Effect of temperature change on interfacial behavior of an acoustically levitated droplet

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Abstract

Under the microgravity environment, new and high quality materials with a homogeneous crystal structure are expected to be manufactured by undercooling solidification, since the material manufacturing under the microgravity environment is more static than that under the normal gravity. However, the temperature change on the interface of the material in space can affect on the material processing. The purpose of the present study is to investigate effect of the temperature change of interface on the large levitated droplet interface. A water droplet levitated by the acoustic standing wave is heated by YAG laser. In order to heat the water droplet by the laser heating, rhodamine 6G is solved in it to achieve high absorbance of the laser. The droplet diameter is from 4 mm to 5.5 mm. The deformation of the droplet interface is observed by high speed video camera. The temperature of droplet is measured by the radiation thermometer. It is noticed that the larger droplet under the higher sound pressure tends to oscillate remarkably by the laser heating..

Introduction

Containerless technology has been well recognized as a method for obtaining liquid undercooling. Particularly in microgravity condition, liquid can remain undisturbed condition and deep undercooling is achieved. One of the major recent advances for experiments in containerless processing is acoustic levitation by ultrasound. For carrying out containerless processing under the microgravity condition, the larger droplet is more desirable. However the larger droplet levitates, the more deformation occurs and influences the solidification process remarkably.

There are many previous studies relating to droplet levitation. Many researches on oscillations and rotations of a levitated droplet have been done to investigate the interfacial behavior and to measure the physical properties. Marston (1980, 1981) analyzed the vibration and the static deformation of levitated droplets and bubbles in the fluid with acoustic radiation pressure. Trinh et al. (1982) conducted the experiment with silicone oil in the water. They identify the resonance frequency for each mode of the oscillation of silicone oil. Wang et al. (1996)

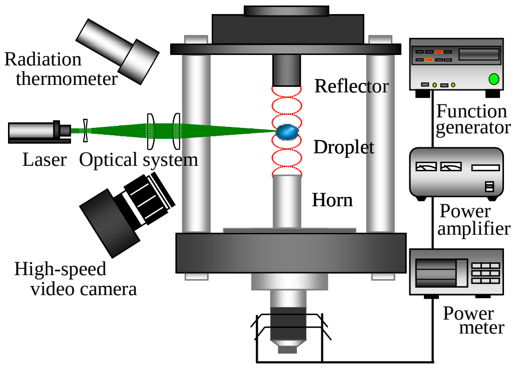
observed the deformation behavior of the rotating levitated droplet in the microgravity environment. Ermoline (2004) observed the position of samples vertically oscillated under the microgravity condition. They conducted the experiment to heat the metal and ceramic samples of 1-3 mm diameter by the laser heating.

Although there are many researches on the shape oscillation of acoustically levitated droplet, the effect of the temperature change on the interfacial behavior of droplet is not sufficiently investigated. The purpose of the present study is to investigate the effect of temperature change on the deformation of large levitated droplets with more than 4 mm in diameter. The deformation and oscillation is observed by high speed camera.

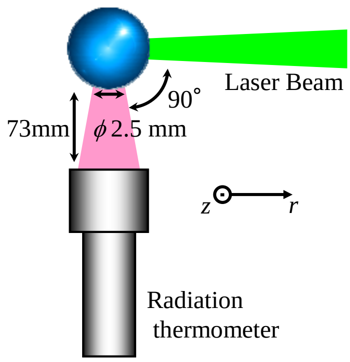
Experimental apparatus and procedure

Figure 1 shows a schematic diagram of the experimental apparatus. The test section is composed of the horn as a solid speaker and the glass plate as a reflector. A sinusoidal wave signal from the function generator is applied to the ultrasonic transducers to emit the ultrasonic wave into the test section. Ultrasonic wave is reflected at the upper glass plate, and ultrasonic standing wave is formed in the test section. The resonance frequency of the transducer is 19.2 kHz. The distance between the horn and the reflector is about 47.5 mm. The sound pressure amplitude at antinode is measured by the probe microphone (Type 4182 produced by Brüel & Kjær). A water droplet is injected at a pressure node by a syringe. The droplet is levitated due to balance between the acoustic radiation force and the gravitational force.

