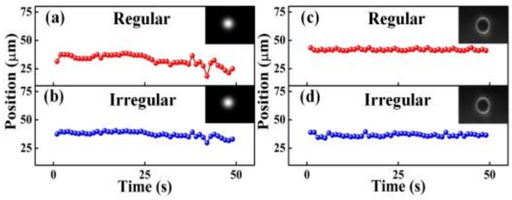

Figure 2 *The stability of regular and irregular particles using the vertical optical trapping scheme. (a) The regular particle in Gaussian trap; (b) The irregular particle in Gaussian trap; (c) The regular particle in hollow beam trap; and (d) The irregular particle in hollow beam trap.*

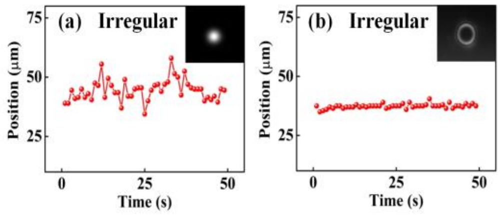

Figure 3 *The stability of irregular particles using the horizontal optical trapping scheme. (a) Gaussian beam trap (b) Hollow beam trap.*

Finally, we studied the trapping efficiency of different particles in different configurations. As shown in Table 1, the regular particles are hardly be stably trapped in the horizontal trapping configuration. While in the vertical trapping configuration, both regular and irregular particles can be captured, but the trapping efficiency is lower for the regular particles.

Gaussian beam	Horizontal trapping	Regular particles	1%
		Irregular particles	98%
	Vertical trapping	Regular particles	74%
		Irregular particles	98%
Hollow beam	Horizontal trapping	Regular particles	2%
		Irregular particles	98%
	Vertical trapping	Regular particles	84%
		Irregular particles	99%

Table 1： *Trapping efficiency*

3 Theory and discussions.

There are mainly three forces working on the particles, including two types of photophoretic force: the $F_{\Delta T}$ force and the $F_{\Delta\alpha}$ force, and gravity G. The $F_{\Delta T}$ force causes by unevenly heated on the particle surface. It is the product of the pressure P and the laser irradiating area S. According to the gas dynamics theory, the pressure can be obtained by:

$$P = \frac{1}{3}\rho_a m_a \frac{8BT}{\pi M} \quad (1)$$

in which ρ_a is the density of the air, m_a is the mass of the air molecules, B is the universal gas constant, T is the temperature on the particle surface, and M is the molar mass of air molecules. And therefore, the $F_{\Delta T}$ force is expressed as [6]:

$$F_{\Delta T} = \frac{1}{3}\rho_a m_a \frac{8BT}{\pi M} S \quad (2)$$

The $F_{\Delta\alpha}$ force causes by a different thermal accommodation coefficient among the particle. Rohatschek has strictly deduced the expression of the $F_{\Delta\alpha}$ force to be [8] :

$$F_{\Delta\alpha} = \frac{1}{2\bar{c}} \frac{\gamma - 1}{\gamma + 1} \frac{\Delta\alpha}{\bar{\alpha}} \frac{P_l}{1 + (P/P^*)^2} \quad (3)$$

in which, γ is the specific heat ratio, P is the gas pressure, P* is the characteristic pressure, $\bar{c}$ is the mean speed of gas molecules, P_l is the effective power of the trapping laser beam illuminated on the particle, $\Delta\alpha = \alpha_2 - \alpha_1$, $\bar{\alpha} = 1/2(\alpha_1 + \alpha_2)$.

Figure 4 shows the force analysis in the vertical optical trapping scheme. If the particle is regular as shown in Fig. 4(a), the thermal accommodation coefficient on each surface are roughly the same. And therefore, the $F_{\Delta\alpha}$ force vanishes as $\Delta\alpha = \alpha_2 - \alpha_1 \approx 0$ according to the Eq. (3). In this case, the particle experiences two forces, the $F_{\Delta T}$ force and the gravity G. The two forces balance with each other and therefore the regular particles can be trapped.

