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Proceedings of Symposium on Ultrasonic Electronics, Vol. 37 (2016)

16-18 November, 2016

Collision Dynamics of Microdroplets
微小液滴の衝突ダイナミクスの観測

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1. Introduction

The recent progress in the inkjet technology has offered us the capability of utilizing microdroplets toward wider application. Although previously, inkjet was looked to as a printing technology capable of distributing the droplets from 'bottom-up', the recent research opens up a new role of inkjet as a factory for generating functional microdroplets.

Schneider and Hendricks first showed a method for creating a monodispersed micrdodroplets using pressure pertubation in liquid cylinder[1]. Takeuchi further improved the technology for rapid and stable generation of microdroplets[2]. This method enables a stable production of more than 100,000 microdroplets a second in which case, the inkjet technology should be viewed as a production line for generating microdroplets, rather than a printing method.

For over a decade, the studies on creating functional droplets using monodisperse droplet generator has been conducted. Two different droplets are brought together to collide for a rapid generation of functional microstructures. Various morphologies can be obtained as a resulting product of collision, such as capsules, beads, and Janus particles. Given that the size of the resulting morphologies is about the size of a cell, applications of these microstructures toward biology and medicine are also studied extensively.

However, the details of dynamics that take place during collision, such as wetting, diffusion, chemical reaction are yet unknown. This is mainly due to the lack of quantitative measurement method to describe the collision dynamics of the microdroplets. Here, we compared the difference between the dynamic configuration of water-water and water-ethanol collision. The new dynamics that arises due to chemical composition is especially emphasized. At the same time, we introduce a method using oscillation to quantify the collision dynamics.

2. Experiment

The microdroplets are produced using continuous inkjet system, as described in our previous work[2]. In this work, two inkjet devices are prepared, so that the microdroplets emitted from the different nozzles encounter in mid-air, as shown in **Fig. 1**. The diameter of both the nozzles are 30 μm. The microdroplets are carefully observed in the x- and y-axis using CCD devices to realize an ideal collision at the center of gravity of the droplets. The frequency of the stroboscopic light is synchronized with that of the droplet emission in order to obtain a stable picture. The experiments were conducted on both the water-water collision and the water-ethanol collision.

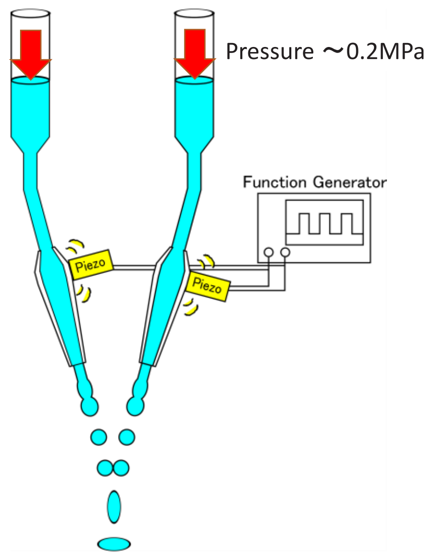

Fig. 1 Schematic view of the experimental set-up of the droplet emission system.

3. Result and Discussion

The static picture of the collisions are shown in **Fig. 2**. For water-water collision, the momentum of the droplets escapes axisymmetrically to form a donut-like configuration. Note that the center of the configuration is still connected. Not only is the configuration axisymmetric, but is also symmetric against the plane of collision.

However, this breaks down in the case of collision between different liquid droplets. The water-ethanol droplet collision shows an axisymmetric behavior, but is not plane-symmetric. The peculiar configuration arises from sudden transition of chemical potential at the interface[3]. Qualitatively, this can be described as the difference in the surface tension between water and ethanol. The competition between the original momentum