The droplet is heated by YAG laser (Excel Laser produced by Laser QUANTUM Ltd.) with a wave length of 532 nm. In order to achieve high absorbance of the laser beam in the droplet, 150 mg/L of rhodamine 6G is solved in the water. Physical properties such as density, viscosity, and surface tension of the droplet are assumed the same as those of water. When the droplet absorbs the laser light, it emits fluorescence light with a wave length of 550 nm. The interfacial behavior of levitated droplet is recorded by high speed video camera (FASTCAM-Max produced by Photron Ltd.). The scattering light of the laser is cut by an optical filter. The surface temperature of the droplet is measured by the radiation thermometer (TEMPERATURE HiTESTER 3445 produced by HIOKI E. E. CORPORATION). The measurement spot of the thermometer is 2.5 mm. The measurement spot is perpendicular to the laser beam on the droplet as shown in Fig.1 (b).



(a) Ultrasonic levitator and measurement equipment



(b) Temperature measurement of a droplet surface

Fig. 1: Schematic diagram of the experimental apparatus

Results and Discussions

Figure 2 shows the correlation between the sound pressure and the equivalent droplet diameter under the stably-levitated condition. The ambient temperature is around 10 °C. The P indicates the sound pressure amplitude in the test section in Fig. 1 (a). The d is the equivalent diameter of a droplet. The equivalent diameter is defined by a volume equivalent diameter by assuming the shape of the levitated droplet as ellipsoid. The plots indicate stably-levitated condition. S. D. Danilov et al. (1992) proposed the upper limit of the sound pressure P_{M} to keep the droplet stable as follows:

$$P_M = \frac{\sqrt{6.8\sigma\rho c^2}}{d}, \quad (1)$$

where r is the droplet radius, ρ the droplet density, c the sound speed, and σ the surface tension of the liquid droplet. The equation (1) was drawn as solid line in Fig. 2. The line is in good agreement with experimental results. The plots are almost under the P_{M}. In the present study, experiments of laser heating are carried out less than the P_{M}.

The surface temperature of a laser-heated droplet depends on the balance between the input power of the laser and the heat release, which is determined by heat transfer, evaporative latent heat, fluorescent emission, optical reflection and transmission. One of the most effected parameters on the surface temperature is diameter of the droplet. For the constant laser power, the surface temperature of the droplet is depending on the droplet diameter as shown in tab. 1. The d is the equivalent droplet diameter, D_{spot} the spot diameter of laser beam on the droplet, E_{laser} the output power of the laser, E_{abs} the estimated absorbed energy of the droplet and T_{max} the maximum surface temperature of the droplet for 30 sec after heating is started.

For example, when the input laser power is set at 1.58 W, the surface temperature of the droplet of 5.5 mm in diameter increases up to 34 °C (on the second line in tab.1). Meanwhile the temperature of the droplet of 4 mm in diameter increases up to about 45 °C (on the third line in tab. 1). In order to keep the surface temperature, the diameter of the heated spot of the laser beam is changed by adjusting the optical system. In the present study, the surface temperature is kept at approximately 34 °C by adjusting the optical system for the laser power of 1.58 W because the 34 °C is the maximum temperature of a droplet of 5.5 mm in diameter. The heated spot diameter is adjusted at 2 mm for the droplet of 5.5 mm in diameter (on the second line in tab. 1). With the spot of 2 mm diameter, the beam of the laser at 1.58 W is all absorbed by the droplet regardless of the reflection of light. On the other hand, the spot of 7 mm in diameter is applied to the droplet of 4 mm in diameter to keep the surface temperature of 34 °C (on the first line in tab.1). The entire beam is not absorbed by the droplet because the spot diameter is larger than that of the droplet. The energy absorbed by the water droplet is estimated about 0.76 W assuming for Gaussian distribution of the laser beam.

