

# An Electrostatically Actuated MEMS Fuel Injector to Enhance Low-Pressure Atomization

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Performance and reliability are primary drivers for military aircraft engine design. However, more stringent environmental regulation will require future engines to have lower emissions as well. It will be challenging to improve the flammability and combustion efficiency while reducing emissions. Modern high performance liquid-fueled combustors typically operate at high space heat release rates, requiring that the fuel be rapidly atomized, evaporated and mixed with the oxidizer. Finely atomized fuel droplets evaporate quickly (even if it is a low vapor pressure fuel like JP-8), thereby reducing the amount of unburned hydrocarbons. Unfortunately, current gas turbine atomizers produce many large droplets. Therefore, microelectromechanical or MEMS atomizers were developed to promote droplet breakup during low-pressure atomization. In our tests we measured Sauter-mean diameters as small as 14  $\mu\text{m}$ .

## Nomenclature

f	=	frequency
h	=	fluid gap height
H	=	wind tunnel height
MEMS	=	microelectromechanical systems or structures
$\Delta p$	=	pressure drop
Re	=	Reynolds number = $\frac{\rho u h}{\mu} \Big _{\text{liquid}}$ or $\frac{\rho u H}{\mu} \Big _{\text{air}}$
$d_{3,2}$	=	Sauter-Mean Diameter (SMD)
$t_s$	=	thickness
u	=	velocity
We	=	Weber number = $\frac{\rho_{\text{air}} (u_{\text{liq}} - u_{\text{air}})^2 h}{\sigma}$
X	=	liquid sheet breakup length
$\lambda_{\text{opt}}$	=	optimal wavelength
$\mu$	=	viscosity
$\rho$	=	density
$\sigma$	=	surface tension

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## I. Introduction

Given the droplet size needed to improve combustor performance, the use of inkjet based printer technology comes to mind. Inkjet printer technology is based on the ability to eject small single droplets on demand at repetition rates high enough for fast printing. This is achieved by building print heads with multiple injectors; each individually addressable and electrically actuated. The injector nozzle size determines the droplet diameter, which is typically  $\sim 20\text{-}40\ \mu\text{m}$  in the printing application. The injector nozzle geometry can be tailored specifically to produce droplets in the desired size range. As we will discuss later, these microscale flows are typically laminar, and droplet formation is driven by the Rayleigh breakup mechanism. Therefore, droplet size scales approximately with the minor dimension of the injection nozzle.

Our atomizer shown in Figure 1 is similar in concept, but not in design, to electrostatically actuated inkjet print heads. As previously reported [1-4] our design uses a double acting diaphragm, with an injection cavity on both sides. The diaphragm (shown as a black line in the figure) is the grounded electrode and the semi-conducting chips (gray bars) form the activated electrodes. DC-DC step up voltage converters provided the needed source voltage to actuate the atomizer diaphragm. Dielectrics (depicted by the yellow lines on the gray bars) prevent voltage breakdown during activation. A manifold delivers fuel through fluidic check valves to the chamber. After exiting the nozzle, the expelled fuel forms a liquid sheet that breaks up into small droplets.

The nozzle geometry plays a key role in droplet formation. In the gas turbine smaller drops allow CO and  $C_xH_y$  emissions to be reduced, since finely atomized sprays are expected to burn more completely. In any case the droplet size and distribution remain important to achieving the desired performance. Therefore, droplet breakup analysis was crucial to understanding the mechanisms leading to droplet breakup and the role that they will play at the micro scale.

In general there are three modes of sheet disintegration; rim, perforated sheet and wave [5]. Viscous fluids tend to breakup via rim disintegration where the surface tension forces at the edge of the sheet contract it into a thick rim, which forms large droplets (Figure 2). A liquid sheet can also be stretched to the point that small holes appear, enlarge and break the sheet into threads (perforated sheet disintegration). The threads then break up into small droplets. Lastly, wave motion disintegration of a thin sheet of fluid begins with instabilities that cause a portion of the sheet to tear away (Figure 3). Surface tension forces then contract and roll the sheet into ligaments, which fairly quickly disintegrate into droplets. In our atomizers thin sheet disintegration occurs through either rim or perforated sheet disintegration depending on the flow conditions.

