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A Miniaturized Surface Acoustic Wave Atomizer with a Disposable Pump-free Liquid Supply System for Continuous Atomization

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***Abstract*-Surface acoustic wave (SAW) atomization has been found to be a rapid and efficient way for generating micron or submicron aerosols within a controllable fashion. The SAW atomizer is small and light-weighted, attractive for many applications, especially for pulmonary drug delivery and biomicrofluidics. Control the sizes of the aerosols generated by SAW is crucial for successful applications. Unlike the theory applied and published in many SAW atomization works—the size of the aerosol can be tuned by manipulating the driving frequency; —we however found the aerosol size is irrelevant to the driving frequency, but governed by the capillary vibration frequency given by the balance between the acoustic forcing and capillary stress. The self-pumping effect of SAW, on the other hand, leads to the design of a disposable pump-free liquid supply system, which is able to deliver liquids to atomizer automatically for continuous atomization.**

I. INTRODUCTION

Atomization is attractive in many applications such as fuel injection, ink-jet printing, mass spectrometry, DNA micro-patterning and pulmonary drug delivery [1]. Traditional atomization methods include hydrodynamic flow focusing (jet atomization) [4], ultrasonic atomization [3,4] and electrohydrodymamic atomization (electrospray) [5,6]. As in many biomedical applications, biomolecules are usually fragile and shear-sensitive, traditional methods as above are having limitations in achieving efficient aerosolization. For example, jet atomization is usually associated with uneven aerosol size distribution and requires an external large air-pump. Normal ultrasonic atomization is usually driven at low frequencies (<1MHz) thus can damage or degrade shear-sensitive molecules, such as DNA. Electrospray, driven with voltage as high as kilo-volts, is not considered as a safe technique for biomedical applications.

Here, we present the use of surface acoustic wave (SAW) for rapid and efficient atomization. SAW atomization, driven at much higher frequency, usually over 10 MHz, is safe for working with many fragile biomolecules such as DNA, as the forcing period is much shorter than the relaxation time of DNA in liquid [7,8]. Furthermore, as SAW atomizer is small, light-weighted and only requires small power (1—3 W) to achieve efficient atomization, it is therefore considered as an ideal device for many biomedical applications, such as working as a pulmonary drug delivery nebulizer [9].

II. EXPERIMENTS AND METHODS

A. *Device and experiment setup*

Surface acoustic wave is a kind of Rayleigh wave propagating along the surface of a piezoelectric substrate, which, in our case, made of 128° y-x cut Lithium niobate (LN). The energy of SAW is mainly located on the LN substrate surface as the wave is rapidly attenuated, disappearing around four to five wavelength depth into the substrate from the surface. Though the amplitude of SAW is only a few nanometers, the acceleration is as high as $10^7 m/s^2$, which gives a huge energy that, when diffracts into the liquid placed upon the atomizer, can destabilize the capillary wave of the drop and cause it break up into micron size aerosols as shown in Fig 1 [10].

We employed the *single-phase uni-directional* transducer (SPUDT) as an alternative to the standard interdigital transducer (IDT) in this work. With normal IDTs, the SAW propagates in both forward and reverse directions. Therefore, the wave travelling in reverse direction can reflect back from a device edge and then interferes with the forwarding signals. SPUDT, on the other hand, travels in single directions such

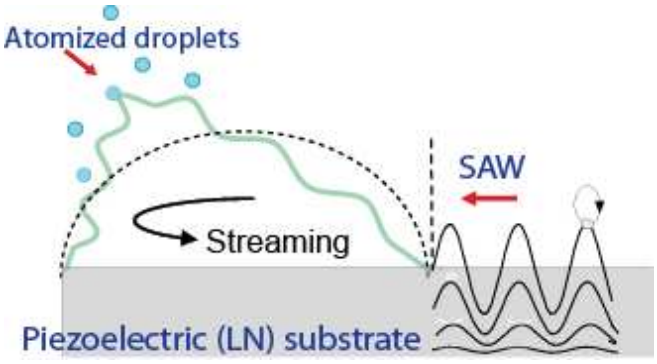

Figure 1 Atomization of liquids via surface acoustic wave.

