

Investigation of SAW Atomization

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Abstract—Surface acoustic wave atomization is promising in various kinds of industrial and pharmaceutical processes. In order to properly apply this technology for a wide range of applications, controlling the aerosol size distribution is crucial. It is widely believed that the aerosol size can be controlled by the driving frequency, our experimental results, show a rather weak frequency dependence, especially when the driving frequency is above 10 MHz. Fundamental studies were therefore carried out to determine the underlying mechanism associated with the destabilization of the liquid interface leading towards atomization with the objective of elucidating this apparent contradiction. Our investigation supports the notion that the droplet sizes appear to be governed by the capillary vibration frequency given by a balance between the capillary stress and viscous forcing, not the driving frequency as previously claimed. Furthermore, the aerosol size can be altered by controlling the surface tension and viscosity. For this case, we employ the laser diffraction to obtain the size distributions of octanol aerosol and water aerosol generated by SAW atomization. The experimental results matches our theoretical prediction that water, with higher surface tension and lower viscosity, generates relatively larger aerosols than octanol.

I. INTRODUCTION

Atomization is a technology that converts a bulk parent drop to a spray or mist with aerosols in ranges of micron or submicron. It is widely employed in many industrial and pharmaceutical processes, for example, fuel injection, agriculture spray, DNA microarray printing and pulmonary drug delivery. The physics of atomization is applying external force to overcome resisting forces— surface tension and viscous stress—within the fluid, leading to capillary destabilization and breakup from free liquid surface. Current common atomization methods include: hydrodynamic flow focusing, which generates droplets by means of forcing liquid ejecting through an orifice using direct pressure or fast moving air stream [1], ultrasonic atomization [2], [3], [12], [4], [5] and electrospray using high charged electric field [7], [8].

Surface acoustic wave (SAW) atomization as one subset of ultrasonic atomization is new to this field, first presented by Kurosawa [9], [10]. It has demonstrated a promising ability by showing a good performance in producing monodisperse aerosol within a fast, controllable fashion [6], [16]. Furthermore, small scales, light weight, low power requirement and easy to mass-fabricate provide SAW atomizers more advantages over other atomization techniques.

A SAW is a nanometer-order amplitude acoustic wave that propagates along the surface of a single-crystal piezoelectric

substrate. The amplitude is rapidly reduced with increasing depth into the substrate, and is entirely absent four to five wavelengths into the substrate from the propagation surface. There are many kinds of SAW waves, though by far the most commonly used for actuation is the *Rayleigh* wave [25], a transverse-axial elliptical electroacoustic wave as shown in Fig. 1(a).

The sound speed in water $c_w = 1485$ m/s, is much less than the SAW propagation speed on the substrate, $c_s = 3965$ m/s. This difference causes the SAW to diffract into the water drop at the *Rayleigh angle* [13] $\theta_R = \sin^{-1}(c_w/c_s) \sim 22^\circ$. The acoustic radiation *leaked* into the fluid drop gives rise to a longitudinal pressure wave which induces bulk recirculation in the drop, known as *acoustic streaming*. At high powers, the velocity of the surface as the SAW passes is on the order of 1 m/s regardless of the excitation frequency. Thus, at excitation frequencies on the order of 10 MHz, we expect the displacement of the surface and the amplitude of the acoustic wave to be only around 10 nm. However, the acceleration of the surface is incredibly high, at around 10^7 m/s². Such huge surface accelerations are transmitted into a liquid drop placed upon it, inducing strong acoustic waves within the drop. When the acoustic energy is strong enough, it can destabilize the free surface of liquid, leading to capillary wave breakup. This is known as SAW atomization (*see* Fig. 1(b)).

