Enhancement of Liquid Flow in a Water Droplet Located on a Super-hydrophobic Surface during Resonant Vibration by Unbalanced-Electric Field

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***Abstract*—To develop an electrostatic stirrer for a small amount of liquid with a volume of a few tens micro litters, enhancement of liquid flow in a water droplet during resonant vibrating motion was investigated. To promote liquid flow in a droplet, unbalanced two electric fields in the horizontal and vertical directions were applied to the droplet placed on a super-hydrophobic plate. The two-directional electric field consisting of the strong vertical and the weak horizontal field with the difference in phase angle between both fields was employed. From the video images of the droplet during vibrating motion, the degree of deformation of the droplet shape was evaluated by deformation rate. The deformation ratio under the field with a different phase angle at the shrinkage state varies irregularly and the height of the droplet increased to 2.2 times larger than that of the original droplet. The performance of stirring a single droplet containing fine powder and of mixing coalesced two droplets were demonstrated.**

I. INTRODUCTION

A water droplet located on an insulating hydrophobic sheet under an ac electric field, a droplet vibrates more or less depending on the frequency of the electric field, especially, involving with strong vibration at a particular resonant frequency [1-4]. Since resonant vibration of a droplet manifests drastic motion, it could be used as a non-contact stirrer or mixer for a millimeter-size droplet [5, 6]. However, it was hard to cause dynamic flow inside of the droplet because of regular resonant motion. To cause mixing a droplet, the effect of a rotating electric field was examined. The droplet seemed to rotate more or less. Although the shape of the droplet deformed corresponding to the rotating field, liquid flow inside of the liquid never caused [6]. On the other hand, our recent work showed that the vertical field superimposing horizontal field was effective to cause disturbance of a droplet placed on a super-hydrophobic surface under resonant vibration [7, 8]. However, liquid flow was not strong enough to stir a droplet containing settled powder in a droplet or viscous droplet.

In this paper, not only the effect of additional vertical electric field but also the phase difference between the horizontal and vertical field on deformation of a 100μL droplet and mixing performance was investigated experimentally. The difference in phase angle of the applied field as well as the stronger vertical field was examined on the deformation of a droplet the under the resonant state by bi-directional field and the mixing performance was demonstrated.

II. EXPERIMENTAL

To cause irregular flow in a droplet and two directional fields on a vibrating motion of a water droplet, two sets of electrode configurations were used. The experimental setup for applying a horizontal field or both a horizontal and a vertical electric field to a water droplet placed on an insulating plate was shown in Fig. 1. The insulating pate to place a water droplet is a 20 mm x 20 mm PMMA plate with 3mm thick coated with super-hydrophobic paint, HIREC1450 (NTT AT), forming micro structure over the surface. A contact angle of a droplet with a volume of 7 and 100 μL is 150 and 120 degrees, respectively.

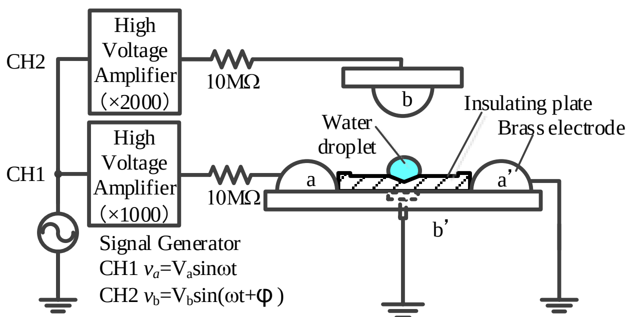
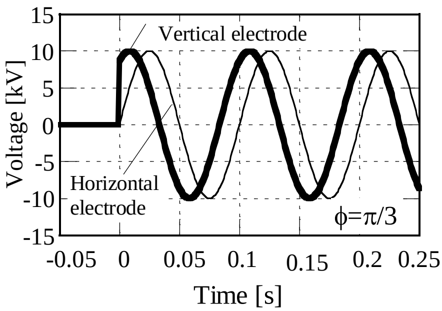


Fig. 1. Experimental setup for enhancing liquid flow in a droplet placed on a super-hydrophobic plate.

