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収束超音波による浮遊液滴の合体・混合挙動

Coalescence and mixing behavior of levitated droplets suspended by focused ultrasonic wave

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1. Introduction

Fluid processes (i.e., mixing and stirring) are necessary in the field of life science, materials chemistry and analytical chemistry. In recent years, as the volume of specimens has become smaller, problems caused by the vessel walls have become more apparent[1)]. Therefore, there is a need for at technology to control the fluid in a non-contact, non-invasive manner. To achieve this, "acoustic levitation", which uses ultrasonic waves levitate objects in the air, is attracting attention. Recently, a technique for levitating and controlling the object in the air using ultrasonic phased array has been reported[2)3)]. Therefore, we expect that ultrasonic phased array can be applied to manipulate droplets without contact. Previous studies have reported the transport, coalescence and mixing of droplets. However, the complete mixing of droplets requires a long time compared to their diameter[3)]. Therefore, it is necessary to accelerate the mixing.

In this study, we visualized the mixing process and flow field of droplets during coalescence and mixing. First, we demonstrate that the mixing enhancement by inducing interfacial oscillation on the droplet. In order to quantify the effect of interfacial oscillation, mixing parameters were calculated based on the images obtained in LIF (laser induced fluorescent) method. Secondly, the internal flow field of the oscillating droplets was measured using PIV (particle image velocimetry) in order to elucidate the mechanism of mixing enhancement. Finally, bi-color images were taken to investigate the effects of coalescence of droplets on the mixing.

2. Experimental apparatus

Figure. 1 shows a schematic diagram of the acoustic levitation apparatus used in this study. The acoustic field for levitating, coalescing and oscillating droplets was generated using an ultrasonic phased array. The phased array was consisted of forty-nine small ultrasonic transducers that arranged in a 7x7 square. A FPGA (Cyclone-IV DE0-Nano, Intel Corp., Santa Clara, CA, USA) was used to control the transducers, and the FPGA was controlled from a PC via a microcomputer. In the experiment, the acoustic wave was emitted from ultrasonic phased array. In order to focus the ultrasonic waves onto the glass plate, each wave emitted from ultrasonic transducers was phase-shifted. The focused ultrasound waves were then reflected on the glass plate, producing localized acoustic standing waves. The ultrasonic phased array enables two droplets to be levitated simultaneously by switching the focal point of ultrasonic waves with a frequency of 500 Hz. After the successful levitation of two droplets, the distance between two focal points was decreased to coalesce the droplets. In addition, the ultrasonic phased array can induce interfacial oscillation by modulating the amplitude of the ultrasonic waves, which results in a deformation of the interfacial shape on the droplet. The modulation frequency can be set to any value.

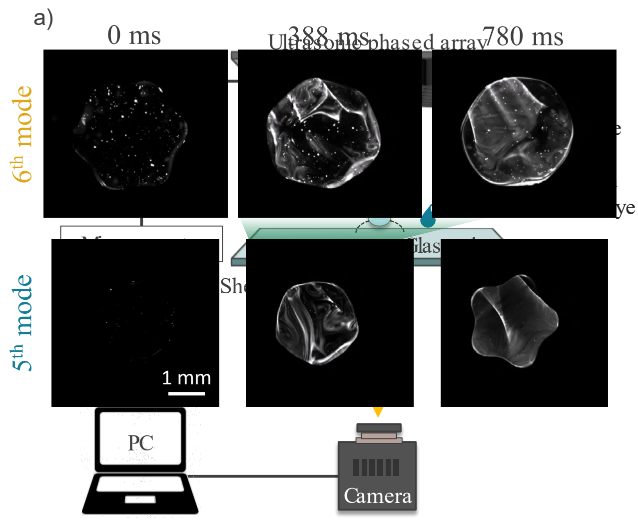

Fig.2 Time variation of luminance in droplet

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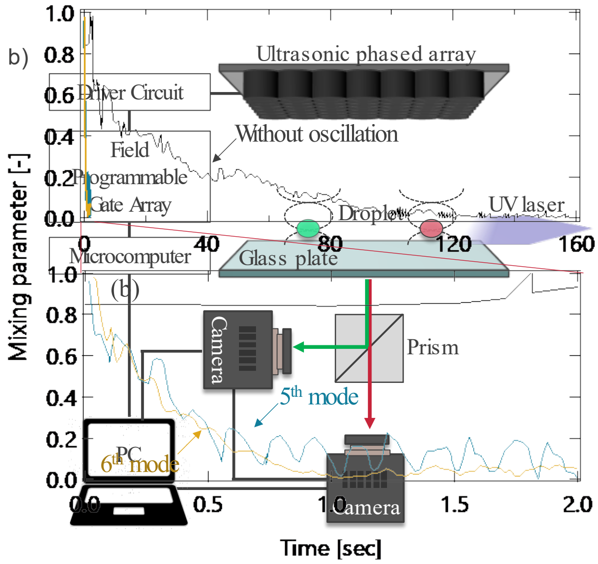