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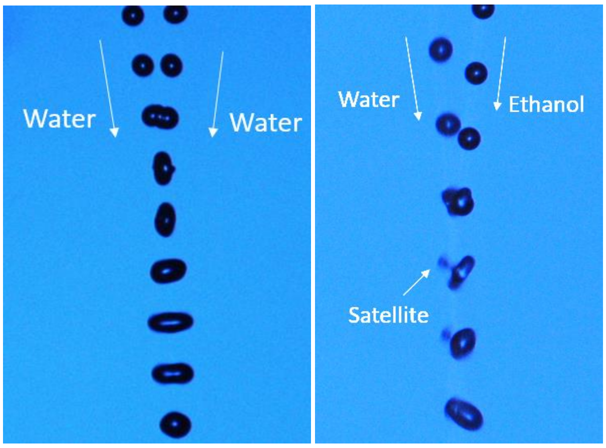

Fig.2 Stroboscopic pictures of collision of water-water droplet (left) and water-ethanol collision (right).

and the surface tension force creates a donut-like structure on the ethanol side, while producing a satellite on the water side.

The behavior can be described quantitatively from the oscillation of the mixed droplets. The role of oscillation as a measure of dynamics of droplets were first elucidated by Stückrad et. al[4]. Stückrad et al. showed that in a homogeneous droplet, the angular frequency ω of a small amplitude oscillation is directly connected to the surface tension σ by

$$\omega = \sqrt{\frac{8\sigma}{\rho R^3}}, \qquad (1)$$

where ρ is the density and R is the radius of the droplet. Therefore, the oscillation of a droplet at a particular moment reflects the state of the surface of the corresponding time.

The principle of the theory should hold even for collision related dynamics. Hence, we apply the oscillation measurement toward understanding the surface phenomena during collision. The angular frequency ω was measured as a function of time after collision. From equation (1), the surface tension σ was also deduced as a function of time. Here, the radius R is measured by a light scattering method[5] and the typical value was 31 µm. The density ρ is assumed to be the density of 50 wt% ethanol solution. The result is presented in **Fig. 3**.

Before 250 µs, the small amplitude oscillatory theory is not adequately satisfied. In the regime, the angular frequency becomes lower than that expected in equation (1). After 250 µs, the surface tension reaches that of ethanol, implying that the small amplitude condition is satisfied. It also supports the previous statement that the ethanol covers the water droplet. The surface tension continues to rise until at around 350 µs, when the surface tension matches that of 50 wt% ethanol solution. Since the rate of

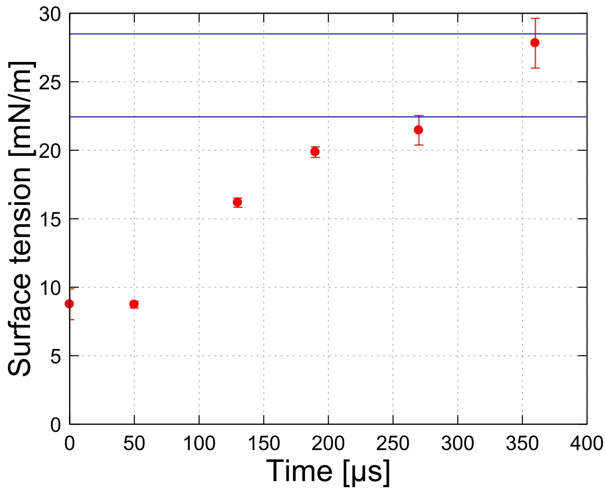

Fig. 3 Surface tension σ deduced as a function of time after collision. The surface tension has been calculated from the angular frequency of the oscillation. The upper blue line shows an ideal surface tension of 50 wt% ethanol solution and the bottom blue line shows that of pure ethanol solution at 20 ºC.

diffusion of water molecules toward the ethanol phase is much slower, which is in the order of 10 ms assuming a 30 µm bilayer capsule, internal dynamics due to the initial momentum and the surface tension may be playing a large role.

4. Conclusion

The collision dynamics of microdroplets were investigated. Not only were the dynamics observed visually, but a new approach to quantify the dynamics through the oscillation was proposed. The result indicates that a large part of the internal dynamics may depend on the initial momentum and the surface tension, rather than diffusion of molecules.

Acknowledgment

This work was partially supported by a Sentan program from Japan Science and Technology Agency, JST.

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