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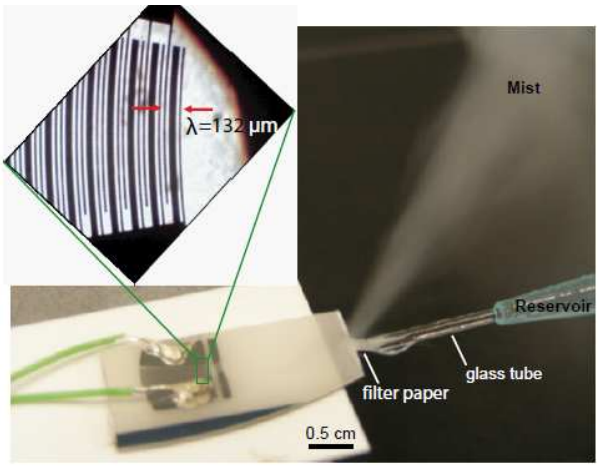

Figure 2 Image of a working SAW atomizer with a disposable liquid supply system. A small piece of paper is embedded in a capillary tube, which, acting like a bridge, connects the SAW atomizer, paper strip to the reservoir. The inset shows the electrodes of SAW device under microscope.

that less energy is lost and the risk of interfering reflections can be also reduced. Furthermore, to achieve the most efficient atomization with limited power input, a concentric elliptical transducer was also employed. Fig 2 shows a concentric elliptical 30 MHz SPUDT SAW device.

The ability to draw fluid through a narrow gap by atomizing the fluid at the end of the gap via SAW was first, but only briefly, demonstrated by Kurosawa [11]. The liquid was placed in a gap between the atomizer substrate and a coverslip. Upon excitation, the liquid was observed to be drawn towards the SAW and subsequently atomized. However, there has yet to be a detailed investigation of the fundamental mechanisms that govern this process on the development of such technology for application in the context of microfluidics. In this work, we present the use of a tissue paper which acts as a pump, drawing liquids out of reservoir for continuous atomization [12], as also shown in Fig 2. At this extent, A high speed camera (Mikrotron, Germany) with a long distance microscope lens (Infinity, USA) was employed to view the atomization at 2754 frames per second to directly observe the effect of changing power, paper and contact conditions between the paper and the SAW device. Paper strip used in following experiments were polyster-cellulose clean room paper (C1, Lymtech Scientific, USA).

B. Aerosol size distribution measurement

The aerosol size distribution is one the most important factors that determine the quality of atomization. In most of the early work regarding SAW atomization, there has been a misconception that the capillary frequency is half of the driving frequency, such that, the aerosol size is tunable via changing the driving frequency [4,13,14]. However, for destabilized capillary wave, the resonant frequency is either due to viscous damping of the drop ($f_c \sim \gamma/(\mu R)$), or inertial forcing ($f_c \sim \gamma/(\rho R^3)$), where γ is the surface tension of the liquid, μ is the viscosity, ρ is the density and R stands for characteristic length scale of the drop placed upon the atomizer [10]. Since inertial forcing is usually confined below the boundary layer of the liquid, which typically between 10^{-6}-10^{-7} m, the dominant phenomenon is capillary-viscous resonance [10]. Therefore, the equation for estimating the diameter of the aerosol generated by SAW atomization was derived to be

$$D \approx \lambda \sim (\gamma H^2)/(\mu f_c L^2), \qquad (1)$$

where H and L stand for the height and length of the parent drop, respectively [10]. Clearly, the ratio of γ/μ has significant influence on controlling the aerosol size distribution. We therefore employed laser diffraction based Spraytec size measurement (Malvern, UK) to test liquid aerosols with different surface tensions and viscosities.

C. Biological applications

Furthermore, as this technology will be mainly utilized in biological applications, the biocompatibility of the SAW atomizer is important. To examine if biomolecules, for example, proteins, were damaged after the extraction-atomization process, we used BSA and ovalbumin as model protein solutions (10 mg/ml respectively). 20 μl protein solution was first loaded onto paper strip and left at room temperature for drying. This step is to mimic certain applications such as bio-reagents transport through paper and recollect using SAW extraction-atomization. Paper strips with proteins were re-wet and placed upon SAW device for protein extraction and atomization. Atomized protein aerosols were collected for subsequent protein-electrophoresis to see if degradation occurred. At this stage, we used Experion™ Automated Electrophoresis System (Pro 260, Bio-Rad, USA) as test platform.

