

# Ultrasonic Atomization Using Silicon-Based High-Frequency Multiple-Fourier Horn Nozzles\*

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**Abstract**—This paper reports on atomization using micro-fabricated silicon-based high frequency ultrasonic nozzles of a novel design. The nozzle is made of a piezoelectric drive and a silicon-resonator consisting of multiple Fourier horns with a central channel for liquid flow. Such a nozzle has a number of advantages over conventional metal-based ultrasonic nozzles such as MEMS-based micro-fabrication technology for mass production, much higher ultrasonic frequency, and much lower electric drive power requirement. It operates at the design resonance frequency with narrow bandwidth and is, thus, capable of producing monodispersed droplets. Potential applications include nanoparticles synthesis and use in pocket-size nebulizers for alveolar delivery of medicines.

**Keywords** - ultrasonic atomization; Fourier-horn nozzles; monodisperse drops; Silicon-based; MEMS

## I. INTRODUCTION

Atomization (spray) is the breakup of a volume of liquid into drops, resulting in a dramatic increase in the surface area available for heat and mass transfer in solvent evaporation and chemical reactions. Ultrasonic atomization (liquid atomization by ultrasound alone) and two-fluid atomization (liquid atomization by high velocity air) are commonly used in industrial applications including combustion, spray coating, spray drying, and spray pyrolysis. Two-fluid atomization has the advantage of high throughput, but also has the disadvantage of broad drop-size distribution. In contrast, the drop-size distribution generated by conventional ultrasonic atomization is much narrower [1, 2]. Also, ultrasonic atomization involves Taylor-mode jet breakup (different from Rayleigh-mode jet breakup in ink-jet printing). Because the drop diameter resulting from Taylor-mode jet breakup is much smaller than the channel (orifice) diameter; the nozzle is less prone to channel plugging.

Conventional ultrasonic atomization utilizes either a metal-based bulk-type nozzle with a piezoelectric transducer isolated from the liquid or a nebulizer with a transducer disk in direct contact with the liquid. Because of manufacturing difficulty, the highest frequency of the former that is commercially

available is 120 kHz, which yields water sprays with a peak drop diameter of 55 $\mu$ m [1, 3]. Ultrasonic nebulizers are commercially available at frequencies ranging from 180 kHz to 2.5 MHz. They basically consist of a piezoelectric transducer disk to provide a vibrating solid surface that is in direct contact with the liquid to be atomized and an electroformed mesh or baffle to filter out large drops [4]. Without the mesh or baffle, the drop size distribution is very broad with a geometric standard deviation (GSD) of 1.6 or larger. Furthermore, because the transducer is in direct contact with the liquid to be atomized, nozzle performance degrades rather quickly over time or no atomization takes place at all.

Silicon-based ultrasonic nozzles, first realized using MEMS technology at 74 kHz [5], possess a number of advantages over conventional metal-based bulk-type ultrasonic nozzles such as potential for mass production using MEMS technology and the ultrasonic frequency far exceeding the 120 kHz limitation of the bulk-type ultrasonic nozzles. Ultrasonic frequency much higher than 120 kHz is required for production of drops <10  $\mu$ m in diameter. Drops <10  $\mu$ m are highly desirable because they can be processed at much lower temperatures and atmospheric pressure, allowing efficient production of nanoparticles. Also, monodispersed drops <10  $\mu$ m of expensive medicines are particularly desirable because they allow efficient target delivery and alleviate side effects resulting from excess dosage of undesirable drop sizes. Other potential applications of such high-frequency nozzles include 3-D spray coating for micro electronics, and interfacing with micro-fluidic on-chip reactions.

## II. EXPERIMENTAL SETUP

The MEMS-based silicon ultrasonic nozzle is made of a piezoelectric drive section and a silicon-resonator consisting of multiple Fourier horns with a central channel 200  $\mu$ m x 200  $\mu$ m for liquid flow as shown in Fig. 1 [6]. Each horn is of half-wavelength design with a vibration amplitude magnification of

two at the horn tip. 3-D simulation was carried out using the commercial ANSYS program [7, 8]. The simulation results and the dimensions for the 0.5 MHz 3-Fourier-horn nozzle used in the atomization experiment are also shown in the figure. Specifically, a pure longitudinal vibration occurs at the resonant frequency of 495 kHz. At this resonant frequency, the vibration amplitude gain at the nozzle tip is equal to the theoretical value of  $2^3$ .

