Surface Disintegration and Atomization of Micro Water Droplet Subjected to Surface Acoustic Wave

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Abstract: This paper concerned with the process of liquid atomization. The dynamic behavior of water droplet subject to surface acoustic wave was observed using a high speed video camera system. Liquid was disintegrated into fine liquid particles by the action of surface acoustic wave. The process of bursting phenomena of water droplet was revealed experimentally. Furthermore, the effect of micro solid particles in water droplet on bursting phenomena was investigated.

Keywords: Liquid Atomization, Micro Water Droplet, Surface Disintegration, Surface Acoustic Wave, Liquid Vibration, Capillary Phenomena

1. Introduction
With the development of combustion technology, the importance of study on the liquid atomization and disintegration is well recognized [1]. Thereafter, investigations on liquid atomization have been conducted and reported. For example, Negeed et al. studied the effects of nozzle shape and spray pressure on the liquid sheet characteristics breakup and the droplets formation of a flat fan jet nozzle from pressure-swirling analytically and experimentally [2]. Lefebvre reported that the average size of formed droplets depends mainly on the initial thickness of the liquid sheet, its velocity relative to the surrounding medium, and the liquid properties of viscosity and surface tension [3]. Suh and Lee investigated the influence of cavitation flow in the different length to width ratio nozzle on the diesel fuel atomization characteristics in terms of Sauter mean diameter (SMD), droplet mean velocity, and counted percentage of droplets, respectively [4]. Badock et al. investigated the cavitating phenomena in a real-size diesel injection nozzle hole and they observed cavitation films and the core of the flow inside of the spray hole using a light sheet method [5]. In these studies, the character of liquid jet disintegration or liquid film disintegration was investigated. It was clarified by those studies that the surface disintegration of liquid depends on the velocity of discharge from various nozzles.

On the other hand, it is necessary to consider atomization of micro droplets in the fields such as micro engine system, micro combustion system, micro channel flow system, and so on. A new method for the atomization of a liquid, called vibration-induced drop atomization (VIDA), was introduced and studied by James et al [6]. Tan et al. exploited large accelerations associated with surface acoustic waves to drive an extraordinary fluid jetting phenomenon [7]. In spite of many investigations there is no study on the dynamic behavior and the bursting of liquid droplet subject to surface acoustic wave.

In this paper, the dynamic behavior of water droplet subject to surface acoustic wave was observed using a high speed video camera system. Bursting phenomena of water droplet on the surface acoustic wave (SAW) device were revealed experimentally. Furthermore, the effect of micro solid particles in water droplet on bursting phenomena was investigated experimentally.

2. Principle of Water Droplet Bursting with SAW Device
All SAW devices utilize the piezoelectric effect to transduce an electric signal into a mechanical wave. A surface acoustic wave (SAW) is a type of mechanical wave motion which travels along the surface of a solid material. SAW devices consist of interdigital transducer (IDT) of thin metal electrodes deposited on a piezoelectric substrate such as quartz or lithium tantalite. The IDT acts as the device input and converts signal voltage variations into mechanical surface acoustic waves. The SAW is generated by applying a sinusoidal electric voltage to an interdigital transducer (IDT) fabricated on single crystal piezoelectric substrate.

In this experiment, Rayleigh waves (a kind of surface acoustic waves) were used to burst a water droplet. Rayleigh waves are a type of surface wave that travel near the surface of solids. Rayleigh waves include both longitudinal and transverse motions that decrease exponentially in amplitude as distance from the surface increases. There is a phase difference between these component motions. If the liquid droplet is placed in the traveling direction of Rayleigh wave, energy of wave is absorbed into the liquid and is attenuated. At this time, longitudinal wave propagates as sound wave, and internal flow is induced in the liquid droplet. The applied high frequency voltage that exceeded the threshold to the IDT produces a sufficient driving force for droplet burst. The resonant frequency $f_R$ of the device is the frequency of the generated surface acoustic wave. It should be noted that the input voltage signal should have a frequency equal to the resonant frequency of the device to maximize efficiency. The important parameter in determining the resonant frequency is the pitch of the interdigital transducer (IDT). The resonant frequency $f_R$ is described as follows:
was introduced and studied by James et al. [6]. It depends on the velocity of discharge from various nozzles. Liquid film disintegration was investigated. It was clarified inside of the spray hole using a light sheet method [5]. In they observed cavitation films and the core of the flow respectively [4]. Badock et al. investigated the cavitation droplet mean velocity, and counted percentage of droplets, characteristics in terms of Sauter mean diameter (SMD), the average size of formed droplets depends mainly on the solid particles.

