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## 対向型収束超音波を用いた浮遊液滴の微粒化メカニズム Breakup mechanism of droplet in acoustic levitation

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#### 1. Introduction

The acoustic levitation attracts broad attention of practical applications in analytical chemistry, biology and materials science, because a container-free sample manipulation can avoid the wall effect, such as an unexpected nucleation and contamination by the container wall <sup>1</sup>). Acoustic levitation, which is one of the promising contactless fluid manipulation techniques, enables a sample (solid and liquid) to levitate in midair by forming an acoustic standing wave between the horn and the reflector <sup>2</sup>). The dynamic and nonlinear behaviors on a levitated droplet such as interfacial deformation and atomization <sup>3</sup>) can be triggered due to the flow fields <sup>4</sup>), and heat/mass transfer <sup>5</sup>). Watanabe et al. <sup>6</sup>) demonstrated the contactless coalescence and mixing of droplets with ultrasonic phased arrays. Although recent studies developed and improved the acoustic manipulation system, the levitation stability for better acoustic manipulation of a sample is only partially understood. The droplets must stably levitate without any interfacial instability or atomization after the levitation and coalescence in midair.

The purpose of our research is to experimentally investigate the deformation and atomization process to understand the droplet dynamics and improve stability of a levitated droplet through its instability mechanism. We show how surface tension and viscosity affects the atomization behavior of levitated droplets and compare with Kelvin-Helmholtz instability (KHI). Our experimental findings provide deeper insights into contactless liquid manipulation for prospective lab-in-a-drop applications.

#### 2. Experimental design

In this study, an opposed ultrasonic phased array levitator generated the acoustic field to levitate the droplet<sup>7</sup>). **Figure 1** shows a schematic of the experimental setup. The sound wave was emitted from the top and bottom transducers. An acoustic standing wave can be formed between transducers. The test liquid was manually injected with a syringe near the third pressure node of the acoustic standing wave. The pushed liquid from the syringe was released within a few seconds and the droplet was formed. The motion of the levitated droplet was observed with a high-speed video camera with backlight illumination. The behavior of the droplet was computer analyzed with an in-house MATLAB code.

The function generator produced a frequency of approximately 40 kHz at room temperature conditions of 25°C and a relative humidity of 50%. The distance of transducers was 114 mm. Water, ethanol, ethanol solution, and silicone oil were used to determine the effect of surface tension and viscosity of droplet. The volume equivalent diameter of a droplet d ranged from 1.2 to 2.3 mm with the initial aspect ratio AR of 3.0. AR is defined as the equatorial-to-polar ratio of the major diameter b to minor diameter a.



Fig. 1 Schematic of experimental setup.

#### 3. Results and discussion

#### 3.1 General observation

The droplet can be levitated with almost spherical shape (Fig. 2 (a)). By increasing the input sound pressure in the test section, the droplet interface transformed into the flattened shape (Fig. 2 (b)). The boundary of the droplet fluctuated, and the interface became unstable. Eventually, the droplet interface could no longer be maintained. It atomized from the edge of the droplet (Fig. 2 (c)). The atomized small daughter droplets aggregated due to the restoring force in an acoustic field in a planetary formation (Fig. 2 (d)). After aggregation, the smaller droplet stably levitated (Fig. 2 (a')).



**Fig. 2** Typical droplet atomization process: (a) stable levitation, (b) deformation, (c) atomization, (d) aggregation, and (a') stable levitation.

#### 3.2 Effect of droplet properties

Stable droplet levitation exists when the acoustic radiation force exceeds the gravitational force on the droplet ( $\ge \rho Vg$ ) and is lower than the surface force to maintain the droplet interface. Here,  $\rho$ , V (=  $\pi d^3/6$ ), and g are the density and volume of the droplet, and gravitational acceleration, respectively. Precise tuning of droplet size and sound pressure is necessary to ensure stable levitation.

**Figure 3** shows the levitation map of ethanol and silicone oil droplets in acoustic levitation. we confirmed that the droplets were atomized by the increase of the droplet size and sound pressure. Droplet atomization can be pushed into interfacial instability on the gas-liquid interface (droplet surface) with higher sound pressure. It was confirmed that the droplets could be stably levitated or become unstable and atomized in an acoustic field. In order to stably levitate and keep the droplet interface in acoustic levitation, it is necessary to better understand the detailed instability process of the levitated droplet and its physical mechanism.



Fig. 3 Levitation map of droplets in acoustic levitation.



(a) Ethanol

(b) Silicone oil

Fig. 4 Atomization process of droplets:

(a) ethanol (d = 1.6 [mm],  $\Delta V = 3.5 \text{ [V]}$ ), (b) silicone oil (d = 1.3 [mm],  $\Delta V = 2.5 \text{ [V]}$ ).