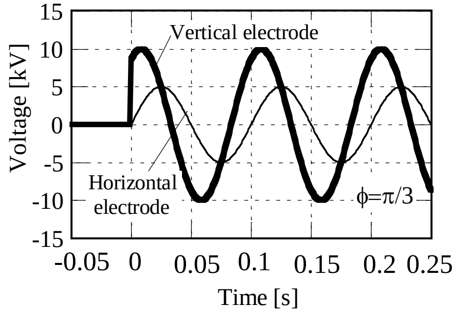
A 100 μL droplet was conveniently used because resonant frequency of the droplet was around 10Hz and it is easy to observe the motion and mixing performance with a relatively low-speed camera. Since the super-hydrophobic HIREC plate has a highly water-repellant or water-sliding property, the upper surface of the 22mm square plate was scraped in circularly with 18mm diameter and 1mm depth to prevent a droplet from contacting with the electrodes. Moreover, to keep the droplet at the center region during the vibrating motion, a conical pit with a depth of 1mm was formed at the center of the insulating plate as shown in Fig 1.

A pair of semi-spherical brass electrodes, a-a', with a radius of 5 mm was fixed at the side of the HIREC plate with a distance of 22 mm for forming a horizontal electric field. To superimpose a vertical field upon a horizontal filed, an additional pair of an upper semi-spherical and a lower-plate electrodes, b-b', was installed. The upper electrode was set at a distance of 10mm above the surface of the HIREC plate.

The sinusoidal voltage with a frequency of around 10Hz was applied to the electrodes at a time of zero through two high voltage amplifiers using a signal generator by which synchronized two sinusoidal waveforms with a different magnitude and phase angle was generated. Fig. 2 shows the examples of two kind of sinusoidal waveforms used in this experiment. The time variation of the shape of a droplet was taken with a high-speed video



(a) $V_a=V_b=20$ kV$_{p-p}$, $\phi=\pi/3$

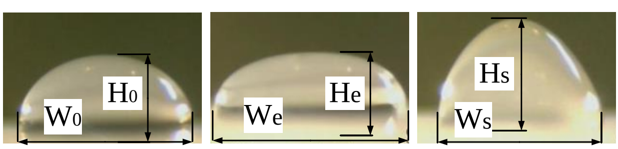


(b) $V_a=10$ kV$_{p-p}$, $V_b=20$ kV$_{p-p}$, $\phi=\pi/3$

Fig. 2. Example of applied voltage to the horizontal and vertical electrodes for enhancing liquid flow in a droplet.

camera (Photoron, RGB Rabit, 250 frames/s) viewing from the side of the plate. The camera was synchronized with the waveform of applied voltage.

During resonant vibration, a droplet extends toward horizontal and the vertical direction, alternatively. In this paper, elongation of a droplet in the horizontal direction is referred as extension and that in the vertical direction does as shrinkage. The degree of change in width or height of a droplet is utilized to identify a resonant frequency. To evaluate quantitatively the degree of deformation of the droplet, three kind of deformation rates were used. One is the width-to-height ratio of a droplet in motion, W/H. The other ratios are the width-deformation rate, We/W_0, and the height-deformation rate, Hs/H_0. These ratio express the extent of change in width or height from an initial size of a standstill droplet placed calmly on the plate W_0 and H_0 as a reference value as shown in Fig. 3.



(a) Standstill droplet (b) Extension (c) shrinkage

Fig. 3 Size for definition for defining deformation rate.

III. RESULT AND DISCUSSION

A. Effect of phase angle of applied voltage on deformation

Fig. 4 shows the deformation rate of 100 μL droplet for the applied filed with 5 to 12 Hz. The magnitude of the applied voltage to the both sets of electrode is 10kVp-p. Since the rate was taken as the width-to-height ratio, the larger rate of W_e/H_e at the extension state or the smaller rate of W_s/H_s at the shrinkage one express the extent the elongation toward the horizontal or vertical direction, respectively. The width-to-height ratio W_0/H_0 of a standstill droplet is 1.9. The maximum W_e/H_e or minimum W_s/H_s appears at 11 Hz or 12 Hz which should be resonant frequency.