Figure 3 shows the time variation of the aspect ratio of levitated droplet and the surface temperature of a non-heated levitated water droplet. In this case, droplet about 4 mm in diameter is levitated.

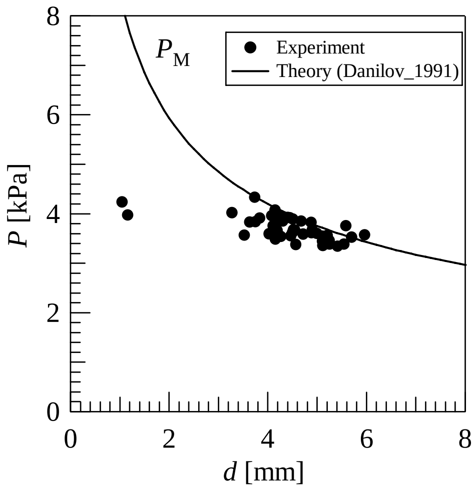


Fig. 2: Correlation between the sound pressure and the equivalent droplet diameter under the stably-levitated condition

Tab. 1: Experimental conditions of droplet diameter and optical devices

	d [mm]	D_{spot} [mm]	E_{laser} [W]	E_{abs} [W]	T_{max} [°C]
Fig.4, 7	4	7	1.58	0.78	31-34
Fig.5	5.5	2	1.58	1.58	34
	4	2	1.58	1.58	45

The aspect ratio α is defined

$$\alpha = \frac{a}{b} \qquad (2)$$

where a is the width and b is the height of a droplet respectively, the T indicates the surface temperature of water droplet. The T and the α are almost constant. The non-heated droplet is levitated stably as shown in Fig. 3.

Figure 4 shows the typical time variation of the aspect ratio and the surface temperature of the levitated water droplet heated by the laser beam. The t is the time from the heating started. The α is the aspect ratio. The T is the surface temperature of the droplet. The droplet of about 4 mm in diameter is levitated. It is observed the variation of the α and translation motion of the droplet between 11 and 18 sec. This oscillation could be due to heating, which raises the temperature of the surrounding air and distorts acoustic field. The energy of 0.76 W is absorbed by the droplet. The temperature rose rapidly and it reached about 34 °C in almost 13 sec. Although

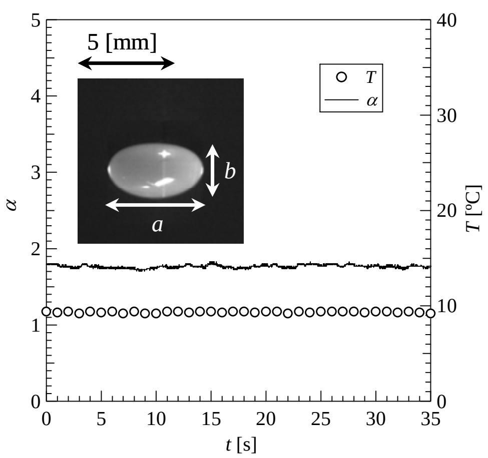


Fig. 3: Time variation of aspect ratio and temperature of non-heated levitated water droplet (equivalent diameter: 4 mm, sound pressure: 3.6 kPa, input energy: 0.0 W)

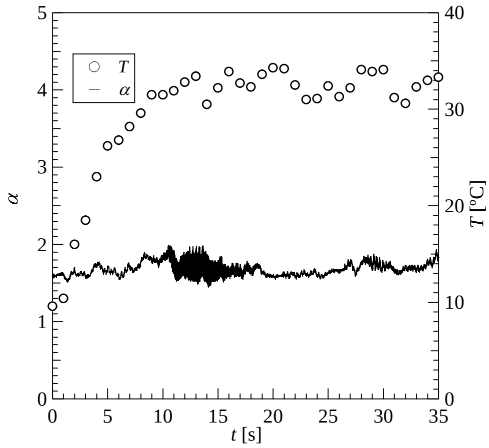


Fig. 4: Time variation of aspect ratio and temperature of levitated water droplet (equivalent diameter: 4 mm, sound pressure: 3.6 kPa, input energy: 0.76 W)

the equivalent diameter of the droplet is 4.2 mm when the heating is started, the diameter decreased to 3.9 mm because the droplet evaporated.