Just as the droplet size is proportional to the jet diameter for Rayleigh breakup, research has shown that the Sauter-mean diameter is proportional to  $t^{0.4}$  for mm-thick sheets [6]. While macro-scale derived correlations may not apply to  $\mu\text{m}$ -thick sheets, data at the micro-scale was not found. Therefore, the empirically derived expression for droplet size (Equation 1 from [6]) was used for analysis.

$$d_{3,2} = 0.071 \left( \frac{t_s X \sigma \mu^{0.5}}{\rho^{0.5} u_{liq}^2} \right)^{1/3} \quad \text{with } X = 0.123 t_s^{0.5} We^{-0.5} Re^{0.6} \quad (1)$$

Based on this correlation very small droplets appear feasible when using microscale devices. Previous researchers have studied the effect of forcing at the macroscale and have shown the preferred mode frequency for sheet breakup to be approximately (Equation 2 from [6]).

$$f = \frac{u_{liq}}{\lambda_{opt}} \quad \text{where } \lambda_{opt} = \frac{4\pi\sigma}{\rho_{air} (u_{liq} - u_{air})^2} \quad (2)$$

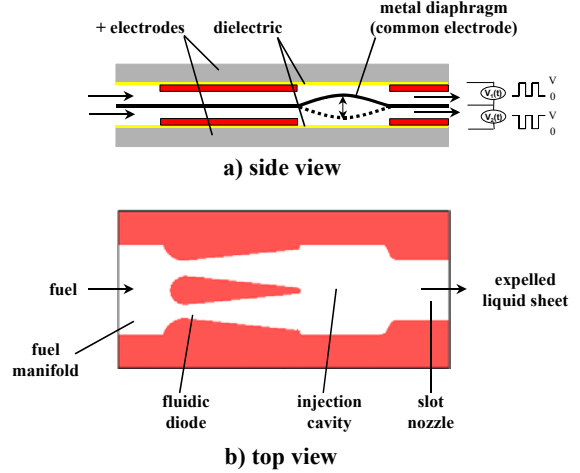
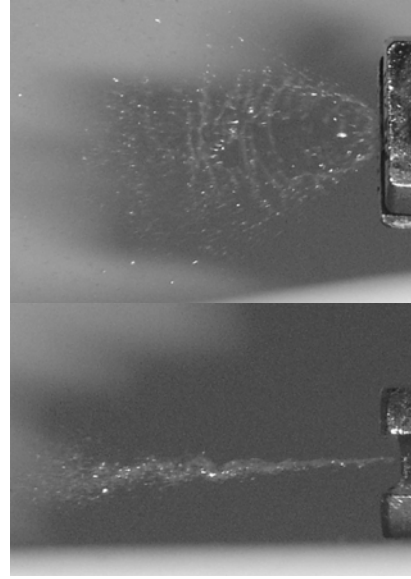


Figure 1. Double acting diaphragm pump configuration and flowpath details.

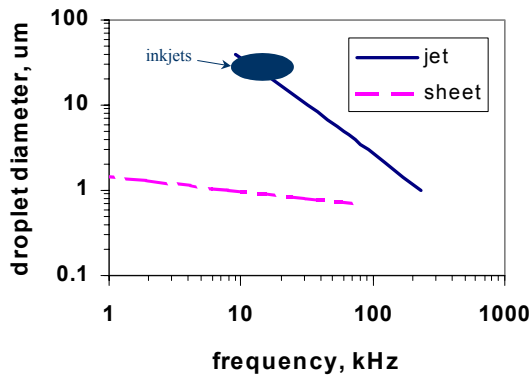


**Figure 2. Rim disintegration of JP-8 fuel.**



**Figure 3. Wavy sheet disintegration of water.**

Rearranging Equation 2 to solve for  $u_{liq}$  and substituting back into Equation 1 gives us an expression for droplet diameter that depends on frequency. Using this we found that the preferred mode frequencies of a liquid sheet are considerably lower than those for a laminar jet given the geometries and flow conditions needed to produce the same droplet size (Figure 4). Thus, forcing at the preferred mode frequency appears very attractive to enhance liquid sheet breakup into micron size droplets when one considers the frequencies needed to excite liquid jets. The analysis assumed 0.5 to 21  $\mu\text{m}$  liquid jet diameters and a 2.0  $\mu\text{m}$  thick liquid sheet (thicker sheets produce larger droplets). Further, the air cross-flow velocity was varied from quiescent conditions to the subsonic velocities typical in an aero-engine inlet.



**Figure 4. Relationship of droplet size to the preferred mode frequency for jets and thin sheets.**

## II. MEMS Atomizer Fabrication

Our electrostatically actuated MEMS atomizer designs were etched into silicon carbide (SiC); a thermal and oxidation resistant ceramic. Atomizer fabrication required a controlled etch of the lithographically patterned SiC wafer to create the flowpath features. A photo mask was placed directly on the photoresist-coated SiC wafer using a Karl Suss MJB3 mask aligner. The wafer was exposed to UV light and subsequently etched to pattern the photoresist. The patterned photoresist layer was then used to pattern a vapor deposited nickel layer. An acetone

bath lifted-off the unwanted nickel as the sacrificial photoresist layer was dissolved. Finally, we reactive ion etched (RIE) the patterned features to the desired depth with a Plasma-Therm model 540.