The SAW atomizer is made of a low-loss piezoelectric substrate, $127.86^\circ Y-X$ -rotated single-crystal lithium niobate, with chromium-aluminum interdigital transducer (IDT) electrodes via UV lithography [26]. The gap and width of the IDT fingers are set to be one-fourth the SAW wavelength λ_{SAW} . The resonant frequency of the atomizer is determined by $f = c_s/\lambda_{SAW}$. A sinusoidal electrical signal is supplied to the substrate through the IDT, generating a *Rayleigh wave* SAW which propagates across the substrate surface. Fig. 2 is a schematic of a SAW device patterned with a pair of IDTs.

Generating aerosols within a controllable size distribution is always the main concern of atomization, no matter what method to apply. It is generally accepted that the diameter of an aerosol is in the same order of capillary wavelength, given by

$$D \approx k \cdot \lambda, \quad (1)$$

where λ is the instability capillary wavelength. Coefficient k has been experimentally found with variable values. In 1871,

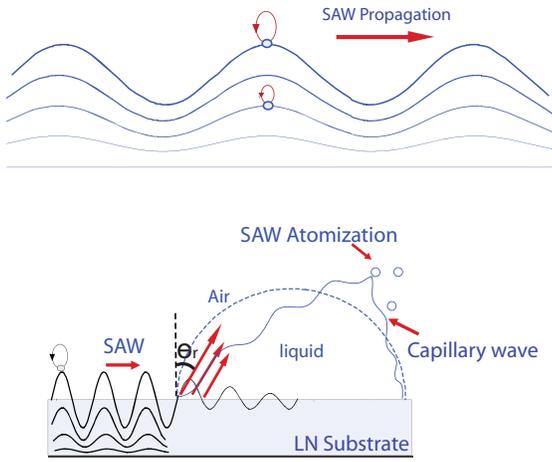


Fig. 1. Schematic of SAW propagation is shown in (a). The SAW propagates from left to right and the trajectory a single particle on the wave is in a counter-clockwise direction. A typical SAW device is shown in (b), consisting of an interdigital transducer fabricated on the piezoelectric substrate.

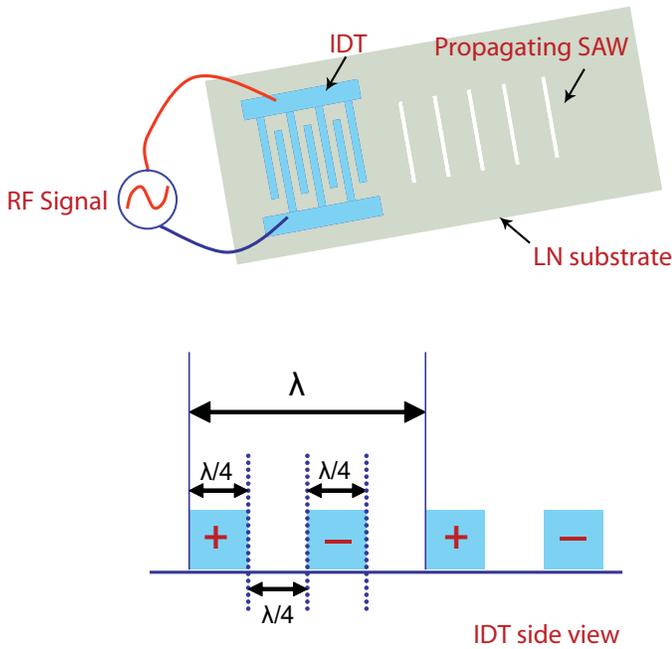


Fig. 2. A schematic of IDT patterned SAW device.

Kelvin first identified that when induced by periodic vertical forcing, the instability wavelength on the free surface of liquid is determined by its surface tension γ , density ρ and the frequency of capillary wave f_c , thus [11]

$$\lambda \sim \left(\frac{2\pi\gamma}{\rho f_c^2} \right)^{1/3}. \quad (2)$$

By choosing the lowest-order resonance frequency $f_c = f/2$, where f stands for excitation frequency, as the weakest non-linearity, the capillary wavelength becomes [27]

$$\lambda \sim \left(\frac{8\pi\gamma}{\rho f^2} \right)^{1/3}. \quad (3)$$

which has been widely applied in many works, relevant theoretical analysis have been thoroughly taken such as in [20], [21], [22], [23], [24], etc..

