JASMAC
Conference of the Japan Society of Microgravity Application

P09

音場浮遊させた懸濁液滴の流動挙動

Flow behavior of suspended droplets levitated in an acoustic field

相子珠希 [1], 本田恒太 [1], 藤原広太 [1], 長谷川浩司 [2], 金子暁子 [1]
Tamaki AIKO[1], Kota HONDA[1], Kota FUJIWARA[1] , Koji HASEGAWA[2] and Akiko KANEKO[1]
1　筑波大学大学院，Tsukuba university
2　工学院大学，Kogakuin university

1. Introduction

The spraying of suspension has been widely used in industrial fields. As an example, spray drying is used in the production of pharmaceutical and food additives. Spray drying is a technique in which a solution or suspension is sprayed to form fine droplets, which are then exposed to a high-temperature gas to evaporate the solvent in the droplets and produce a powder[1)]. This method is useful for products that are easily damaged by heat and allows good control of the properties of the produced powder, such as particle size and residual solvent content. However, it was difficult to predict the shape of the product, and the operating conditions were determined based on empirical rules. On the other hand, nano-fuels, in which nanoparticles are added to the fuel, are also expected to be used to improve heat transfer efficiency[2)]. Since nanoparticles synthesized from metals and non-metals have better thermal conductivity than conventional heat transfer liquids, dispersion of nanoparticles in fuels is expected to improve the performance of combustion systems. It is important to understand the drying behavior of droplets containing nanoparticles for the practical use of nano-fuels because fuel is vaporized by spraying in actual heat engines. In order to observe the drying behavior of a single droplet, we focused on acoustic levitation. Acoustic levitation is a non-contact method to levitate a droplet of 2~3 mm in size in the air by creating acoustic standing waves in the space using ultrasonic waves, which enables us to observe the behavior of a single droplet. In the previous studies, nonlinear and complex flow due to acoustic flow occurs internal and external of a levitated droplet[3)]. However, the internal and external flow of a levitated droplet with heating and its effect on droplet drying has not been elucidated. There are no studies that visualize the flow field of the internal and external flow inside a particle-suspended droplet.

Therefore, the purpose of this study is to clarify the internal flow fields of a particles-suspended droplet in an acoustic field with heating. In this paper, we describe the results of visualization of the internal flow of the particles-suspended droplets and the technique of internal visualization of highly concentrated particles-suspended droplets by refractive index matching.

2. Experimental setups

Fig. 1(a) shows the schematic diagram of the flotation device and the measurement system used in this study. The system consists of a test section for levitating droplets and peripheral equipment. The function oscillator oscillates a sinusoidal signal, which is amplified by an amplifier and output from the horn. Sound waves emitted from the horn are reflected by the reflector to form acoustic standing waves in the test section. In addition, a sample is injected by a syringe at the node of the sound pressure, and a droplet is levitated. In this experiment, the diameter of the horn is 36 mm, the distance between the horn and the reflector is 47.5 mm, which is equivalent to approximately 2.5 times the wavelength, the resonant frequency of the ultrasonic wave is 19.4 kHz, and the wavelength is about 19 mm.

Next, we explain the measurement system used for the stereo measurement of the internal and external flow fields of an acoustic levitated droplet by using PIV(particle Image Velocimetry). In this experiment, the internal flow of a droplet was captured in stereo by setting the camera's image element and lens at an angle based on Scheimpflug's theorem as shown in Fig. 1(b). Fluorescent particles with a diameter of 15 μm were used as tracer particles to visualize the flow structure inside the droplet, and a long-pass filter was attached on the camera lens.

Physical properties of liquid and suspended particles are tabulated in Table 1. Particles loading rate varying between 1 ~ 10 wt%. The suspension was obtained by dispersing the particles in a liquid. Amorphous silica particles of 0.3 μm and 2.5 μm in size and cellulose fibers of 50 μm as nonspherical particles were used as suspended particles. In addition to the solid particles, fluorescence particles were added for PIV measurements. In order to observe fluorescence tracer particles clearly to measure the flow structure in droplets, refractive index matching was applied. To match the refractive index of amorphous silica with droplet material, 72 wt% glycerol aq. is used as a droplet.