### III. Laboratory Setup

TDA measured the JP-8 fuel droplet expulsion characteristics of fabricated MEMS atomizers using both open-air and Malvern MasterSizer S particle analyzer setups (Figure 5). We used a Sony TR7 8mm video camera and a Nikon D-1 digital camera to record images of the ejection and breakup process. We used a Malvern MasterSizer S with a 300 mm range lens for the forward scattering measurements. The Malvern system uses a He-Ne laser to image the spray field. The MasterSizer S particle size analyzer assumes MIE scattering of light from spherical droplets. The intensity of diffracted light is measured by a ring diode array. The intensity spectrum can be correlated to droplet size, since small droplets diffract light at large angles and vice-versa. In these experiments the fuel Reynolds number was varied from 8 to 160 and the Weber number was as high as 0.5 for injection into quiescent air.

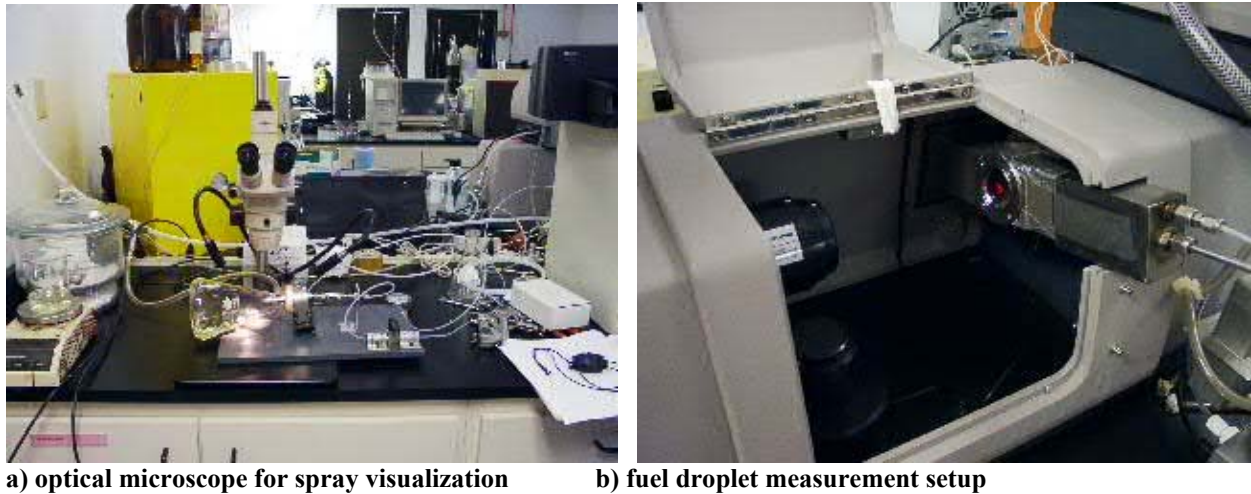


Figure 5. Spray characterization setups.

We measured droplet distributions of instream injection into a wind tunnel using the laboratory setup shown in Figure 6. It was designed for installation into the Malvern MasterSizer. The air inlet was attached to an air compressor capable of delivering flow velocities up to 100 m/s in the test section. JP-8 fuel was supplied to the atomizer from a positively pressurized fuel tank. The atomizer axial position was adjusted by sliding the fuel line in and out as desired. The SwageLok compression fitting locked the atomizer into position. Although not shown the atomizer was supported by an aerodynamic strut. The industrial actuation control electronics are shown in the foreground.



Figure 6. Laboratory wind tunnel setup for droplet size measurements.

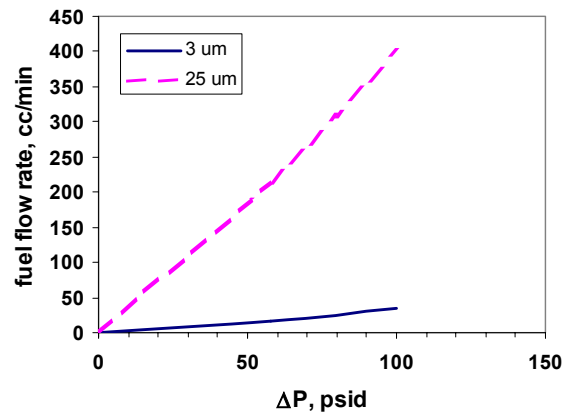


Figure 7. Measured flow rates for MEMS SiC and demonstrator atomizers.