In Fig. 5, the droplet about 5.5 mm in diameter is levitated and heated. The α varies from 1.1 to 2.7. The oscillation frequency of α is approximately 27.8 Hz between 22.0 sec and 26.1 sec. The frequency of ultrasonic transducer is about 19.2 kHz. The oscillation frequency of the droplet dose not seems to be related to that of ultrasonic acoustic field. There is an increase of T. The temperature increased from about 10 to 33 °C in almost 15 sec. The oscillation is complex as shown in Fig. 6. Images from 22.000 sec to 22.044 sec are the one cycle of the oscillation. The large size of the droplet probably made the droplet oscillates easily.

Figure 7 shows the experimental results of the levitated droplet of 4 mm in diameter. The droplet of the same size is levitated in Fig. 4. The higher sound pressure than Fig. 4 induces the oscillation as shown in Fig. 7. The α varies from 0.8 to 4.4. The oscillation of the second-order mode of the droplet is observed as shown in Fig. 8. The shape of the droplets vertically and horizontally oscillated clearly. Images from 16.012 sec to 16.044 sec represent the one cycle of oscillation.

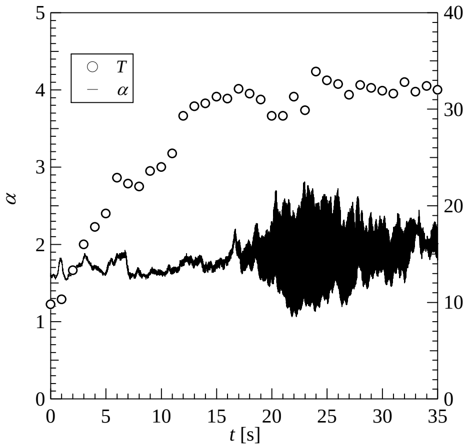


Fig. 5: Time variation of aspect ratio and temperature of levitated water droplet (equivalent diameter: 5.5 mm, sound pressure: 3.6 kPa, input energy: 1.58 W)

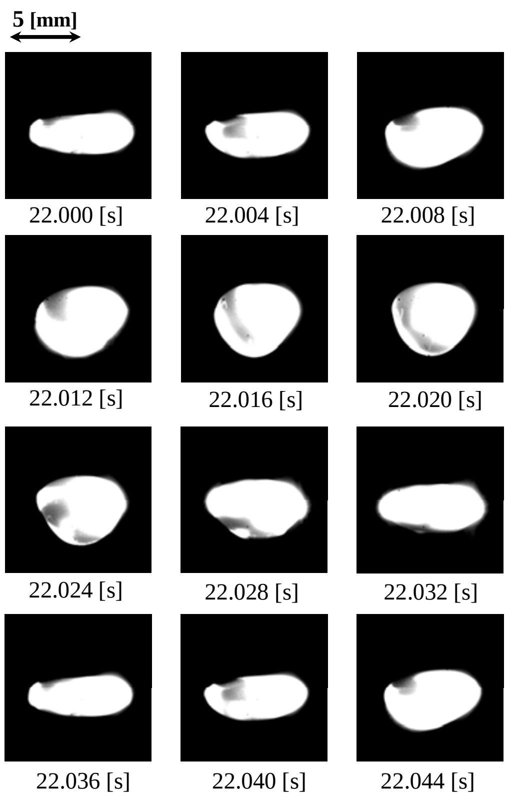


Fig. 6: Typical snapshots of oscillation of a levitated droplet (equivalent diameter: 5.5 mm, sound pressure: 3.6 kPa, input energy: 1.58 W)