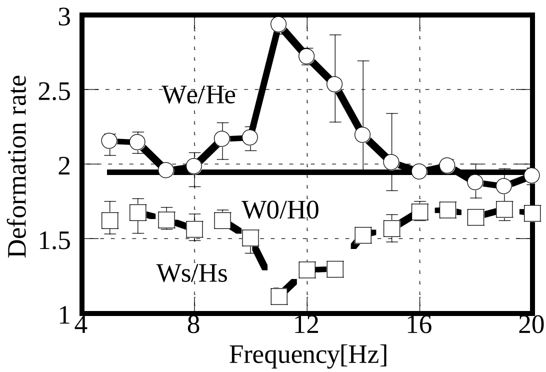


Fig. 4. Deformation rate for an applied voltage of 10kVpp around resonant frequency.

Fig. 5 shows an example of the time variation of deformation of a 100 μL droplet in the resonant state during a half cycle of vibrating motion driven by different applied voltages with 21.8kVp-p to the vertical electrode and 10kVp-p to the horizontal electrode. The reference of the time was set at the maximum extension in the horizontal direction at the elapsed time of around 5s after voltage application. The droplet during vibration is drastic motion. At shrinkage state, the droplet forms long conical shape. Although such a motion is typical during resonant vibration, the change in height or width is not reproducible and each vibration manifests its unique motion.

To express the extent of a deformed droplet quantitatively, the width-deformation rate W_e/W_o at the extension state and height-deformation rate H_s/H_o at shrinkage one were obtained. Fig. 6 shows both deformation rates for one second from 4 to 5 seconds elapsed from a voltage application with different phase angle of the voltage with 21.8kVp-p applied to the vertical electrode and 10kVp-p to the horizontal electrode. The error bars in the figure show the maximum and minimum deformation rate during one second. The average rate of H_s/H_o is 1.75 and 1.9 for 0 and $\pi/3$ radians of phase angle, respectively. The average

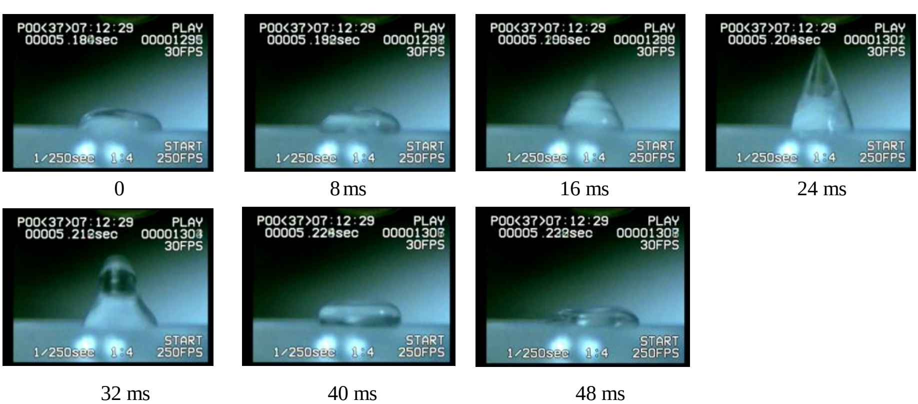


Fig. 5. Resonant vibration of a droplet under the condition of the phase angle of 60 degrees and 21.8kVp-p applied to the vertical electrode and 10kVp-p to the horizontal electrode. Frequency is 11Hz.

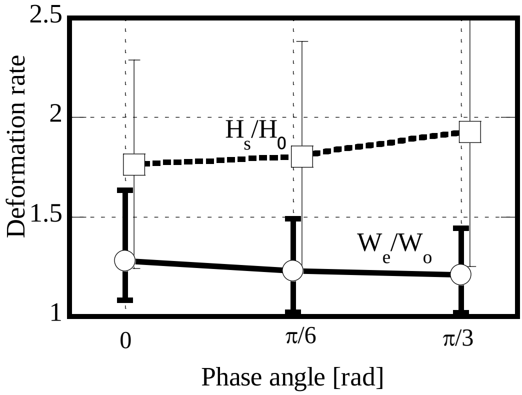
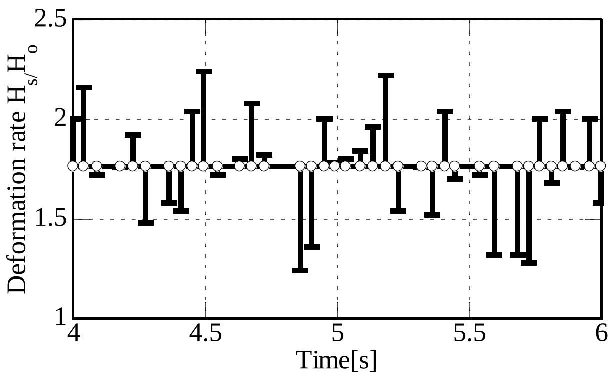
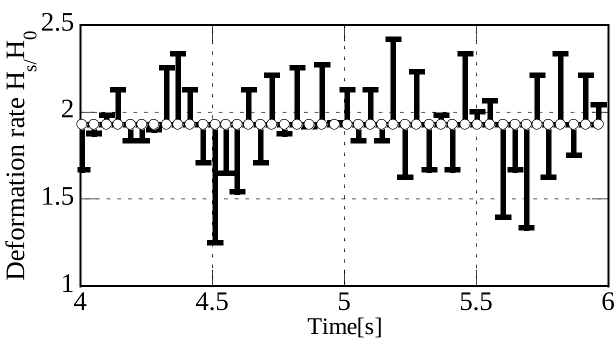