Positive pressurization of the fuel tank delivered fuel to the atomizer. A two-stage filtering process removed particulates down to  $0.5\ \mu\text{m}$ . We measured the expelled fuel mass from the atomizer nozzle over a known time interval at supply pressures from 0 to 100 psi. The measured flow rates of single atomizing elements with 3 and  $25\ \mu\text{m}$  high slot nozzles are shown in Figure 7.

#### IV. Experimental Results

Liquid spray atomization tests were conducted in quiescent air and wind tunnel environments. For the static or unforced case the liquid sheet from two stacked  $25\ \mu\text{m}$  high slot nozzles was bifurcated into two fairly large round jets by the rim breakup mechanism (Figure 8a). These large jets formed roughly  $800\ \mu\text{m}$  diameter droplets. When actuated or forced, the breakup mechanism appears to be the perforated sheet mechanism as described by Williams [5]. The liquid sheet was torn and splintered into multiple small threads, which formed much smaller droplets than for the unforced case.

A Malvern Mastersizer S was used to measure droplet size distributions from our MEMS atomizers in low speed air flows ( $\leq 20\ \text{m/s}$ ). Two atomizers were tested; one with  $3\ \mu\text{m}$  high slot nozzles and the other with  $25\ \mu\text{m}$  high slot nozzles. When actuated, we see a large decrease in the volume contained in large droplets with a corresponding increase in smaller droplets (Figures 9 and 10). The MEMS atomizers formed droplets as small as  $10\ \mu\text{m}$  concurrent with a substantial reduction or even elimination of large droplets when forced. As fuel pressure was increased the droplet size was also substantially reduced (Figure 10a and b). Note that at high air flow velocities the effect of forcing was reduced (Figure 10b and c), since the aerodynamic forces dominated the liquid sheet breakup process. The advantage of very thin sheets is evident for all flow conditions, but for the present devices forcing was most effective when aerodynamic forces were small.

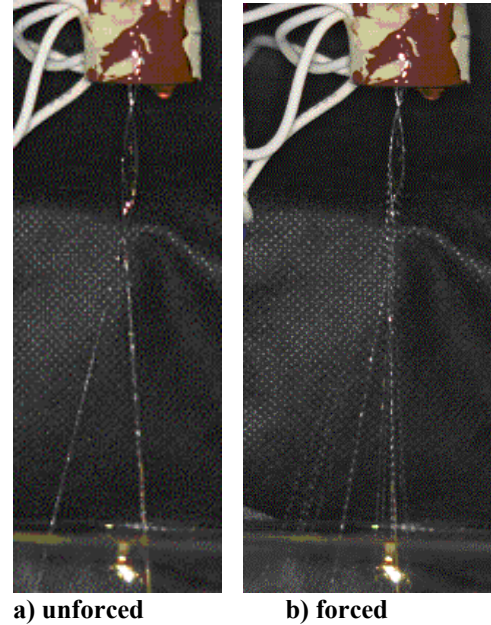


Figure 8. Liquid sheet breakup mechanisms leading to droplet formation at low pressure; a) rim mechanism and b) perforated sheet mechanism for an approximately  $50\ \mu\text{m}$  thick sheet expelled from a MEMS slot nozzle atomizer.