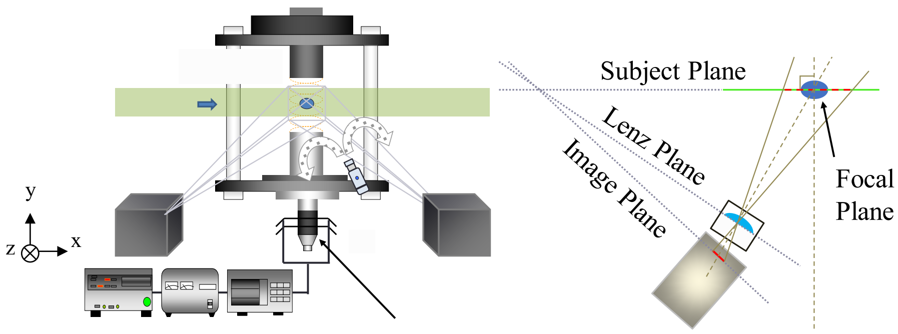

Fig. 1 Measurement principle:
(a) Schematic of experimental apparatuses
(b) Scheimpflug's theorem

Table 1 Physical properties of the base-liquids and particles

	Viscosity[mPa·s]	Average particle size [μm]	Density [kg/m³]	Refractive index
Water	1.085	-	-	1.33
72 wt% glycerol aq.	29.92	-	1.2	1.43
Amorphous silica (SiO_2)	-	0.3	2.2	1.43
	-	2.5	2.2	1.43
Cellulose fiber	-	50	1.5	-

3. Results and discussions

3.1 Agglomeration inside the suspended droplet with the passage of time

Agglomeration of suspended materials is expected to occur inside the suspended droplet. Figure 2 shows the agglomeration inside the 1 wt% dispersion of cellulose fibers as time passes. Figure 2 shows that the levitated droplet has a rotational motion around a certain axis on x-y plane in the direction of the red arrow. Figure 2(A) shows the view from the direction of rotation of the droplet, and Fig. 2(B) shows the view from the axis of rotation of the droplet. Fig. 2(A) shows that the cellulose fibers are agglomerated in a band on the droplet in the center of the rotation direction after t = 50 s after levitation. Fig. 2(B) shows that there is no agglomeration in the direction of the rotation axis. This is thought to be because the centrifugal force causes the suspended matter to agglomerate in the circumferential direction, which has maximum velocity. Focusing on this agglomeration, we can see that the agglomerated material increases with evaporation of water. As the droplet diameter decreases due to evaporation, a flocculent film covers the entire droplet diameter, leading to a clustered powder state as shown in t = 4320 s.

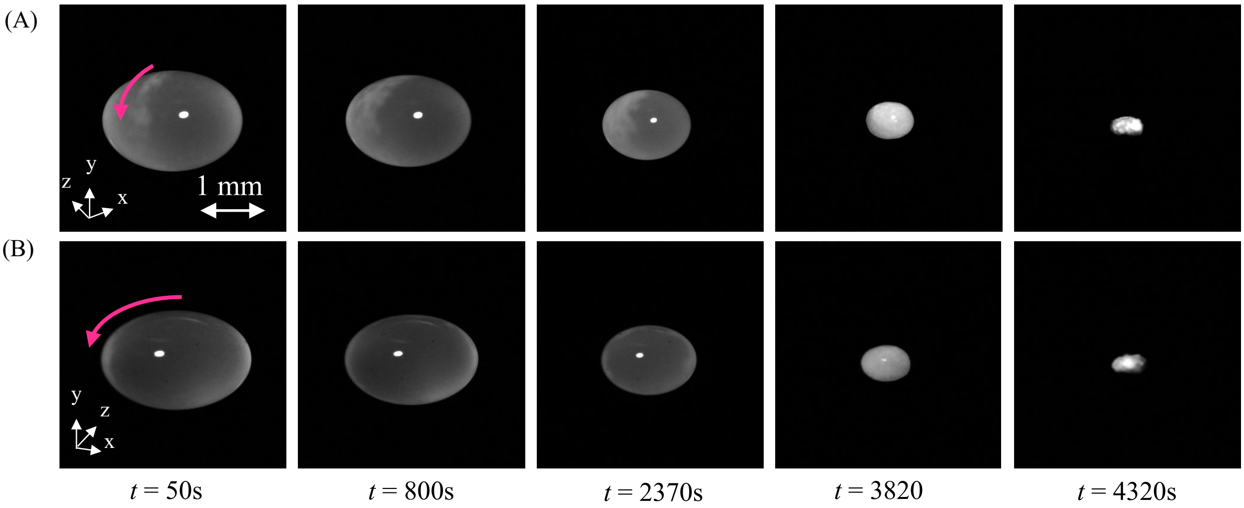

Fig. 2 Typical snapshots of internal cohesion of 1 wt% cellulose fiber laden droplet:
(A) Radial view of rotational flow (B) Axial from of rotational flow