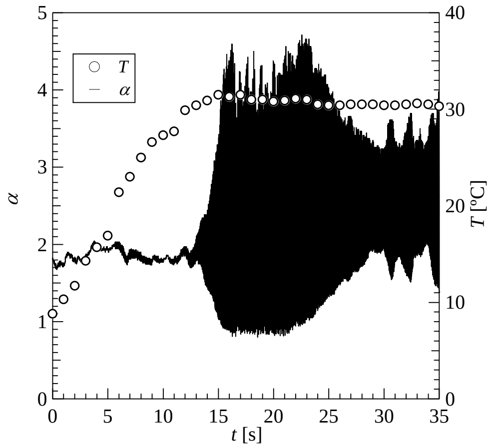


Fig. 7: Time variation of aspect ratio and temperature of levitated water droplet (equivalent diameter: 4 mm, sound pressure: 4.0 kPa, input energy:0.76 W)

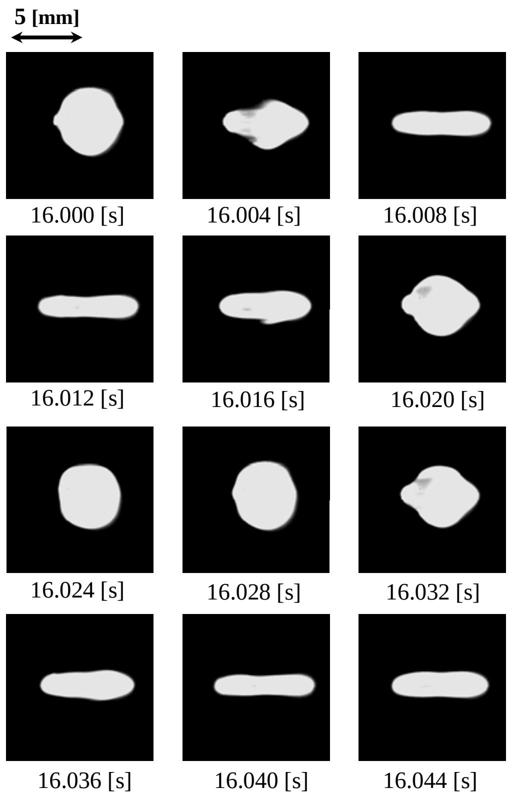


Fig. 8: Typical snapshots of oscillation of a levitated droplet (equivalent diameter: 4 mm, sound pressure: 4.0 kPa, input energy:0.76 W)

The oscillation frequency is approximately 34.2 Hz between 16.0 sec and 20.1 sec. The frequency is higher than that of Fig. 5. This difference is probably due to the size of the droplets. In Fig.5, the droplet of 5.5 mm in diameter is levitated and the droplet of 4 mm in diameter is levitated in Fig. 7. The smaller a droplet is, the higher a frequency is. The energy of 0.76 W is absorbed by the droplet. The rise of *T* continued until it reached 31 °C and *T* is steady at 31 °C after 15 sec.

According to Yutaka Abe, et al. (2007), the interface of the non-heated droplet tends to be unstable when diameter of droplet is larger and sound pressure is higher. In the present experiment with the laser heating, either larger droplet or droplet on higher sound pressure tends to oscillate remarkably. Although the droplet is stable before the laser heating, either larger droplet or higher sound pressure induces the oscillation.

K. Ohsaka, et al. (2002) observed the inner flow of droplet and the inhomogeneous distribution of temperature of the locally heated glycerin drop. They confirmed that the 2 symmetry circulations are induced in the droplet from the heated spot. One of the possible reasons of the oscillation in our experiment could be the influence of the inner flow. Further investigation to the trigger mechanism of the oscillation by the local heating is expected.

Conclusions

In the present study, the temperature dependence of the large levitated droplet interfacial behavior is investigated. The shape oscillation of droplet of diameter of 4 mm and 5.5 mm are observed when the droplet is heated. Following conclusions are obtained.

(1) The shape oscillation of drop is observed when the droplet is heated and the surface temperature of droplet increases.

(2) It is indicated that the large droplet shows the larger oscillation in the case of heating.

(3) It is also indicated that the droplet in the higher sound pressure field shows the larger oscillation in the case of heating.

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