**Figure 4** shows the general observation of the atomization process of (a) ethanol and (b) silicone oil with time *t*. The droplet became stable after 30 seconds at a maximum from the droplet injection (initial shape in **Fig. 4**). The sound pressure was increased approximately 6 ms before the droplet atomization. Then, each droplet deformed from its initial shape, spread horizontally, and *AR* increased ( $t \le -3$  ms). The droplet interface drastically deformed and eventually atomized (t = 0 ms). The daughter droplets of the ethanol were finer than those of the water droplet. This is caused by the lower surface tension of ethanol droplet compared to water droplet. The daughter droplets of the silicone oil were larger than those of the ethanol droplet due to the higher viscosity.

#### 3.3 Comparison with KHI

Interfacial instability on the droplet surface can play a vital role in the breakup dynamics in acoustic levitation. In order to demonstrate the atomization mechanism of an acoustically levitated droplet, the clear observation of the atomization process on the droplet is required with high spatiotemporal resolution. Figure 8 shows the observation of the water droplet atomization process from the top of droplet. The sound pressure was started to increase at t = -6 ms. Then, the droplet deformed and spread radially (t = -3.0 ms). After that, the capillary wave initiated from the edge of the droplet and the droplet started atomizing (t = 0 ms). The capillary wave propagated from the edge to the center of the droplet after the droplet atomization ( $t \ge 3.60$  ms).



Fig. 4 Atomization process of ethanol droplet (top view).

**Figure 5 (a)** presents the time evolution of the interfacial velocity  $v_{exp}$  during the last 10 ms before the droplet atomization. As the levitated droplets spread horizontally, the edge of droplet interface was protruded from the equatorial plane and the droplet atomized from the rapidly developed liquid film on its edge (-1 ms  $\leq t \leq 0$  ms). The rapid dynamics of the droplet atomization can be triggered by interracial instability. In the present study, the interfacial velocity of the droplet was compared with the critical velocity  $v_{crit}$  driven by KHI as shown in Eq. (1)<sup>8</sup>.

$$v_{crit} = \sqrt{\frac{2(\rho_l + \rho_g)}{\rho_l \rho_g}} \sqrt{\sigma(\rho_l - \rho_g)g},\tag{1}$$

where, subscripts *l* and *g* represent the liquid and gas phase and  $\sigma$  is the surface tension of droplet. The theoretical critical velocity was presented with the dashed line in **Fig. 5 (a)**. For the ethanol droplet, the experimental interfacial velocity of 4.75 m/s before the droplet atomization quantitatively agreed with the theoretical critical velocity of 4.75 m/s. With other droplets the experimental data compared with KHI were summarized in **Fig. 5 (b)**. It is noted that all droplet in the present study showed a good agreement with the theoretical prediction described by Eq. (1).



(a) Interfacial velocity of ethanol droplet(b) Experimental data compared with model predictionFig. 5 Breakup mechanism of droplet in acoustic levitation.

#### 3.4 Daughter droplet distributions after the primary droplet atomization

Figure exhibits the size distribution of the atomized daughter droplets for (a) ethanol, (b) 50 wt% ethanol solution, and (c) silicone oil. The blue broken line represents median diameter of the atomized droplets. A wide range of median diameter droplets was observed in each droplet. A wide range of droplet size distribution was observed in all the droplets. For silicone oil, the median diameter was a larger than the other droplets due to the higher viscosity.



Fig. 6 Size distribution of atomized daughter droplets.

#### 5. Conclusions

In this study, the breakup dynamics of levitated droplets via opposed acoustic phased array levitation were experimentally evaluated and compared with the theoretical prediction. It is confirmed that the fluid properties affect the levitated area and the droplet size distribution after atomization of the sound field. Immediately before the droplet atomization ( $-1 \le t \le 0$  [ms]), the growth rate of the interface at the equatorial plane of the droplet rapidly and nonlinearly increased. The interfacial velocity before atomization showed a good agreement with the critical velocity based on KHI.

#### References

- 1) V. Vandaele and P. Lambert: Precis. Eng., 29 (2005) 491.
- 2) D. Foresti, M. Nabavi, M. Klingauf, A Ferrari and D. Poulikakos: Proc. Natl. Acad. Sci. U.S.A, 110 (2013) 12549.
- 3) K. Aoki and K. Hasegawa: AIP Adv., 10 (2020) 055115.
- 4) Y. Sasaki, K. Kobayashi, K. Hasegawa, A. Kaneko and Y. Abe: Phys. Fluids, **31** (2019) 102109.
- 5) Y. Sasaki, K. Hasegawa, A. Kaneko and Y. Abe: Phys. Fluids, 32 (2020) 072102.
- 6) A. Watanabe, K. Hasegawa and Y. Abe: Sci. Rep., 8 (2018) 10221.
- 7) A. Marzo, A. Barnes and B. W. Drinkwater: Rev. Sci. Instrum, 88 (2017) 085105.
- 8) S. Basu, A. Saha and R. Kumar: Appl. Phys. Lett., 100 (2012) 054101.



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