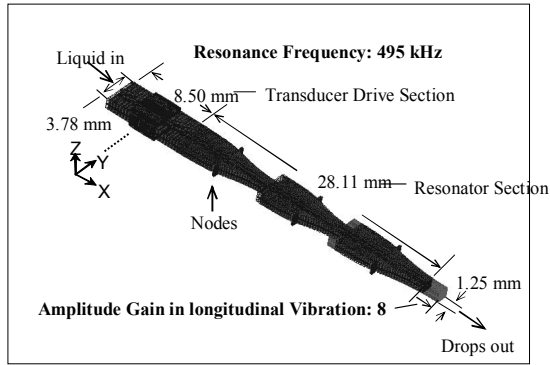


Fig. 1 Dimensions and 3-D simulation results on the amplitude gain at the nozzle tip of a silicon-based 3-Fourier-horn 0.5 MHz ultrasonic nozzle.

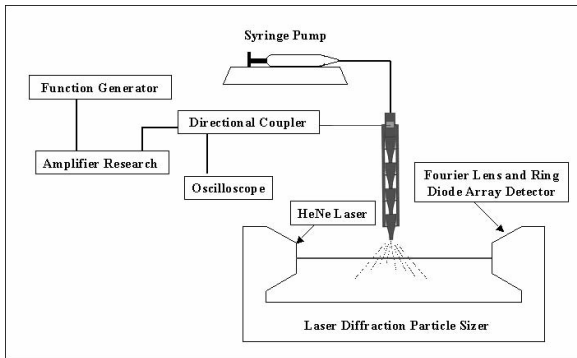


Fig. 2 Schematic diagram of the atomization setup.

A schematic diagram of the atomization setup is shown in Fig. 2. Major components of the setup are: (1) a PZT drive system to provide an alternating current (AC) electrical signal to the Si-based ultrasonic nozzle, (2) a Syringe Pump to provide a constant liquid flow rate, and (3) a Malvern Particle Sizer for analysis of drop sizes and size distribution. As shown in the figure, the pair of PZTs of the nozzle is driven by the AC electrical signal.

### III. RESULTS AND DISCUSSION

#### A. Atomization Results

As water (the liquid to be atomized) is pumped, at a constant flow rate ranging from 10 to 200  $\mu\text{l}/\text{min}$ , into the central channel of the nozzle, a curved thin liquid film is maintained at the nozzle tip that vibrates at the resonant frequency of 484.5 kHz, resulting in formation of standing capillary waves on the free liquid film surface [9, 10].

Temporal instability of these standing capillary waves sets in as the tip vibration amplitude exceeds a threshold [11], and a spray of droplets (mist) is produced as shown in Fig. 3. The required drive electrode voltage is set as low as 5.5 V. In contrast, a liquid drop forms at the nozzle tip, but no atomization takes place when the frequency of the drive electrode voltage differs by 2.0 kHz from the resonant frequency. We believe that the narrow bandwidth of the resonant frequency for atomization leads to production of monodispersed droplets with GSD of only 1.1 as shown in Fig. 4. In fact, over 83% of the droplets measured by laser diffraction technique (Malvern Particle Sizer) are 7.0  $\mu\text{m}$  in diameter. This measured drop diameter ( $D_p$ ) is in good agreement with the 6.7  $\mu\text{m}$  diameter predicted by the capillary wave atomization mechanism [9-11]:  $D_p = 0.34\lambda$ , where the capillary wavelength  $\lambda$  is determined by the Kelvin equation,  $\lambda = \sqrt[3]{8\pi\sigma/(\rho f^2)}$ , with  $f$ ,  $\sigma$ , and  $\rho$  being the ultrasonic frequency, the surface tension and the density of the liquid, respectively.

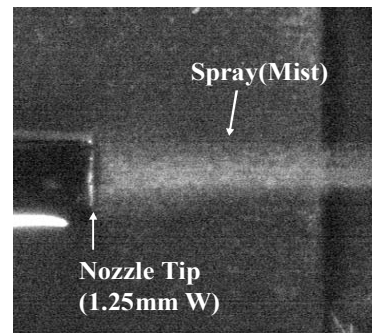


Fig. 3 Stable atomization of water using a Si-based 3-Fourier horn nozzle (nozzle tip 1.25 mm wide and 1.06 mm thick, see Fig. 1 for horn geometry) at the resonant frequency of 484.5 kHz and drive voltage of 5.5 V.