Small spherical styrene particle was used as solid particle in the experiment. It was found that the dispersion time of water droplet was delayed by the solid particles in the water droplet. The dispersion time of droplet depended on the number of particles by the action of surface acoustic wave. The process of bursting phenomena of water droplet was revealed experimentally. Furthermore, the effect of micro solid particles in water droplet on bursting phenomena was investigated.

Fig.1 Photograph of experimental apparatus for water droplet atomization with SAW device

![Fig.1 Photograph of experimental apparatus for water droplet atomization with SAW device](image1)

Fig.2 Close-up photograph of SAW device

![Fig.2 Close-up photograph of SAW device](image2)

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f_R = \frac{v_R}{\lambda_R} = \frac{v_R}{2l_p}
\]

where \(v_R\) is the velocity of SAW, \(\lambda_R\) is the wavelength of SAW, and \(l_p\) is the pitch of the IDT. In the experiment, the frequency of SAW device was fabricated at \(f_R = 3.16\) MHz.

3. Experimental Apparatus and Procedures

3.1 Surface disintegration experiment

A photograph of the SAW (surface acoustic wave) device and an optical recording system is shown in Fig.1. Experimental apparatus is composed of the SAW device system, the voltage supply system, and the optical observation system. The ultrasonic vibration for liquid drop bursting was generated by the fabricated surface acoustic wave (SAW) device. Magnified photograph of the SAW device with a millimeter scale is shown in Fig.2. In this SAW device, the pitch of IDT was designed as \(l_p = 0.50\) mm. The fabricated surface acoustic wave device consists of a glass plate and an interdigital transducer arranged on the piezoelectric substrate (LiNbO₃). The alternating current signal was supplied from the frequency synthesizer.

\(v\) \(= 400\) V, \(\delta = 0.2s\)

(NF Corporation Multifunctional Generator WF1943), and it was amplified by the bipolar power supply (NF Corporation HSA4012). In the experiment, a single water droplet was located on the fabricated surface acoustic wave device by the micropipette, and the droplet was vibrated at 3.16 MHz. In Fig.2, a water droplet with the volume \(V_{drop} = 10^{-9}\) m³ is placed on the SAW device. In this case, the droplet diameter is about 1.45 mm at the base of SAW device. The dynamic behavior of the water droplet on the vibrating base was recorded by the high-speed video camera system, Photron FASTCAM-Ultima SE. The Photron Ultima SE is an ultra-high-speed video recording system with the ability to record up to 4,500 full frames per second (or up to 40,500 partial frames per second) for immediate playback. The imager is equipped with a C-mount lens adapter. In this experiment, a lens Micro-Nikkor 55mm f/2.8 was attached to the C-mount lens adapter of the Imager. A series of frames of the free surface behavior of the water droplet on the SAW device were analyzed by the personal computer.

3.2 Bubble rupture experiment

In this paper, bubble rupture below the air-water interface of droplet dome was studied experimentally, because it was expected that thin water jet ejection and fine water particle ejection from the surface of droplet subjected to SAW are closely related to bubble rupture at the interface in droplet. Firstly, water droplet was dropped on the acrylic plate by the micropipette. Then, air with a constant volume was injected in the droplet by the micropipette. Air bubble rupture at the air-water interface in water droplet was observed by the high-speed video camera system. The phenomena were recorded at 13500 frames per second, and a series of frames of the phenomena were analyzed by a personal computer. The experiment was performed under the condition of room temperature.

4. Experimental Results and Discussion

4.1 Spreading of water droplets by SAW

Responses of water droplet on the SAW device to ultra-high-frequency surface acoustic wave were investigated. Figure 3 shows selected frames from high-speed movie. In Fig.3, the time interval between each frame is \(\delta = 0.2s\), and the total amplitude of applied voltage to the SAW device is \(E_0 = 400\) V. Water droplet is elongated to the direction of wave propagation after the excitation immediately (number 2 in Fig.3). Then, the droplets continue to atomize gradually, and its volume is decreased (from number 2 to 6 in Fig.3). These phenomena are interpreted as follows: the wave energy of SAW is consumed by droplet atomization and mist ejection. Surface area of the water droplets is increased by the
excitation of SAW. If we neglect the gravitational energy and assume the droplet as hemispherical, water droplet at rest state has the surface energy, $E_{d\text{surf}}$ as follows:

