Optical Trapping of a Growing Water Droplet in Air

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A water droplet, which was formed as a nucleation center from an aerosol of ammonium chloride, was trapped by a converged c.w. IR laser ($\lambda = 1064$ nm) using a 100× objective lens, and the successive growth of the droplet was observed under supersaturated water vapor. The size of the droplet increased linearly with time and its maximum radius was 5.7 μm at a laser at 5 mW, indicating that the axial trapping efficiency Q was 0.46. This efficiency is much greater than those reported previously; for example, according to Ashkin and Dziedzic [*Science* **1975**, *187*, 1073], $Q = 0.08$ for a glycerol droplet of radius 6 μm at 40 mW ($\lambda = 514.5$ nm).

1. Introduction

Despite the current active application of laser trapping of objects in the liquid phase,[1,2] it is difficult to trap a liquid droplet in the gas phase. More than 20 years ago, Ashkin and Dziedzic performed an experiment on the optical levitation of liquid droplets, delivered into a chamber as sprayed mist with an atomizer, by using a focused laser beam from below.[3] After this pioneering study, a considerable number of reports have appeared on optical trapping of a liquid droplet in the gas phase.[4−11] However, to date the axial trapping efficiency has not improved so much (see, e.g., Table 1). This may be due to the inherent difficulty of using the weak force, on the order of pN, exerted by laser trapping.[1] Moreover, it is almost impossible to obtain such a small droplet directly from a large pool of liquid because of surface tension. For example, if we consider a liquid with a surface tension γ of 10 mN m^{-1} ($\gamma = 72$ in distilled water), the force necessary to obtain a droplet on the order of 10 μm is $F \sim 10$ mN m^{-1} × 10^{-5} m = 10^5 pN. Thus, we have to find another strategy to realize the optical trapping of such a droplet in the gas phase. In this study, we trapped a droplet generated under a supersaturated vapor.

2. Experimental Method

The experimental setup is shown in Figure 1. In a narrow chamber (10 mm × 15 mm × 200 μm thick), NH_4Cl particles smaller than the submicrometer level are spontaneously formed as a result of the chemical reaction between HCl and NH_3 vapors. The microparticle of NH_4Cl behaves as a nucleation center in supersaturated vapor of water. For optical trapping, a c.w. Nd:YAG laser ($\lambda = 1064$ nm, SL902T, Spectron) at 5 mW was focused within the chamber using a 100× oil-immersed objective lens. The convergence angle was 120°. The time course of the growth of a single droplet after nucleation was monitored with an inverted microscope (TE300, Nikon) and recorded through an image processor (Argass-10, Hamamatsu Photonics). The experiments were carried out at 22 ± 1 °C.

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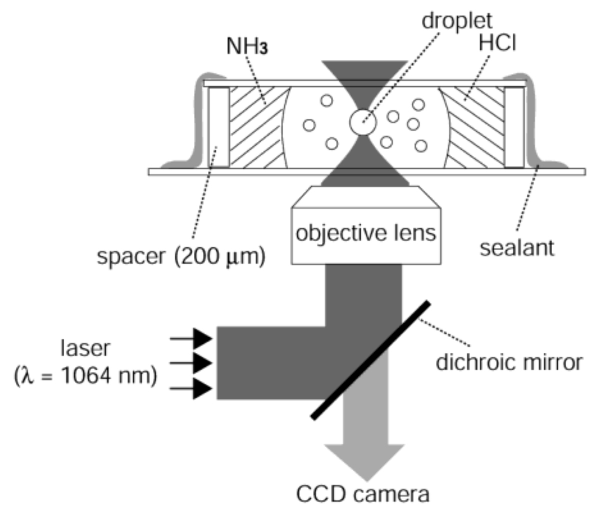

Figure 1. Schematic illustration of the experimental setup. The chamber was irradiated with the laser from below through the reflecting mirror and objective lens.

