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Experimental investigation of surface acoustic wave atomization

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ABSTRACT

Surface acoustic wave (SAW) atomization is a promising and relatively new method in the atomization field. However, the exact process is obscure due to the difficulty of observing such a small-scale series of complicated hydrodynamic processes. Lacking enough observations also makes it difficult in predicting the atomized droplet size distribution. Therefore, this study employed fundamental experimental methods to investigate the mechanism for SAW atomization. Firstly, a 20 MHz SAW device was fabricated by UV photolithography technology. The whole atomization process was then recorded by using a high-speed camera and classified each reaction stage according to the applied power. The experiment reveals three main peaks in the size distribution and corresponding mechanisms are employed to provide a detailed explanation for each. Experimental results also show that Eckart streaming and Schlichting streaming dominate different stages in generating different scale droplets. Two methods of predicting the mean diameter of atomized droplets are compared in this work.

1. Introduction

Producing micron or submicron-scale droplets or spray is significant in a wide range of industrial and pharmaceutical applications, including ink-jet printing [1], mass spectrometry [2–4], fuel processing [5], film coating [6,7] and pulmonary drug delivery [8,9]. In most of these applications, a uniform and monodispersed droplets size distribution is required. Various types of atomization methods are employed in order to meet this target and, regardless of which method is used, the mechanism for atomization uses an external energy source, such as an electric field, acoustic field to disturb the surface tension that maintains the surface profile and stability. Once the disturbance is large enough to overcome the capillary stabilization, a liquid film or parent droplet starts to break up into atomized droplets or a liquid thread and an atomization phenomenon ensues under continuous power input.

SAW is a nanometer-order amplitude acoustic wave that travels along the surface of a single-crystal piezoelectric substrate. With the increase of substrate depth, the SAW energy decays exponentially and completely disappears when the depth reaches to four wavelengths or more. By contrast, in the horizontal direction, the wave motion will propagate over thousands of wavelengths of distance in a low-loss piezoelectric substrate, normally lithium niobate ($LiNbO_3$). The most commonly spurred wave which is generated from interdigital transducer (IDT) electrodes deposited onto the piezoelectric substrate is the Rayleigh wave [10].

As shown in Fig. 1, the SAW has an elliptical displacement on the surface, which can be decomposed into two displacements: a longitudinal component along the direction of SAW propagation and a transverse one perpendicular to the surface [11]. When the high frequency electrical signal is imposed on the IDT electrodes, an inverse piezoelectric effect is generated by oscillation of the substrate causing the Rayleigh wave propagation. The attenuation of the energy conveyed by SAW is minor until it meets the edge of the target droplet or the thin water film placed on the substrate, which refracts into the water at the Rayleigh angle $\theta_R = \sin^{-1}(v_W/v_S) \sim 22^\circ$ [12] because of the mismatch between the sound speed in water ($v_W = 1485$ m/s) and the SAW propagation speed on the substrate ($v_S = 3965$ m/s). The acoustic radiation leaking into the fluid drop gives rise to a longitudinal pressure wave which induces bulk recirculation in the drop [13] known as acoustic streaming [14]. When the diffracted energy increases to a threshold degree, the capillary wave could not sustain the stability of the free surface of liquid and starts to breakup. This is the mechanism that dominates the SAW atomization.

Generating fine mist within a controllable size distribution is of great importance in the atomization process. It is crucial to build the relationship between the excitation frequency, the applied power and diameter of drop.

In Kelvin's theory [15], the mean diameter of liquid is in the same order of capillary wavelength. Kelvin's theory formulated the

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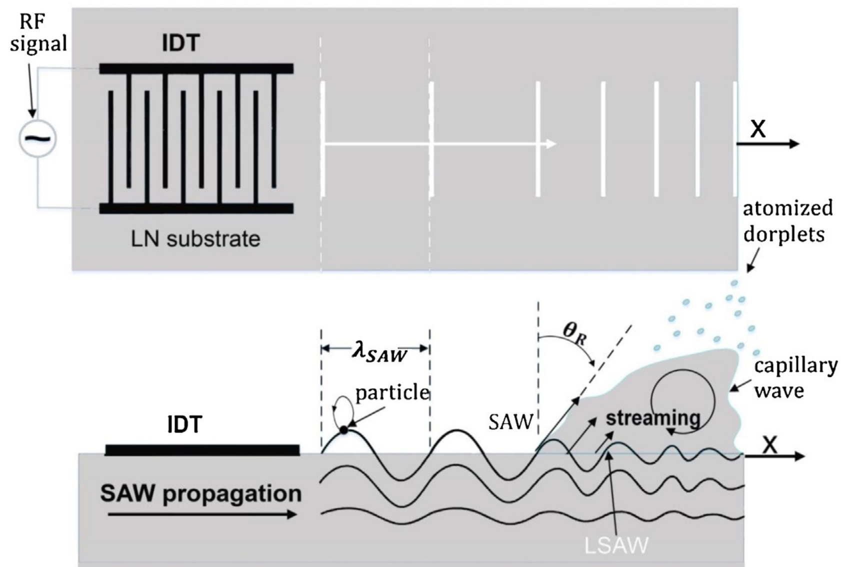