The ultrasonic atomization, performed by Lang [2], showed that the aerosol diameter observed is in the same order of the capillary wavelength calculated using the assumption above. By applying Eq. 1, The coefficient k is obtained as 0.34. Similar work has done by Barreras in [19], where he found out k is about $1/\pi \approx 0.32$.

However, this theory appears to be incorrect when being applied in SAW atomization at much higher driving frequencies (>10 MHz) [10], [29] compared to former occasions (<1 MHz). But the half-frequency subharmonic assumption, and the modified Kelvin's equation (Eq. 3), were not questioned, the difference between the true aerosol diameter and the one calculated using Eq. 1 and Eq. 3 was amended by fitting in varied k values, and the cause was either unidentified or blamed to be experimental errors [10], [29]. For example, in reference [10], k was fitted to 1 and 3.8 with exciting frequency f at 10 and 50 MHz respectively.

According to another large group of literatures, the capillary frequency is either due to internal capillary-viscous resonance [8], [28], given by

$$f_c \sim \frac{\gamma}{\mu R}, \quad (4)$$

or inertial forcing [8], [28], given by

$$f_c \sim \left(\frac{\gamma}{\rho R^3} \right)^{1/2}. \quad (5)$$

Hence, for ordinary liquids, such as water, with viscosity $\mu \sim 10^{-3}$ kg/m·s and surface tension $\gamma \sim 10^{-2}$ N/m, having a characteristic length scale $R \sim 10^{-2}$ – 10^{-3} m, the viscous-capillary resonant frequency from Eq. (4) is $f_c \sim 1$ – 10 kHz. With a density of $\rho \sim 10^3$ kg/m³, the capillary-inertia resonant frequency from Eq. (5) is $f_c \sim 10^{-2}$ – 10^{-1} kHz. At low driving frequency, the differences between either of these capillary frequencies above and subharmonic frequency $f/2$ is small, however, when the exciting frequency is high, like over 10 MHz, both of these frequencies are based on the physical behavior of the free surface of the drop, yet neither correspond to the subharmonic relation $f_c = f/2$. Therefore, at high exciting frequency, Eq. 2 should be applied instead of Eq. 3.

In this paper, our motivation is to investigate and analyze the capillary destabilization and breakup process, finding out the true mechanism that dominates the SAW atomization, therefore, providing a correct guide for further applications. Detailed work is presenting in the following sections.

II. METHODS AND MATERIALS

A scanning laser Doppler vibrometer (MSA-400, Polytec PI, Waldbrunn, Germany) with fast Fourier transform (FFT) of the measurement signal was used to scan the free surface of liquid upon SAW excitation. It is hoped to obtain the resonant frequency of capillary waves in order to identify the true mechanism that dominant the SAW atomization.

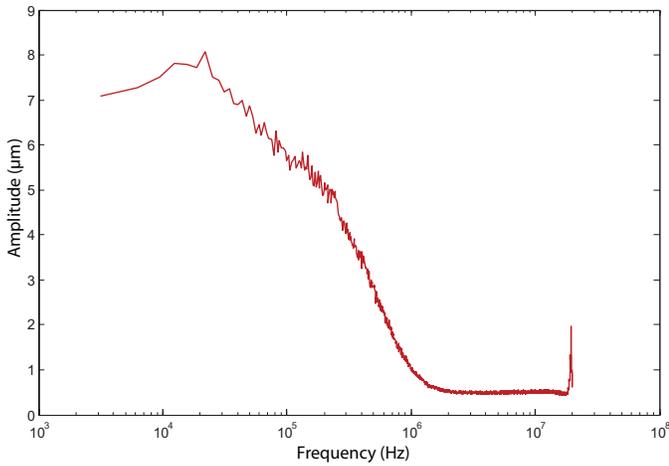


Fig. 3. FFT frequency sweep using the laser Doppler vibrometer shows the frequency at which the capillary wave on the free surface of the drop is excited. While the excitation frequency is at 20 MHz, the capillary frequency is approximately 10 kHz. No peak is observed at the half driving frequency (10 MHz).