For the irregular particle shown in Figs. 4(b) and (c), the $F_{\Delta\alpha}$ force exists together with the $F_{\Delta T}$ force and the gravity G . For the irregular particle, the center of gravity (denoted as c) doesn't overlap with geometric center (denoted as o). The $F_{\Delta\alpha}$ force points from the gravity center to the geometric center. The particle can be trapped only when both the vector sum of the forces equals to zero. Due to the moments of $F_{\Delta T}$ and G, the particle would rotate. When it rotates from angle θ_1 to angle $\theta_2(=0)$, [Fig. 4(b) to Fig. 4(c)], the particle is possible to be trapped, because the condition $\sum \vec{F_i} = 0$ can be satisfied only in this case. We can see $F_{\Delta\alpha} + F_{\Delta T} = G$ for the trapped particle, which means the two types of photophoretic force are in the same direction for the trapped particle and conquer the gravity together. We think the point that the photophoretic force is always positive might be rooted from the situations in which two types of photophoretic force cannot be distinguished, just like the situation in this case.

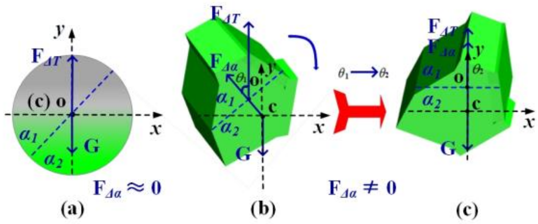

Figure. *4 The force analysis of the vertical optical trapping scheme. (a) The force analysis of regular particle; (b)-(c) The* *force analysis of irregular particle and the rotation of particles to balance.*

Figure 5 shows the force analysis of the horizontal optical trapping scheme, in which the x-axis stands for the laser propagating direction. If the particle is regular as shown in Fig. 5(a), the particle experiences two forces, the $F_{\Delta T}$ force and the gravity G. However, these two forces cannot balance the particle, so that the regular particles are hardly to be trapped in the horizontal trapping configuration.

If the particle is irregular, shown in Fig. 5(b), the $F_{\Delta\alpha}$ force exists together with the $F_{\Delta T}$ force and the gravity G. The direction of the $F_{\Delta\alpha}$ force may vary arbitrarily, decided by the orientation of the particle. The $F_{\Delta T}$ force and gravity G would produce moments on the particle, which make the particle rotate until the vector sum of the forces equal to zero. As shown in Figs. 5(c), in order to balance the G and $F_{\Delta T}$ forces, the $F_{\Delta\alpha}$ force must be in the indicated direction and its two components shadowed on x and y axis has the following relationships: $F_{\Delta\alpha}\sin\theta_2 = G$ and $F_{\Delta\alpha}\cos\theta_2 = F_{\Delta T}$.

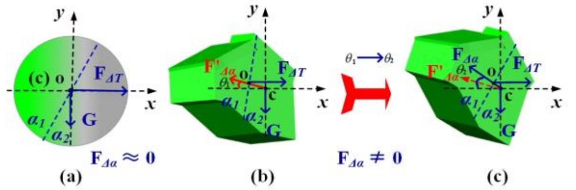

Figure 5 *The force analysis of the horizontal optical trapping schemes. The direction of laser is from left to right. (a) is the force analysis of regular particle; (b) is the force analysis of irregular particle.*

In the experiments, we also found the hollow beam trapping has higher stability and efficiency than the Gaussian beam trapping. When a light-absorbing particle is irradiated by Gaussian beam, as shown in Fig. 6(a), the $F_{\Delta T}$ force at the light irradiation center is stronger than that at the edges because the light is in a Gaussian distribution. By contrast, the $F_{\Delta T}$ force at the edges is stronger than that at the center in the hollow beam trapping case. The $F_{\Delta T}$ force at the edges has a lateral confinement on the particles. Because the lateral confinement is stronger in the hollow beam trap than that in Gaussian beam trap, the trapping stability in the hollow beam trap is higher.

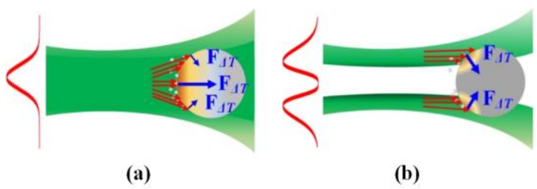

Figure 5 *The force analysis of particle in Gaussian and hollow traps.*

4 Conclusion

In this work, we designed two trapping systems (horizontal and vertical) using Gaussian and hollow laser beam to study the trapping efficiency and stability of both regular and irregular light-absorbing particles. It was found that both the regular and irregular particles can be trapped in the vertical configuration. But the regular ones cannot be trapped in the horizontal configuration. Besides, trapping of the irregular particles is of higher efficiency and stability. Moreover, the hollow beam trapping is of higher stability and efficiency than the Gaussian beam trapping. The useful information in this work is of value in the applications of single particle analysis.

5 Acknowledgement

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