Fig. 1. Schematic shows the mechanism of SAW propagation along a piezoelectric substrate and capillary wave motion on the fluidic free surface. The SAW launched by an interdigital transducer (IDT) is a traveling wave in retrograde. The motion of the SAW is an elliptical trajectory that can disintegrate in two directions: (i) the horizontal component of the SAW leads to the bulk recirculation in the drop, which is known as an acoustic streaming phenomenon; and (ii) the vertical component of the SAW causes the deformation of the drop tilting at the Raleigh angle to form an asymmetric conical shape. Once the SAW touches the boundary of the drop, the wave changes the mode to a leaky surface acoustic wave (LSAW) with the attenuation of the acoustic force due to the viscous damping of the propagating wave. The mismatch between the capillary and external acoustic energy eventually ruptures the drop.

following relationship for capillary wavelength known as Kelvin's equation:

$$\lambda = \sqrt[3]{\frac{2\pi\gamma}{\rho f_c^2}} \tag{1}$$

where γ and ρ are the surface tension and the density of the liquid, and f_c is the frequency of the surface waves. Later Lang [16] measured drop size distribution produced by ultrasonic vibrator excited in a range from 10 to 800 kHz and proposed a modified form of Kelvin's equation to predict the size distribution of droplets:

$$D = 0.34\sqrt[3]{\frac{8\pi\gamma}{\rho f^2}} \tag{2}$$

where D is the atomized droplet diameter and f is the excitation frequency, which is different from the capillary frequency in Eq. (1). The factor 0.34 is an empirical coefficient, which may vary from different excitation frequencies such as 3.8 by Kurosawa et al. [17] and $1/\pi$ by Barreras et al. [18]. While the approximation of the mean diameters can be accurate after adding the coefficient, the value of the coefficient will be larger under high frequency exciting signal and correspondingly smaller at lower vibration intensities [17].

However, other researchers have questioned the wave theory that originated from Faraday's work [19]. According to Qi et al. [20], the dimension of the ejected droplets D can be described as a capillary–viscous stress balance:

$$D \sim \lambda \sim \frac{\gamma H^2}{\mu f_c L^2} \tag{3}$$

where γ is the surface tension, μ is the liquid shear viscosity, f_c is the capillary wave frequency and H and L are the characteristic height and length scales of the liquid sample (thin film or drop) respectively. There are two main differences between Eqs. (2) and (3). Firstly, rather than assuming that the capillary wave frequency f_c is one-half of the excitation frequency f, in correlation Eq. (3) f_c is either given by:

$$f_c \sim \frac{\gamma}{\mu R} \tag{4}$$

as the capillary wave frequency governed by internal viscous damping of the drop [20], or

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

as the capillary wave frequency governed by inertia forcing of the drop [21,22], where ρ is the density of liquid sample and R is the characteristic length of liquid sample, typically at the 10^{-2}–10^{-3} m scale. Secondly, the geometrical profile (characteristic height H and characteristic length L) underestimated by Faraday's theory is taken into consideration in Eq. (3), assuming that the geometrical parameters possessed by the liquid sample really have a huge influence on size distribution. Furthermore, the film shape is also affected by the applied power and frequency of the SAW [23].

This paper describes an experiment conducted by the authors to determine which of the two theories mentioned above can provide a good prediction of the mean diameter of an atomized droplet. A high-speed camera was used to capture the moment of the atomization phenomenon. A laser diffraction analyzer was also applied to detect the accurate size distribution of the liquid sample produced by the 20 MHz SAW device. A scale model was used to estimate the droplet size and the images from the experiment were used to provide detailed description of the whole atomization process as well as the mechanisms for each stage. Finally, to provide a better understanding of the role of the aspect ratio (H/L), a paper-based platform for atomization was developed as an alternative to the sessile drop.

2. Methods and experiments

2.1. The SAW device

The SAW device used in the experiment was fabricated by using sputtering, standard UV photolithography technologies and etching the electrodes onto single crystal 128.68° *y*-cut-*x* lithium niobate ($LiNbO_3$) piezoelectric substrate. The SAW atomizer was the conventional type SAW device generating a high-frequency wave in both directions. The configuration of the IDT contained 25