III. RESULTS AND ANALYSIS

A. Self-pumping effect of SAW

The self-pumping effect of SAW makes it possible to use a filter-paper strip embedded capillary tube for delivering continuous liquid flow to the atomizer surface automatically [12]. Fig. 3 shows the liquid inside the filter paper being pulled out towards the SAW for atomization. Specifically, when the thickness of the liquid is similar to or less than the wavelength of excitation wave in liquid, Schlicting streaming [15,16] is dominant by driving the fluid motion via viscous shear, which appeared to pull liquid out of paper towards the SAW, as shown in Fig 3 (a). On the other hand, when the liquid

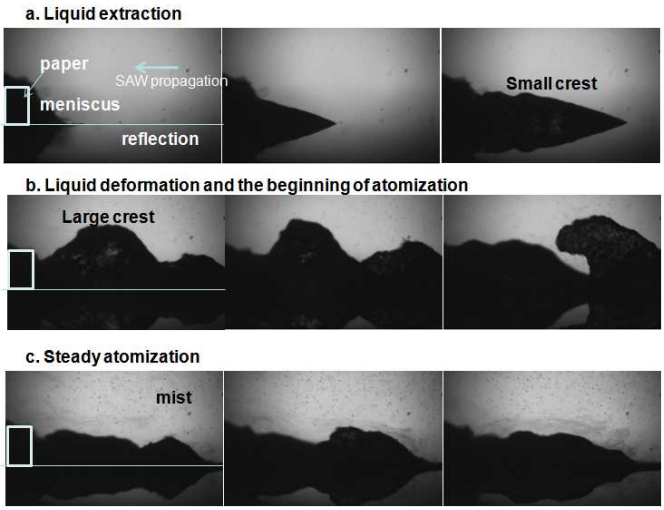

Figure 3 Atomization of fluid supplied by paper over time, The small box on the left indicateds the position of the paper strip. Images in a show that, at the beginning of the excitation, liquid was pulled out from the paper towards the SAW because of Schlichting streaming. Images in b show the large liquid deformation because of Eckart streaming when the amount of liquid was accumulated at the tip of paper. As atomization starts, as shown in c, liquid was consuming by atomization and the amount of liquid was kept at an almost constant volume. The time between each snapshot in each group is 49 ms.

thickness becomes several time larger than the excitation wavelength, the force in the normal direction builds up inside the liquid due to Eckart streaming [15,16] which deforms the liquid perpendicularly to the SAW device surface, as shown in Fig 3 (b). During this process, capillary waves on the free surface of the liquid became destabilized and subsequently broke up into aerosols; atomization started. As shown in Fig 3 (c), steady atomization consumes liquid while Schlicting streaming pulling liquid out of paper. When the flow rate of the liquid flowing out of paper matched the atomization rate, the volume of free liquid in the meniscus remained almost constant and steady. Continuous aerosols were therefore generated from the capillary surface of the meniscus.

B. Aerosol size distribution

As suggested by equation (1), the aerosol size distribution is governed by the following factors, ratio of surface tension-viscosity (γ/μ), capillary resonant frequency (f_c) and parent liquid drop/film characteristic length ratio (H/L). According to our previous work, f_c was found to be in 10 kHz order due to capillary-viscous damping [10], and H/L was close to the paper strip thickness [12]. Therefore, the ratio of γ/μ is the most important factor that affects the aerosol size distribution.

Fig. 4 shows the size distribution of two liquids: octanol and water. If assuming the octanol drop and water drop have similar shape while being atomized, octanol, with lower surface tension and higher viscosity compared to water, shows a smaller size distribution, proving our theory as above.