$$E_{d\text{surf}} = S\sigma = 2\pi r^2$$  \hspace{1cm} (2)

where $S$ is the surface area, $\sigma$ is the surface tension, and $r$ is the radius of droplet. When the wave energy is injected into the droplets, Surface area is enlarged. Then $E_{d\text{surf}}$ is described as follows;

$$E_{d\text{surf}} = (S+\Delta S)\sigma$$ \hspace{1cm} (3)

where $\Delta S$ is increased surface area by droplet deformation. $\Delta S$ is determined by the energy of surface acoustic wave. Assuming simple harmonic oscillation as the SAW, the energy of the SAW per unit time and unit area is described as follows;

$$I = \rho_V \omega^2 \delta t$$ \hspace{1cm} (4)

where $\rho_V$ is the density of the medium, $\omega$ is the angular frequency, and $\delta$ is the amplitude of the wave. At the lower value of $I$, the water surface of droplet responds to the SAW energy as surface waves. At the higher value of the SAW, the free surface motion becomes very violent.

Fig.4 Change of maximum height of water droplet

Fig.5 Surface disintegration and mist ejection produced by SAW device ($\delta t=0.22\text{ms}$)

Fig.6 Jet formation produced by bubble rupture in droplet ($\delta t=0.74\text{ms}$)

And these capillary waves may disintegrate, form a dense spray, and thereby generate misting and atomization from the droplet. The droplet burst occurs in this way. Fig.4 shows a change of the maximum height of the water droplet at the condition of $E_0 = 375\text{V}$. The maximum height is changed with time by violent wavy surface motion. In $Z_t$ curve, the peak value just after starting of vibration corresponds to the generation of lower mode in surface wave on the droplet. The volume of water droplet is decreased by the atomization and mist ejection from the droplet surface. Figure 5 shows the surface state of the droplet subject to the SAW at $E_0=300\text{V}$. In Fig.5, the time interval between each frame is $\delta t=0.22\text{ms}$. It can be seen that the mist is like the rising cloud. Many super micro droplets are scattered at fast speed into the sky. The super micro droplets are ejected from the liquid jets above the water surface (Fig.5). Generally, the liquid column jets are produced by air bubbles collapse at the air-water interface [8]. In the next paragraph, we consider the liquid column jet formation from the water droplet.

4.2 Jet formation produced by the bubble rupture

Liquid jet produced by bubble rupture at the air-water interface is one of the most interesting fluid mechanics subjects and has been investigated extensively by many scientists and engineers. In this paper, bubble rupture in the micro water droplet was studied with the high speed video camera system. Figure 6 shows one example of experimental results. In this case, the volume of water droplet is $V_{\text{droplet}}=10\times10^{-3}\text{m}^3$, and the volume of air bubble is $V_{\text{air}}=4\times10^{-3}\text{m}^3$. In Fig.6, the arrows show the diameter of cavity in the droplet. The time interval between each frame is $\delta t=0.74\text{ms}$. It can be seen from Fig.6 that the rupture process involves several major dynamic events in cascade. The bubble rupture starts at the thinnest apex of the film cap where a hole is formed, followed by a rapid expansion of the hole boundary ($t=0\text{s}$: number 1 in Fig.6). The water film thins to a critical thickness before the bubble collapses. The maximum speed, $u$, of the receding bubble film is represented by the Culfic Equation as follows [9]:

$$u = \left(\frac{2\sigma}{\rho \omega^2}\right)^{1/2}$$  \hspace{1cm} (5)
where $\rho_w$ is the density of water, and $\varepsilon$ is the film thickness. When this high speed flow reaches the liquid layer surrounding the bubble cavity, it pushes the water to flow inward underneath the bubble cavity. The water flow beneath the bubble cavity has been approximated by a boundary-layer flow. When this symmetric flow meets at the bottom of the bubble cavity, a stagnation point is created, resulting in high pressure. This high pressure pushes the water to form two water jets, one downward into the water and one upward over the bubble cavity ($t \geq 2.96\, \text{ms}$). The velocity, $v_j$, of the rising water jet before breakup is shown in Fig.7 with the symbol $\bigcirc$. The maximum velocity of the rising water jet before breakup is about $v_j = 1.7\, \text{m/s}$. Eventually the water jet breaks into small water droplets flying over the water surface. This fact suggests possibility of the fine droplet generation by air bubbles in water droplet on the SAW device. Many air bubbles may be produced by the reduced pressure in the water subjected to SAW.