The resulting capillary waves on the free surface of the drop were visualized using a high speed video camera (iSpeed, Olympus, Tokyo, Japan) with a frame rate up to 10000 frame/second.

Spraytec (Malvern Instrument, UK), a laser diffraction particle size system, was used to obtain an accurate size distribution of aerosols generated by SAW atomization.

III. RESULTS AND DISCUSSIONS

A. Resonant Capillary Frequency

Figure 3 shows the broadband excitation of capillary waves. Though driven by SAW at 20 MHz, there is no capillary wave at one-half the excitation frequency $f/2 \sim 10$ MHz nor even at the excitation frequency $f \sim 20$ MHz. Instead, the majority of the capillary wave response is centered around 10 kHz. This is comparable to the results of Eq. (4), suggesting that the surface waves are dominated by capillary-viscous resonance. Figure 4 is a group of snapshots showing droplets pinching off from capillary waves. Within large scales (*see* Fig. 4(a)), at the rise-half cycle of a propagating capillary wave, a crest is formed. At the fall-half cycle, the capillary wave propagates forward, leaving the crest behind, thinning its thread. Eventually, a droplet, about $300 \mu\text{m}$, is formed and pinched off from the capillary wave. The whole process takes about 1 ms, suggesting the capillary frequency is at 1 kHz order. Within a smaller scale (*see* Fig. 4(b)), a much smaller droplet, about $10 \mu\text{m}$, is formed and pinched off from the tip of a capillary wave. The time sequence here is ~ 0.1 ms, meaning that the capillary frequency is ~ 10 kHz.

Therefore, from the visualization about SAW atomization, the time that takes a droplet to form and pinched off from a propagating capillary wave is in the order of 1-10 kHz, gives another proof to our theory discussed above—the dominant mechanism of SAW atomization is capillary-viscous resonance

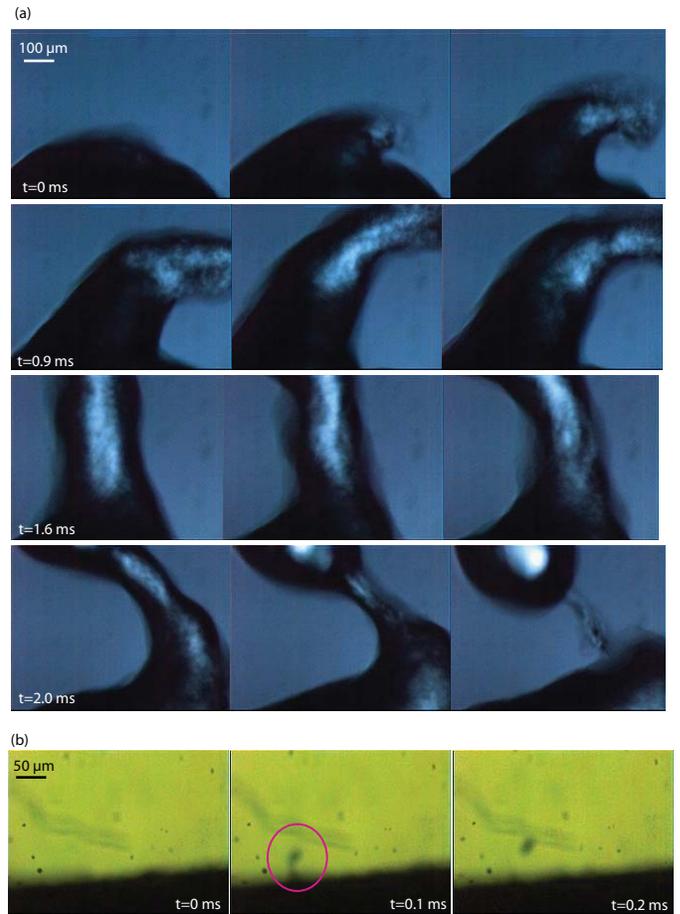


Fig. 4. Drop deformation and atomization in (a) large and (b) small scales. Images are acquired at 10000 frames/sec showing a droplet formed from a drop (*see* (a)) and a thin film (*see* (b)), respectively.

and it is incorrect to employ the half-frequency subharmonic assumption for high frequency driving atomization.