3.2 Internal flow field of suspended droplets

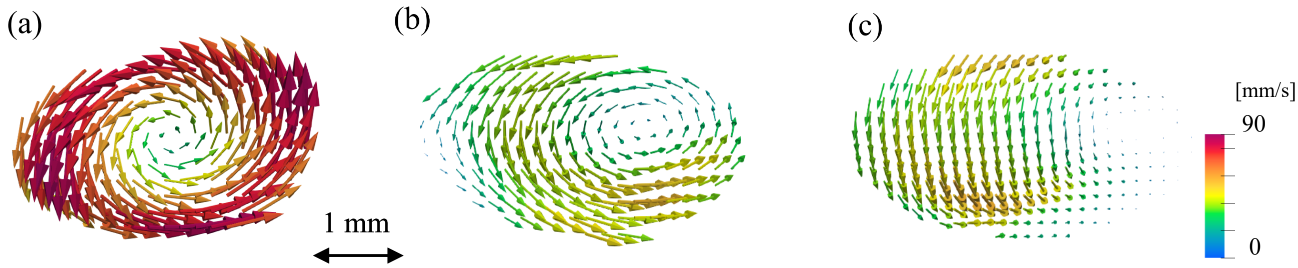

Fig. 3 Average flow structure in a levitated droplets:
(a) Water and (b) Water + 1 wt% SiO_2 0.3 μm (c) Water + 1wt% cellulose fiber

In section 3.1, it was shown that there is an agglomeration phenomenon unique to inside the suspended droplet. To investigate the internal flow structure of suspended droplets, stereo PIV was applied to three different samples with different suspended materials, and the results of visualization of the internal flow field of suspended droplets are shown in Fig. 3. Fig. 3(a) shows the internal flow of a water droplet without particles, Fig. 3(b) shows the internal flow of a 1 wt% aqueous dispersion of SiO_2 with a particle size of 0.3 μm, and Fig. 3(c) shows the internal flow of a 1 wt% aqueous dispersion of cellulose fibers. As can be seen in Fig. 3, both water droplets and suspended droplets are rotating around one axis. The internal flow is caused by the external flow around the droplet due to the acoustic flow, and the asymmetry of the shear stress at the interface between the top and bottom of the droplet applies the rotational torque at the interface, which results in the rotational motion[3)]. The internal velocity of the suspended droplets was smaller than that of the water droplets, as shown in Fig. 3.

3.3 Visualization of Internal Flow Field of a suspended droplet by Refractive Index Matching

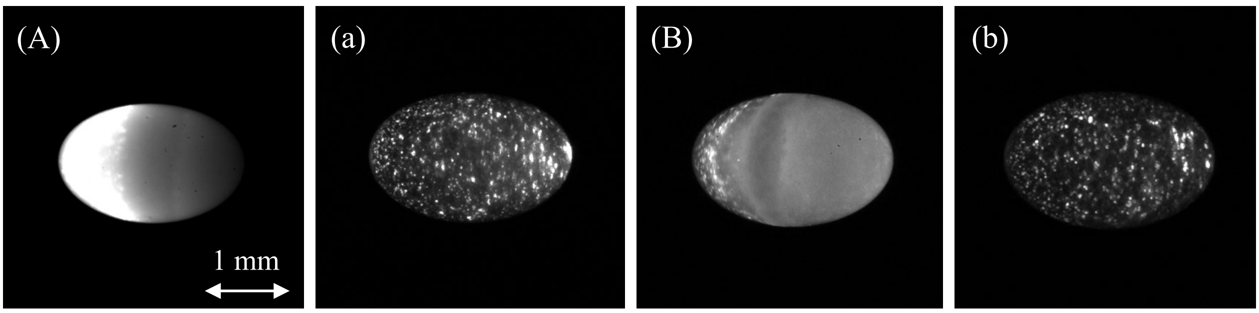

Fig.4 Visualization of droplet interior:
(A) Water + 10 wt% SiO_2 0.3 μm and (a) 72 wt% glycerol aq. +10 wt% SiO_2 0.3 μm
(B) Water + 1 wt% SiO_2 2.5 μm and (b) 72 wt% glycerol aq. + 1 wt% SiO_2 2.5 μm