Fig.3 Time variation of mixing parameter

nternal frow of the droplet. b) for the bi-color PIV

In order to measure the mixing, LIF method was implemented. In the experiment, a droplet without the fluorescence dye was levitated. Afterwards, a droplet with the dye was brought into close proximity with suspended by needle tip and allowed to coalesce. The amplitude of the ultrasonic wave was varied to induce interfacial oscillation of the droplets.

In the visualization of internal flow of the droplet with interfacial oscillation, PIV was used. In this experiment, a single droplet containing tracer particles was levitated and interfacial oscillation was induced at the interface. To imaging the internal flow field, the green sheet laser was irradiated horizontally to the equatorial plane of the droplet.

In order to visualize the flow field and mixing simultaneously, the bi-color PIV was conducted. In this experiment, two particles with a common excitation wavelength but different fluorescence wavelength (Lumisis Marker®, Central techno Co., Ltd., Japan) were employed as tracer particles. Firstly, two droplets containing different fluorescent-emission-wave particles each other were levitated. Secondly, the distance between two focal points was decreased from 6 to 2 mm to cause the coalescence of droplets. The ultra-violet seat laser was irradiated horizontally to the equatorial plane of the droplet. A series of images were taken by two high speed cameras (FASTCAM-Mini AX200, Photron Co., Ltd., Japan) placed behind the dichroic-prism.

3. Measurement of mixing by LIF (Laser Induced Fluorescence) method

In the experiment, to compare the effect of mixing enhancement, droplets oscillating with 5th mode, 6th mode caused by modulated amplitude of the ultrasonic waves and no interfacial oscillation of its surface were visualized. **Figure 2** shows the series of images of droplet with interfacial oscillation. It can be seen that the internal brightness of droplets increases and becomes more uniform with time. Thus, the progress of mixing in the droplet were visualized by LIF method.

To quantify the mixing efficiency of each condition, the mixing parameter was introduced[4)]. The mixing parameter was calculated by the equation as follows:

$$\eta = \frac{\left(\frac{\sigma}{\mu}\right)_t - \left(\frac{\sigma}{\mu}\right)_{t=\infty}}{\left(\frac{\sigma}{\mu}\right)_{t=0} - \left(\frac{\sigma}{\mu}\right)_{t=\infty}} \tag{1}$$

where, σ represents the standard deviation of the brightness, μ represents the average brightness in the droplet. The subscript t represents the time from the coalescence. The time just after the coalescence was set to 0, and the time when the whole was sufficiently homogeneous by mixing was set to ∞.

Figure 3 shows the variation of mixing parameter. The mixing parameter of droplet without oscillation was approaches 0 in about 100 sec. In contrast, the mixing parameter of droplets with 5th and 6th mode oscillation were approaches 0 in about 1 sec. It indicates that the efficiency of mixing was enhanced by the interfacial oscillation at the droplet surface.

4. Internal flow field in droplets with interfacial oscillation

To reveal the mechanism of mixing enhancement, the PIV (particle image velocimetry) was applied to the droplet with interfacial oscillation. **Figure 4** shows the internal flow of the droplet with 5th mode oscillation on its interface. From the figure, radial flow was observed. Furthermore, the direction of the flow changed periodically as the shape of interface changed. Therefore, it is considered that the internal radial flow induced by the interfacial oscillation enhanced the mixing.