Fig. 6. Deformation rate of a water droplet under the ac applied field for the lead phase angle of the vertical field to the horizontal field.



(a) $\phi = 0$



(b) $\phi = \pi/3$

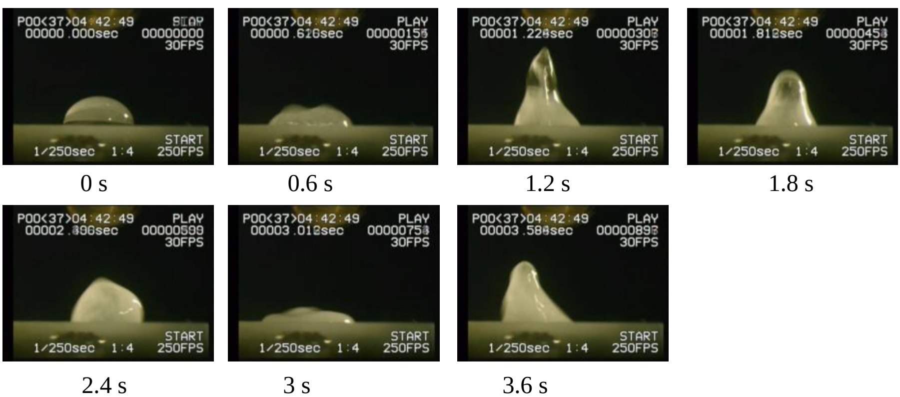
Fig. 7. Time variation of deformation rate of a water droplet at elongation and shrinkage state.

height-deformation rate increases and width one decreases slightly with a phase angle. Furthermore, during one second of 22 times of vibration under 11Hz field, the rate of H_s/H_o are varies from 1.25 to 2.3 or 2.5 depending on the phase angle.

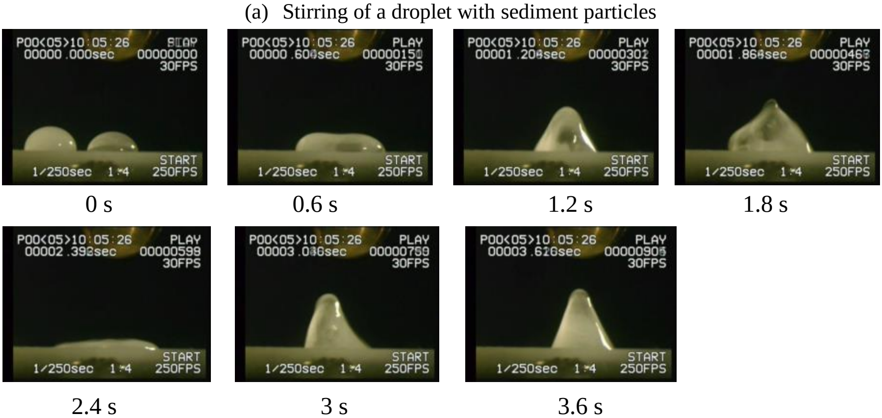
Fig. 7 shows the time variation for two seconds of the height-deformation rate H_s/H_o Under the condition of the stronger applied field to the vertical direction, the difference in phase angle of the vertical field as well as stronger vertical field affect the enhancement of the irregular motion of the droplet. From the comparison of Fig.7 (b) to Fig. 7(a), the larger or smaller deformation than average one occurred much often. This frequent and larger deformation must promote the liquid flow in the droplet.