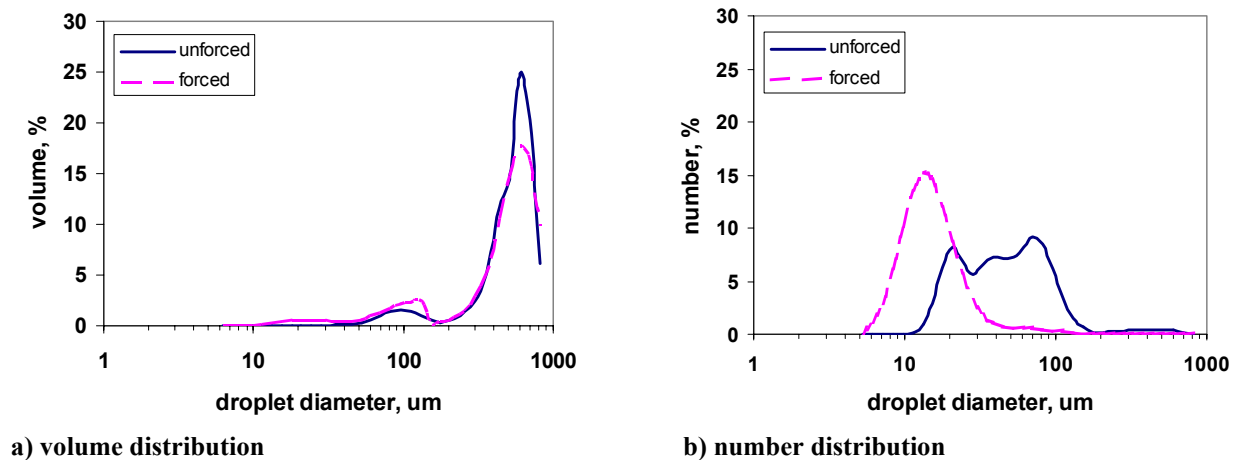


Figure 9. Droplet size distribution results for the MEMS atomizer w/  $3\ \mu\text{m}$  high slot nozzle; 75 psi fuel pressure and  $4.8\ \text{m/s}$  air flow velocity.

## V. Conclusions

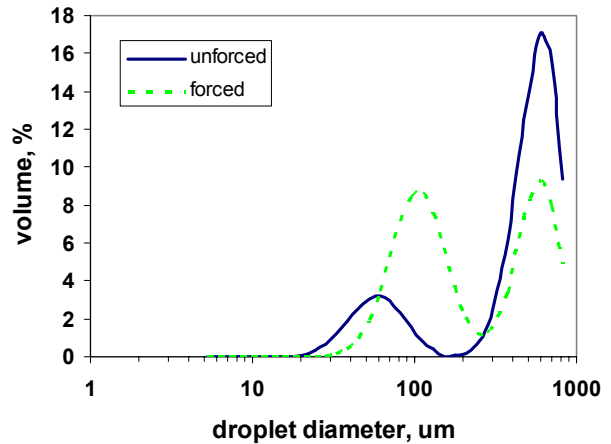
Flow visualization and droplet size measurements of JP-8 liquid sprays showed the ability of our atomizer to significantly improve low-pressure atomization. Upon MEMS atomizer actuation the liquid sheet perforated to form small threads of roughly the same diameter as the liquid sheet thickness. These threads or jets then broke up into droplets about 2X the diameter of the jet according to the Rayleigh mechanism. At some test conditions we achieved Sauter-mean diameters as low as 14  $\mu\text{m}$  with all droplets less than 40  $\mu\text{m}$  in diameter.

## Acknowledgments

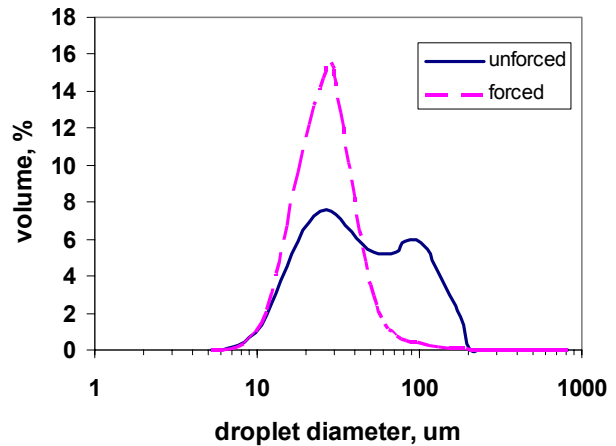
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## References

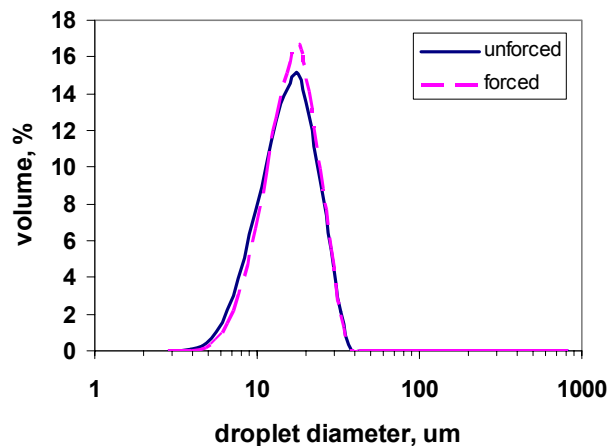
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a) 11 psi fuel pressure, 4.8 m/s air flow velocity



b) 40 psi fuel pressure, 4.8 m/s air flow velocity



c) 40 psi fuel pressure, 20 m/s air flow velocity

Figure 10. JP-8 droplet size distribution results for a MEMS atomizer w/ 25  $\mu\text{m}$  high slot nozzle.