3. Results and Discussion

In the absence of laser irradiation, thermally agitated droplets on the order of a micrometer were observed. Upon irradiation by the converged laser, a droplet was trapped at the focal point of the laser due to attractive force. Under these conditions, the droplet tended to escape from the focal point due to collision with other droplets. To observe the growth of the droplet in the gas phase without the effect of such collision with other droplets, the trapped droplet was moved to a region within the chamber with a lower density of free droplets. Since the chamber was shielded, the inside was saturated with water vapor. Thus, we could follow the whole process of growth of a droplet until it fell due to gravitational force at a critical size.

The whole growth process of a trapped droplet is exemplified in Figure 2, where Figure 2a shows images of a droplet and Figure 2b is a spatio-temporal plot of growth. The size of the droplet, r, increased linearly with time, dr/dt = 0.40 μm/s. The droplet then fell at a critical radius $r = 5.7$ μm. It has been confirmed that the growth rate, as well as the critical radius,

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TABLE 1: Trapping Efficiency of Liquid Droplet

reference	substance	radius [μm]	laser power [W]	efficiency (Q)
Ashkin and Dziedzic[3] (1975)	glycerol	6	0.04	0.08
Lettieri et al.[4] (1981)	glycerol	6	1	0.003
Lettieri and Preston[5] (1985)	dioctyl phthalate	12.5	0.5	0.05
Thurn and Kiefer[6] (1985)	glycerol/water	15	1	0.05
Schweiger[7] (1990)	dibutyl phthalate/1,1,2-trichloro-1,2,2-trifluoroethane	8	0.25	0.03
Carls et al.[8] (1990)	dioctyl phthalate	10	0.25	0.05
Carls et al.[8] (1990)	glycerol	10	0.25	0.05
Essen et al.[9] (1996)	SOMOS 3100	15	0.5	0.09[a]
Trunk et al.[10] (1997)	capric acid/heptane	7.5	0.1	0.05
Musick et al.[11] (1998)	stylene and polyester	5	0.1	0.017
present study	water	5.7	0.005	0.46

[a] We assume that ρ is 1.1.

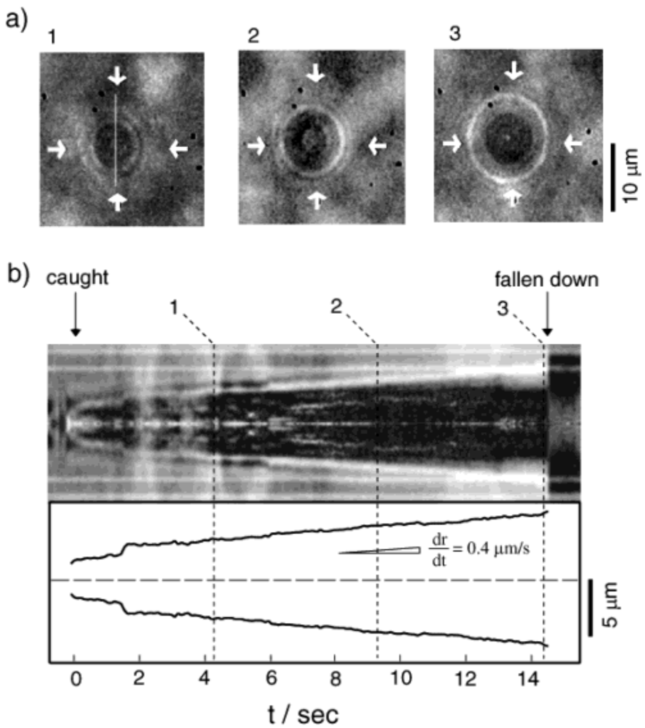

Figure 2. Growth of an optically trapped droplet. (a) Images on a trapped water droplet at a time interval of 5 s. The focus of the laser is indicated by the arrows. (b) The upper picture shows a spatio-temporal plot of a growing droplet, reconstructed from time-successive video frames. The bottom picture shows the time development of the interface on the same droplet. Under optical trapping, the droplet started to grow at $t = 0$ s and fell down at $t = 14.4$ s. The maximum diameter is found to be 5.7 μm. The vertical axis in the upper figure is the cross section of the droplet indicated by the white line in (a)-1. The horizontal axis is time. The numbers in (b) correspond to those in (a).

remains essentially constant; the deviation among the observations on more than 10 droplets is <20%.