As described in Section 3.2, when water is mixed with a suspended substance, it is difficult to visualize the tracer particles of the droplet when the suspended substance is highly concentrated or when the particle size is large due to the difference in refractive indices between the suspended substance and water. Fig.4(A) show the interior of a 10 wt% aqueous droplet of SiO_2 with a particle size of 0.3 μm and Fig.4(B) show the interior of a 1 wt% aqueous droplet of SiO_2 with a particle size of 2.5 μm. In both cases, it is difficult to visualize the tracer particles added inside the droplet. Fig.4(a) and (b) show the results of matching the refractive indices of the suspended solids by using glycerin solution. It can be seen that matching the refractive index facilitates the visualization of the tracer particles inside more clearly.

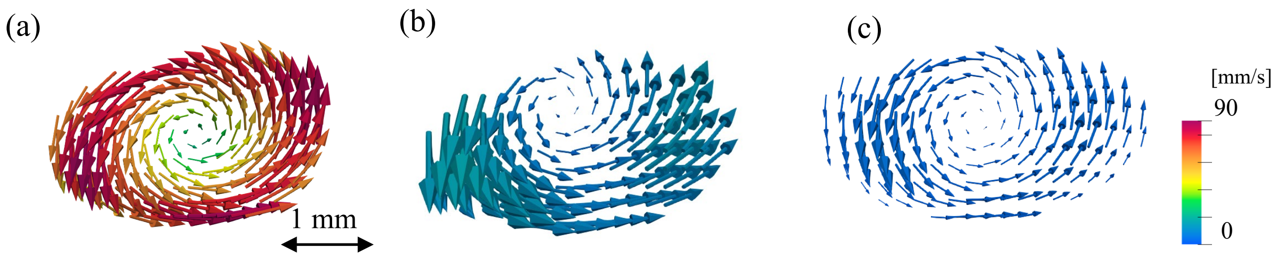

Fig. 5 Average flow structure in droplets:
(a) Water and (b) 72 wt% Glycerol aq.(c) 72 wt% Glycerol aq.+ 1wt% SiO_2 2.5μm

Figure 5 shows the visualization results for droplets of water, 72 wt% glycerol aq., and 1 wt% SiO_2 with a particle size of 2.5 μm suspended in 72 wt% glycerol aq. Figure 5 shows that the inside of the droplet rotates even in 72 wt% glycerol aq. The velocity of the glycerin droplet is smaller than that of the water droplet. The viscosity of the 72 wt% glycerol aq. is higher than that of water, resulting in a smaller velocity. When the glycerol aq. is mixed with suspended particles, the flow velocity becomes even smaller.

4. Conclusion

To clarify the internal and external flow fields of a suspended droplet levitated in an acoustic field with heating, the internal flow of a droplet with different suspension materials was visualized.

(1) The internal agglomeration of cellulose fiber dispersed droplets with time was visualized, and it was confirmed that the suspended material agglomerated in the direction of rotation and covered the entire droplet as it dried.
(2) Both water and suspended droplets have an internal flow field around a certain axis. The velocity of the suspended droplet was smaller than that of the water droplet.
(3) By matching the refractive index of the solvent and the suspended material using a glycerol aq., the internal flow can be visualized even when the suspended particles are large or have a high concentration. When the glycerol aq. is mixed with particles, the flow velocity becomes even smaller than a water and a glycerol aq. single phase droplet.

References

1) Krzysztof cal, Krzysztof sollohub: Pharmaceutical sciences, **99**, 2 2010, 575
2) Khushboo Pandey and Saptarshi Basu: Phy. Fluids, **30**, 107103, (2018)
3) Y. Sasaki, K. Kobayashi, K. Hasegawa, A. Kaneko, and Y. Abe: Phy. Fluids, **31**, 102109, (2019)