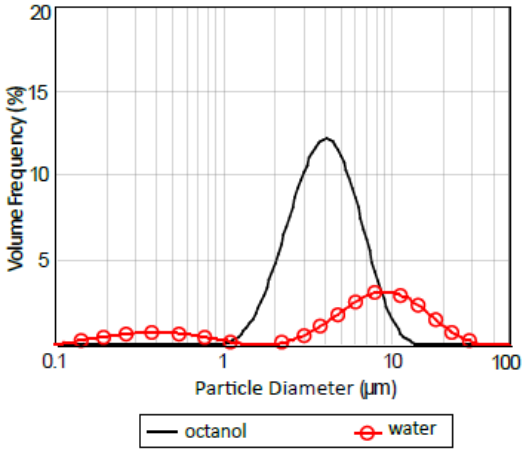

Figure 4 Size distributions of octanol aerosols and water aerosols generated by SAW atomization.

C. Protein extraction and atomization through paper

To examine the biocompatibility of this SAW atomizer, protein molecules BSA and ovalbumin were used as the model drug to perform protein-electrophoresis *pre* and *post* SAW atomization. Fig. 5 is the virtual gel-electropherogram generated by the Experion^{TM} Automated Electrophoresis System. Specifically, the first column on the left is the Ladder indicating protein sizes ranging from 10 kDa─260 kDa. Columns A and C are the original protein (BSA and ovalbumin) before the SAW extraction-atomization process, while columns B and D represent protein molecules after the SAW extraction-atomization process. Bands showing above the original size (larger size) suggest the aggregation of molecules while bands showing below the original size (smaller size) indicate the degradation of the protein molecules. Clearly, while there are certain amount of aggregation which may due to the high concentration of the solution, there is no visible band showing below the original size, indicating no obvious degradation.

The data in Table I provide detailed data from this experiment: molecular masses and the degradation ratios.

Table I	Molecular Mass (kDa)	Degradation (%)
BSA control	71	-
BSA post-atomization	75.3±0.1	0.4±0.3
Ovalbumin control	44.0	-
Ovalbumin post-atomization	45.3±0.3	0.8±0.4

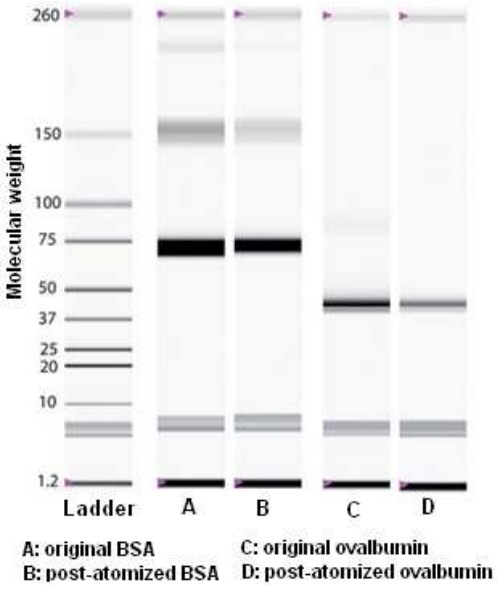

Figure 5 Protein electrophoresis of BSA and ovalbumin before and after SAW atomization.

Clearly, the degradation here is negligible (<1%) which indicates this is a safe process for biomolecules thus has great potentials in biomedical applications, such as drug delivery, biomolecules transportation and recollection, etc.

IV. Conclusions

In this paper, we have demonstrated a novel technology of using surface acoustic wave (SAW) as the excitation wave to drive rapid and efficient atomization. The SAW atomizer is small and light-weighted, attractive for many applications, especially for pulmonary drug delivery and biomicrofluidics. The system was further improved by employing a paper-capillary tube based liquid supply system. Because of the self-pumping effect, liquid can be drawn to the SAW device surface for continuous atomization automatically which is attractive in making the system as an independent pump-free system.

The aerosol size distribution is important in evaluating the performance and efficiency of the atomization. We have found that, the aerosol size is irrelevant to the driving frequency, but governed by the capillary vibration frequency given by the balance between the acoustic forcing and capillary stress. In another words, there are three factors that affect the aerosol size: the ratio of surface tension-viscosity (γ/μ), capillary resonant frequency (f_c) and parent liquid drop/film characteristic length ratio (H/L).

Protein-electrophoresis was performed to examine the protein molecules *pre-* and *post-* atomization. Results suggest the protein degradation is below 1% after the SAW extraction-atomization process. Therefore, this presented technology is safe for handling biomolecules and has great potential to be applied in biomedical applications.

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