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Liquid Jet Breakup by High Frequency Pressure Fluctuations

高周波圧力変動による液体ジェットの自励発振分裂

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1. Introduction

Technique of fluid particle emission in micro-meter scale is widely used in inkjet printing. As a new application of particle emission, we aim to fablicate microcapsules with nano-coating layer. When two insolble liquid particles collide, one spontaneously wraps the other and the coating layer is formed if we choose two liquids properly. By adding polymer into outer liquid, we can make a microcapsule. For this application, mass production of microcapsules is needed and continuous-mode particle emission is suitable for this purpose.

Many kinds of continuous-mode particle emission methods have been developed so far[1,2] and their principle is based on the theory given by Rayleigh[3], dealing with a cylindrical liquid jet breakup. A cylindrical liquid jet fountaining from the nozzle is unstable with respect to the thickness perturbation and spontanously breaks up into multi-sized droplets. The theory shows that perturbation grows if $\lambda > 2\pi a$ and the evolution becomes maximum at $\lambda \sim 9a$, where a is the initial radius of the jet and λ is the wavelength of perturbation. In the continious-mode liquid particle emission, perturbation on the jet is artificially induced by, for example, vibrating the nozzle. The generation of the aligned monosized particles is thus possible, whose radius corresponds to the wavelengh of the perturbation, λ. In this study, we reports our new continous-mode particle emission based on this theory.

2. Experiment

A schematic view of a liquid particle generator is shown in **Fig.1**. The particle generator consists of glass nozzle, piezoelectric actuator and liquid-filled pressure tank made of glass. Our glass nozzle is chemically tough and is expected to be applied to producing fluid particles of various kinds of liquid samples. We employ a glass capillary with a squeezed edge having an aperture diameter of 8-30 μm as the nozzle. The other side of the glass capillary is connected to the pressure tank by a teflon tube. Constant pressure, ranging 50-200 kPa, is applied to the buffer tank by a compressor to eject liquid jet from the capillary. The glass capillary is sandwiched between two piezoelectric actuators, which apply a sinusoidal wave to induce perturbation of the thickness of the liquid jet. The frequency of pressure modulation f ranges from 20 to 150 kHz, which is equal to the number of particles produced in 1 s. Distilled water is chosen for sample liquid in this experiment.

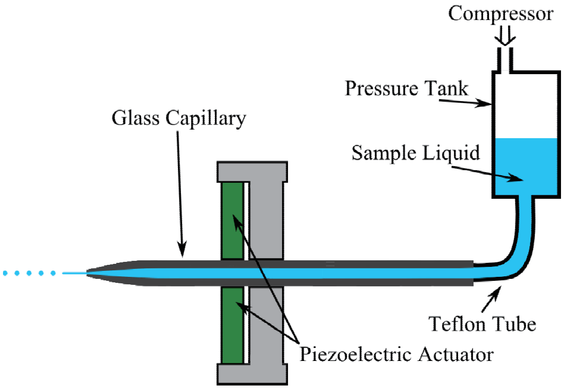

Fig. 1 Schematic view of the particle generator.

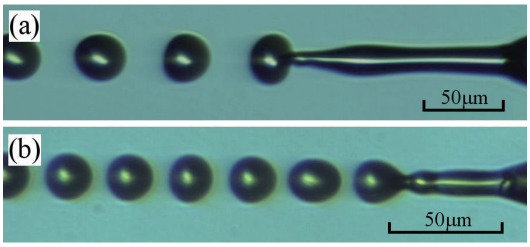

Fig 2. Photograph of distilled water jets and droplets,
(a) $f = 83$ kHz $a = 7.5$μm $v_d = 4.4$ m/s $v_j = 6.0$ m/s,
(b) $f = 106$ kHz $a = 4$μm $v_d = 2.9$ m/s $v_j = 5.1$ m/s.

To observe the particles motion, a microscope equipped with a stroboscopic observation system is employed. Stroboscopic light with duration of 180 ns illuminates the particles synchronized with piezoelectric driver and delay circuit.