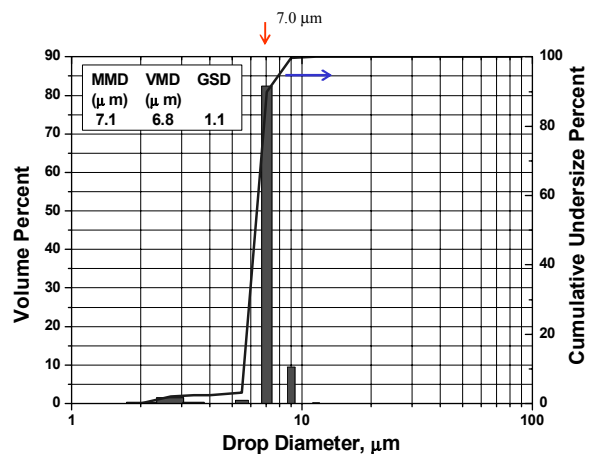


Fig. 4 Drop-size distribution of ultrasonic atomization of water using a 3-Fourier horn 0.5 MHz nozzle.

Similar results were also obtained in water atomization using a 4-Fourier horn 0.3 MHz nozzle except the drop-size distribution as shown in Fig. 5 is slightly broader. Whether or the broadening of drop-size distribution is caused by the reduced resonant frequency (288.5 kHz versus 484.5 kHz) is under investigation.

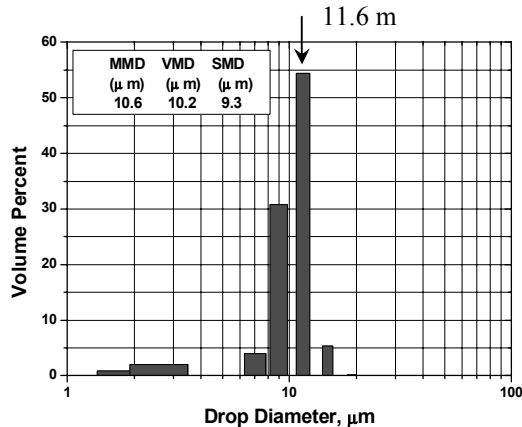


Fig. 5 Drop size distribution of water atomization using a 4-Fourier horn 0.3 MHz nozzle.

#### B. Comparison with Commercial Ultrasonic Nebulizers

For comparison, the drop-size distribution of water atomization using a commercial ultrasonic nebulizer (Model NE-U22V, Omron, Vernon Hill, IL) was also measured using the Malvern Particle Sizer. The Omron ultrasonic nebulizer utilizes a mesh with a 2-D array of openings approximately 20 $\mu\text{m}$  in diameter. The mass median diameter (MMD) and geometric standard deviation (GSD) obtained are as large as 10.0  $\mu\text{m}$  and 1.6, respectively. Furthermore, compared to the drop-size distribution obtained by the 0.3 MHz multiple-Fourier horn nozzles, a much larger percentage (25% versus 5% as in Fig. 5) of the droplets are larger than 11.6  $\mu\text{m}$ . Clearly, the MEMS-based Multiple-Fourier horn ultrasonic nozzles produce a much narrower drop-size distribution than the commercial ultrasonic nebulizers.

#### IV. CONCLUSIONS

Monodispersed droplets are produced for the first time in ultrasonic atomization via use of MEMS-based 3-Fourier horn MHz silicon nozzles. The measured droplet diameter is in good agreement with that predicted by the capillary wave atomization mechanism, and unequivocally verified the Kelvin equation with the Lang's constant of 0.34 at MHz ultrasonic frequencies. The size uniformity of droplets produced enable the MEMS-based multiple-Fourier horn MHz ultrasonic nozzles for potential applications to spray pyrolysis for nanoparticles synthesis, spray coating of polymers and bio dispersions for nano- and micro-electronics processing, drug preparation, and pulmonary drug delivery.

#### ACKNOWLEDGMENT

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