B. Mixing performance

To confirm the presence of enhanced liquid flow in a droplet, the effect of unbalanced field on stirring and mixing was observed. Fig. 8 shows the examples of the deformation of a 100 μL droplet under the stirring and mixing performance for the lead phase angle of π/3

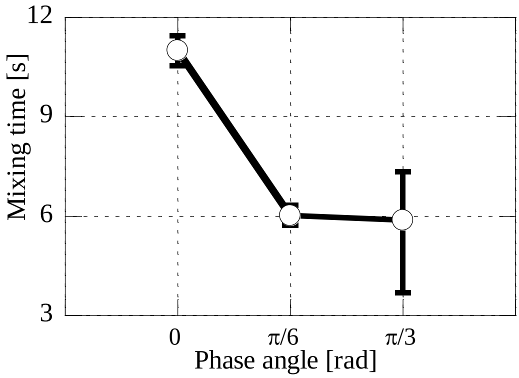


(a) Stirring of a droplet with sediment particles

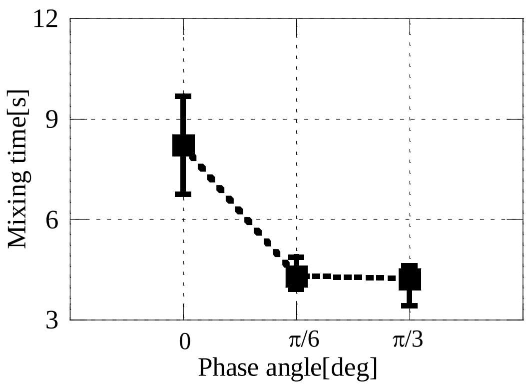


(b) Mixing of two droplets

Fig. 8. Effect of unbalanced electric filed under the phase difference of π/3 (a) on stirring a droplet with settled powder and (b) on mixing two droplet containing powders.



(a) Stirring a single droplet with sediment powders



(b) Mixing of two droplets

Fig.9. Stirring time for a droplet with sediment particle and mixing time of two droplets to phase angle of applied voltage to the vertical electrode to the horizontal electrode.

of the vertical electrode and 11 Hz. Stirring effects was examined by 100μL ionized water droplet with settled fluorescent powder at the bottom, while and the mixing effect was confirmed using a 50 μL ionized water droplet and 50 μL droplet with unsettled fluorescent powder.

When the droplet driven by two-directional filed with the same magnitude of sinusoidal voltage was applied to the both sets of electrode, never invoked inside the droplet due to lack of disturbance of the liquid flow inside of a droplet[8]. In contrast, the unbalanced filed causes strong liquid flow at the inside of the droplet. By vibrating motion, white powder settled at the bottom moved into the bulk of the droplet as shown in Fig. 8(a). At the elapsed time of 1.2 s or 1.8 s the colour of the higher region of the droplet in the shrinkage state is not white and transparent. At 3.6 s elapsed, the colour of the higher region is white. Thus, settled powder became dispersed in it. In case of mixing two 50 μL droplets as shown in Fig. 8(b), two droplets was merged to a 100 μL droplet by voltage application, thereafter the merged droplet began to vibrate in a similar manner to stirring to be mixed.

The mixing time or dispersing time of fluorescent powder is shown in Fig 9. The mixing time is when the white colour of a powder in the higher region of shrinkage state was uniform. The mixing time driven by the strong vertical field with difference in phase angle is much faster than that by without phase difference. In addition, mixing time of a merged-two droplet is slightly faster than stirring of a single droplet with settled powder. This would be due to difference in powder condition between settled powder of a whole droplet and dispersed powder of either droplet.

IV. CONCLUSION

The resonant vibration of a 100 μL water droplet placed on a super-hydrophobic plate under the horizontal and vertical electric field was investigated. Under an unbalanced bi-directional filed, the droplet vibrated vigorously. Especially it extended to the upward direction and deformed to round-cone shape due to larger vertical field. Mixing performance of a viscous droplet should be cofirmed.

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