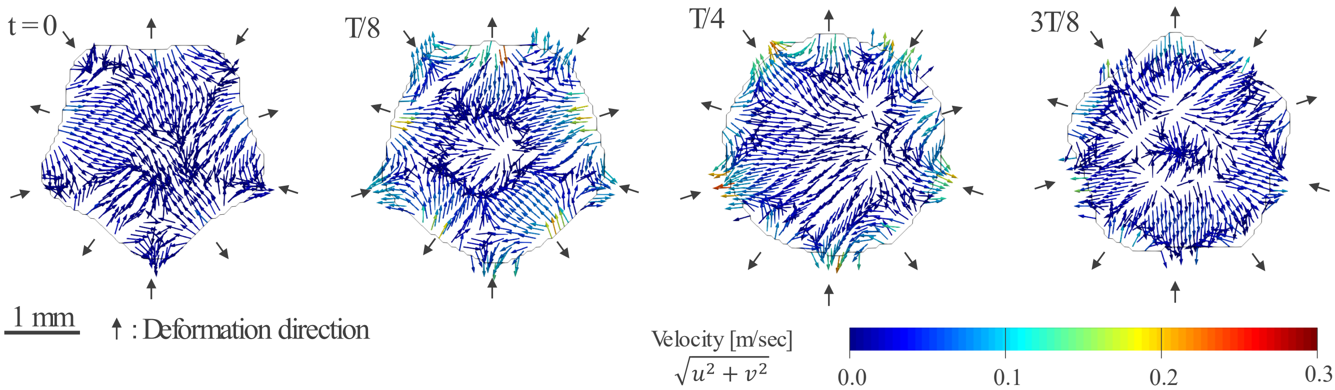

Fig.4 Instantaneous flow field in the droplet with 5th mode oscillation

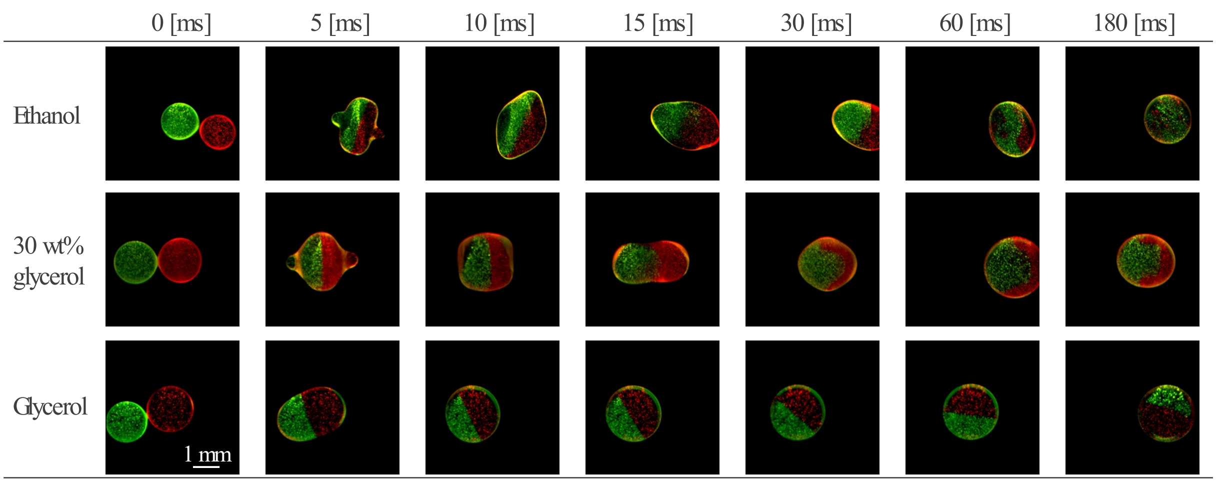

Fig.5 Time-series images in the droplet coalescence.

5. Internal flow field and the mixing in droplets with coalescence

For the practical use of contactless droplet manipulation, the effect of coalescence on mixing needs to be understood. In order to visualize the internal flow field and the mixing behavior of droplets during coalescence, bicolor PIV was performed. **Figure 5** shows time series of images in the coalescence. The images taken at the short-wavelength are shown in green, and those taken at the long-wavelength in red. In the experiment, ethanol, glycerol and 33 wt% glycerol aqueous solution was employed to determine the effect of droplet properties on mixing. From the figure, ethanol and 33 wt% glycerol aq. droplet had oscillation on its interface after coalescence. For the ethanol droplet, mixing of two particles was observed after 30 ms. On the other hand, the interface of glycerol droplet was very stable even immediately after the coalescence. In addition, two types of particles had not mixed after 2 seconds. Though, the effect of coalescence is expected on mixing when kinematic viscosity of droplets relatively small. However, if the kinematic viscosity of droplet is relatively high, it is difficult to achieve complete mixing only by coalescence. The effect of applying interfacial oscillation on mixing is expected to be important.

6. Conclusion

In this study, we visualized the mixing process and flow field of droplets during coalescence and mixing. First, the mixing enhancement effect of interfacial oscillation of droplets is experimentally demonstrated.

By inducing interfacial oscillation, the time to complete mixing was reduced from 120 sec to about 1 sec. In order to clarify the mechanism of mixing enhancement, PIV was applied to the flow field of droplet with interfacial oscillation. The results show that radial flow was induced by the interfacial oscillation. Additionally, we take the bi-color images of the droplet coalescence were taken to investigate the effect of coalescence of droplets on mixing. The result shows that, the effect of coalescence is expected to be effective when kinematic viscosities of droplets relatively small. On the other hand, if the kinematic viscosity is relatively high, complete mixing only coalescence is thought to be difficult.

7. References

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