### 4.3 Dispersion time of the water droplet by SAW

As was stated previously, the water droplet subjected to SAW disperses finally. When the water droplet is vibrated by SAW, larger amplitude motion appears on the droplet surface at first. Then the droplet is enlarged to the direction of wave propagation. Figure 8 shows the details in the elongation state of the water droplet ($E_0=375\, \text{V}$). In Fig.8, the time interval between each frame is $\delta t=3.3\, \text{ms}$. The droplet is extended with surface wave by SAW energy. When the expansion of the droplet ends, phenomena of droplets ejection and misting from the water surface occur. This state of violent surface motion at $E_0=375\, \text{V}$ is shown in Fig.9. The time interval between each frame is $\delta t=0.22\, \text{ms}$. In Fig.9, some droplets are ejected, and mist is rising up toward the air. Finally, the water droplet subject to the SAW disappears by the ejection of small droplets and mist from the water surface. Figure 10 shows the dispersion time, $\tau_d$, of the water droplet subject to the SAW. The dispersion time, $\tau_d$, is decreased with the applied voltage to the SAW device, $E_0$. The increase of the applied voltage, $E_0$, leads to the increase of the amplitude, $A$, of the SAW in Eq.(4). The increase of the energy of SAW is
proportional to square of $A$. The increase of the energy of SAW leads the decrease in $\tau_0$.

### 4.4 Effect of fine styrene particles on the dispersion time

Effects of solid particles in the water droplet were studied in this paragraph. In the experiment, small styrene particles were submerged in water droplet. Diameter of the spherical styrene particle is $d_p=0.5\text{mm}$, and the density is $\rho_p=1050\text{kg/m}^3$. Bursting phenomena of water droplet containing particles subject to the SAW were observed with the high speed video camera. Figure 11 shows bursting phenomena of the water droplet containing one styrene particle subject to the SAW at the condition of $E_0=400\text{V}$. The solid particle moves in the droplet by violent surface motion. The energy of the SAW is spent on not only the droplet deformation, but also particle motion. Therefore, the dispersion time, $\tau_0$, becomes longer when the droplet includes the particles. Fig. 12 shows a comparison in the bursting process between the droplet containing one particle and the droplet containing three particles at $E_0=400\text{V}$. In Fig. 12, the time interval between each frame is $\delta t=1\text{s}$. The arrows in the Fig. 12 (a) show the position of the particle and the ovals in the Fig. 12 (b) show the position of three particles. One particle in Fig. 12 (a) and the cluster comprised of 3 particles in Fig. 12 (b) show random motion. It can be seen from Fig. 12 that the droplet volume in (a) decreases faster. The increased surface area of droplet with one particle is $\Delta S\geq 3.1\text{mm}^2$ at $t=1\text{s}$. For the droplet with three particles, the increased surface area is $\Delta S\geq 2.7\text{mm}^2$ at $t=1\text{s}$. Energy of the SAW is spent by the movement of 3 particles. This fact shows the possibility of the control for bursting phenomena with the solid particles. In this experiment, the dispersion time for a pure water droplet at $E_0=400\text{V}$ was $\tau_0=0.8\text{s}$. On the other hand, the dispersion time for a water droplet with one particle was $\tau_0=8.6\text{s}$. In the case of water droplet with three particles, the dispersion time $\tau_0$ was more than 10 seconds at $E_0=400\text{V}$.

### 5. Conclusions

In this paper, the details of bursting phenomena of water droplet subject to the SAW were investigated experimentally. Furthermore, the effect of micro solid particles of styrene in water droplet on bursting phenomena was also investigated. The results obtained are summarized as follows:

1. The micro droplet on the SAW device bursts by the surface acoustic wave. The bursting phenomena progress with free surface motion, small droplets ejection, and mist ejection.
2. The dispersion time of water droplet subject to the SAW depends on the applied voltage to the SAW device. The droplet disappears by higher voltage fast.
3. The dispersion time is delayed by the small solid particles in the water droplet. The dispersion time of droplet depends on the number of particles.

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### References