The wavelength λ is easily obtained by the equation $\lambda \sim v_j / f$, where v_j is jet velocity. However, the jet velocity v_j is hardly while the droplet velocity v_d is easily measured by examining the motion of one particle. According to Schneider, et al.,[4] v_d is given by

$$v_d = v_j (1 - v_c^2 / v_j^2) .$$

Here $v_c = \sqrt{\sigma / \rho a}$, σ is the surface tension and ρ is the density. We estimated, therefore, v_j from this equation. For a jet with large radius, v_c

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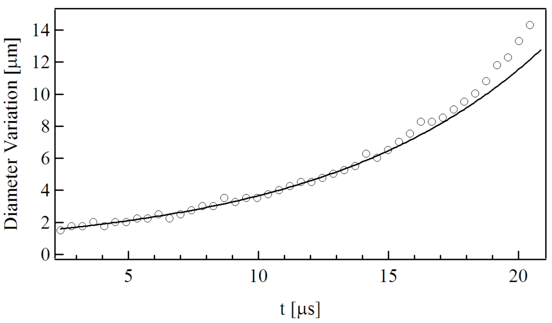

Fig. 3 Changes in diameter variation with time.

is much smaller than v_j and then $v_j \sim v_d$ holds. However in this work, we use a jet with small radius, $a \sim 10$ μm, and the contribution of v_c cannot be ignored; v_c is around 3 m/s for this radius, while the typical jet speed is $v_j \sim 5$ m/s. The difference between v_d and v_j should be noted in the present experiment.

3. Results and discussion

A photograph of the typical water jet and its break up are shown in **Fig.2**. In (a), the diameter of the nozzle is 15 μm and the volume of the droplet is about 15 pl. The wavelength of the surface wave, induced by the pressure modulation, was calculated to be $\lambda = v_j / f = 9.3a$. This value is close to the wavelength of the surface wave growing most rapidly. We also estimated the growth rate of surface wave by analyzing time dependence of diameter of the jet. Amplitude of modulation in the diameter is obtained at each point along the axis of the jet and the distance from the nozzle to the point is converted to time by using the jet velocity v_j. The result is shown in **Fig.3**. The origin of t is taken as the time in which the jet exits from the nozzle. The amplitude of the modulation increases exponentially and the jet breaks up at about $t = 24$ μm.

According to the Rayleigh's linear approximation, the surface wave grows exponentially and the time constant of the growth is written as follows,

$$\tau = \left[\frac{\sigma k}{\rho a^2}(1-k^2a^2)\frac{I_1(ka)}{I_0(ka)} \right]^{-1/2},$$

where k is the wave number and defined by $k = 2\pi / \lambda$, and $I_n(ka)$ is the hyperbolic Bessel Function of order n. The time constant calculated from this equation is $\tau = 7.4$ μs. On the other hand, we obtained time constant $\tau = 8.5$ μs by fitting the result with exponential curve at the section where diameter variation is relatively small. We found the Rayleigh's approximation well reproduces the experimental result, and we consider the discrepancy between the theory and the experiment would be the effect of viscosity, which is ignored in the approximation.

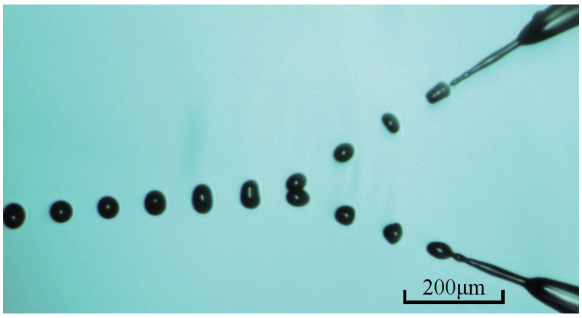

Fig. 4 Collision of two droplets.

In Fig.2 (b), a nozzle having a diameter of 8μm was used. The volume of a droplet is about 2 pl. The gap between two particles is very small and is only $5.0a$, because of decelerating at the pinch point.

We succeeded in oblique collisions of two droplets emitted from our liquid particle generators as shown in **Fig.4**. The diameter is 15 μm and the colliding liquid particles are distilled water. The driving frequency of both generators is the same value and $f = 34$ kHz. By changing the phase difference of the two modulation signals, we can adjust the position and the aspect of the collision. Though this system is under development, we aim to produce over 100 thousand microcapsules per second with this technique.

4. Conclusions

We developed a new liquid particle generator, which can produce over 100 thousand droplets per second. With the nozzle having the diameter of 8μm, we can produce particles as small as 2 pl, which is comparable in size to conventional drop-on-demand generator. We also observed collisions emitted of two liquid particles by our generators.

Acknowledgment

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