We now discuss the axial trapping efficiency of the droplet, based on knowledge of the critical size. The axial trapping efficiency, Q, is given as eq 1,[12,13]

$$Q = \frac{fc}{nP} \tag{1}$$

where f, c, n, and P are the trapping force, velocity of light, refractive index of medium, and laser power, respectively. Trapping force along the vertical axis is also described as

$$f = mg = \frac{4}{3}\pi r^3 \rho g \tag{2}$$

where r and ρ are the radius and density of the droplet, respectively, and g is the gravitational constant. Under our experimental conditions, n, r, ρ, and P are 1.0, 5.7×10^{-6} m, 1.0×10^3 kg m^{-3}, and 0.005 W, respectively. Using eqs 1 and 2, we obtain Q as 0.46. This efficiency is an order of magnitude greater than those in previous reports;[3-11] for instance, according to Ashkin and Dziedzic,[3] a laser ($\lambda = 514.5$ nm) of 40 mW, which was mildly converged, was necessary to levitate a glycerol droplet ($\rho = 1.26 \times 10^3$ kg m^{-3}) with a radius of 6 μm. Thus, the axial trapping efficiency is calculated as $Q = 0.08$. The Q values in the past studies are summarized in the table, where the density of each pure substance was used to calculate the corresponding Q. There are two essential factors on the improvement of the trapping efficiency in our study. (I) We have adopted an objective lens of higher magnification compared to past studies to obtain a larger convergence angle of laser. (II) By choosing the experimental condition to minimize the effect of translational motion of a droplet, it has become possible to trap a larger droplet. In other words, the strategy to catch the droplet through the process of nucleation and growth causes a successful result in the present study because the droplet generated around the focus exhibits essentially no inertia on the translational freedom. With use of current methodologies to produce a droplet, say transferring a droplet generated outside the chamber onto the laser focus, its inertia becomes larger with the increase of the size or mass. Therefore, the optical potential cannot overcome the inertia for large droplets.

Next, let us briefly discuss the process of growth. Suppose that water vapor is supplied to the surface of the droplet in constant flux $\boldsymbol{j}_{\rm surf}$, which is normal to the surface,

$$|\mathbf{j}_{\rm surf}| = \rho_{\rm v} \upsilon_{\rm v} = \text{const.} \tag{3}$$

where $\rho_{\rm v}$ and $\upsilon_{\rm v}$ are the density and flow velocity of water vapor, respectively. Then the rate of the change in volume is given as the product of the surface area and the flux of water molecules across the unit surface element d$\mathbf{S}$.

$$\begin{aligned} \frac{dV}{dt} &= \frac{1}{\rho_{\rm d}} \int_S \mathbf{j}_{\rm surf}\, d\mathbf{S} \\ &= \frac{1}{\rho_{\rm d}} \rho_{\rm v} \upsilon_{\rm v} S \end{aligned} \tag{4}$$

where V and S are volume and surface area of the growing droplet, respectively, and $\rho_{\rm d}$ is the density of liquid water. Since $V \sim r^3$ and $S \sim r^2$, eq 4 gives the relationship as eq 5,

$$\frac{dr}{dt} = \text{const.} \tag{5}$$

We can then obtain eq 6:

$$r = kt + \text{const.} \tag{6}$$

This simple consideration reproduces the experimental results: the size of the droplet increases linearly except in the initial stage of growth. The experimental kinetics in our study implies that the spatial change of the vapor concentration has a negligible effect due to the rather high degree of supersaturation, and also to thermal convection within the chamber. As an additional factor, thermal heating owing to the absorption of laser on the droplet should be considered. However, the experimental evidence on the growth of a micrometer-sized droplet suggests that the heating effect would not be so serious.

4. Conclusion

We have demonstrated the optical trapping of a water droplet in the gas phase with a converged laser. The present results suggest that optical trapping is useful for observing the dynamic instability of micrometer-scale systems.[14] The critical size of the trapped droplet indicates a rather high axial trapping efficiency. This means that, in the cabin of a space shuttle or space station under the gravitational constant of $10^{-6}g$, it may be easy to optically trap a droplet with a radius on the order of submillimeter $\sim$ millimeter by converged laser of 0.1$\sim$1 W.

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