A simple scaling argument arising from a viscous-capillary force balance is provided here to predict the instability wavelength. We note that the capillary stress has to be adjusted to account for the dominance of the axial capillary stress $\gamma(\partial^2 H/\partial x^2)$ over the azimuthal capillary stress γ/H for a thin film of thickness H , and hence the viscous-capillary force balance reads

$$\frac{\gamma H}{L^2} \sim \frac{\mu U}{H}, \quad (6)$$

where $U \sim \lambda f_c$ is the wave velocity. Rearranging then gives

$$\lambda \sim \frac{\gamma H^2}{\mu f_c L^2}, \quad (7)$$

for the instability wavelength, which is roughly 1–10 μm , in approximate agreement with the jet and droplet dimensions observed in the experiments.

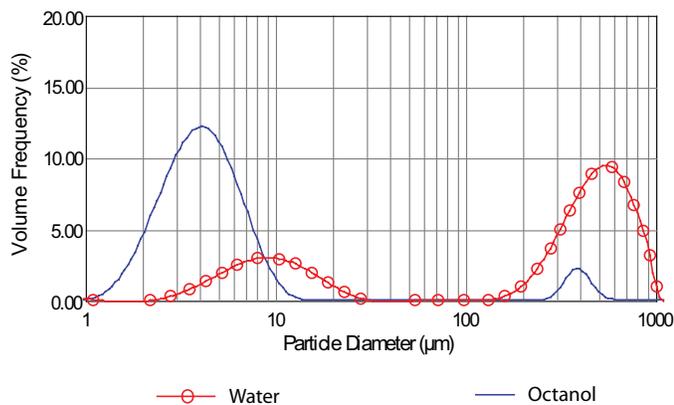


Fig. 5. The comparison of volume size distribution between water and octanol SAW atomization.

B. Effects on aerosol size distribution from the properties of a liquid.

As a consequence of capillary-viscous resonance, the capillary wavelength, which in turn determines the aerosol diameter, is governed by the properties of liquid, suggested by Eq. 7. Therefore, different liquid, with varied surface tension and viscosities, generate aerosols with varied size distributions. Here, we use Spraytec to obtain the size distribution of water aerosol and octanol aerosol, respectively. Power has kept at the same level for water and octanol atomization (~ 2 W). Fig. 5 represents the comparison of size distribution between water and octanol aerosol. It can be seen that water, with higher surface tension (71.99 mN/m) and lower viscosity (0.890 mPa s) than octanol (27.10 mN/m and 7.288 mPa s), produces relatively larger aerosols. The results give proof to our theory that by manipulating the properties of liquid, the aerosol size can be controlled.

IV. CONCLUSIONS

In this paper, we report on work carried out on elucidating the fundamental mechanism of the SAW atomization process. A laser doppler vibrometer was used to scan the free surface of a liquid upon SAW excitation and a high speed camera was also used to visualize the droplet pinch-off from the destabilized interface of a parent drop or a film. It has been found out that instead of subharmonic frequency response at one-half the excitation frequency, the capillary frequency is actually due to capillary-viscous resonance. In this case, the size of aerosol generated by SAW atomization, can not be controlled by driving frequency as it was accepted in traditional ultrasonic atomization using piston-like periodic vertical acoustic forcing, but can be altered by controlling the surface tension, viscosity and characteristic length scale with a capillary frequency usually at 1–10 kHz. The theory was proved by comparing the size distribution of water aerosol and octanol aerosol, where the former, with larger surface tension and lower viscosity appears to be relatively larger than the other.

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