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## VELOCITY-MODULATION ATOMIZATION OF LIQUID JETS

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**SUMMARY** A novel atomizer based on high-amplitude velocity atomization has been developed. Presently, the most common methods of atomization can use only the Rayleigh instability of a liquid cylinder and the Kelvin-Helmholtz instability of a liquid sheet. Our atomizer is capable of atomizing liquid jets by the excitation and destabilization of many other higher-order modes of surface deformation. The potential benefits of this sprayer are more uniform fuel air mixtures, faster fuel-air mixing, extended flow ranges for commercial nozzles, and the reduction of nozzle plugging by producing small drops from large nozzles. The piezoelectric driver can be included into schemes for feedback control of combustion instabilities. To create this atomization by high-order modes, we excite the jet both spatially and temporally. We exploit the mathematical similarity between a compressible gas and a liquid jet to create steepening of the waves on the liquid jet. If the applied velocity perturbation is sufficiently large, the pulse steepens into a form of shock and atomization occurs. The temporal excitation of the fluid jet is created by a piezoelectric driver. The spatial excitation of the fluid jet is created by placing perturbations in the perimeter of the electroformed nozzle that forms the jet. No electrostatic force or air supply is used. The atomization of many liquid jets in the forms of cylinders, sheets, cones, and rectangles has been observed. Quantitative measurements of the sprays from several of these electroformed nozzles and the spray from a commercial conical nozzle have been made. The spray from a commercial nozzle can be drastically altered, with respect to the wavelength of the drop clusters and the spatial distribution of the fluid mass. Sprays from circular nozzles have a Sauter mean diameter less than half the jet (equivalent) diameter. A rectangular orifice requires lower electrical power to generate a spray than a circular orifice. The sprayer has been used with flow rates from .06 ml/min. to 30 gallons/hr. Sprays with a Sauter mean diameter of This atomizer is suitable for both fundamental studies and practical applications.

**DISCUSSION** Many types of drop generators and sprayers have been developed for diverse applications such as ink-jet printing, calibration standards, agricultural spraying, spray drying, and combustion. These drop generators use many methods for creating

the spray such as air-blast, electrostatic forces, electromechanical vibrations, mechanical shutters, and impact of the fluid with a wall or another fluid jet. Most commonly sprays are formed using pressure nozzles that create a cone or sheet of fluid which atomizes due to contact with the surrounding air. Two naturally occurring instabilities that are frequently seen in spray formation are the Rayleigh capillary instability and the Kelvin-Helmholtz instability [1,2,3]. The Rayleigh instability is the sausage or varicose instability, driven by surface tension, that appears on a cylinder of fluid. The Kelvin-Helmholtz instability is the flag-flapping instability and it is driven by the difference in velocities of a fluid sheet and the surrounding air. The Kelvin-Helmholtz instability usually breaks the sheet into ligaments which then break into drops by the Rayleigh instability.

The problem with the Rayleigh instability is that the drops that form are usually twice the diameter of the initial fluid cylinder. To obtain small drops, a smaller cylinder must be formed.

The Kelvin-Helmholtz instability is commonly used by pressure-swirl atomizers [4] to produce fuel sprays for combustion. The instability causes the sheet to flap; consequently, the droplets tend to be concentrated in packets (or clusters), thereby making the spray spatially and temporally nonuniform [5]. The combustion of these clusters can lead to periodic variations in the heat-release rate and pressure in the combustor and, in turn, may result in various combustion problems such as combustion roar, combustion-driven oscillations, various pollutants formation, and even lower combustion efficiency.

**POTENTIAL ATOMIZATION TECHNOLOGIES** Rose [6] published photographs that show unstable, star-shaped, higher-order magnetohydrodynamic modes on a cylindrical plasma. Chandrasekhar [3] shows the similarity between these unstable modes on cylindrical plasmas and stable modes on liquid cylinders. Electrohydrodynamic and magnetohydrodynamic instabilities of liquid jets [7] and liquid sheets have been studied because of their similarity to magnetohydrodynamic instabilities in plasma containment devices for thermonuclear power generation. The idea was to sense the instability, in both space and time, and create a drive signal, in both space and time, that eliminates the liquid instability.

Another potential concept for atomization is shock formation. Shapiro [8], in his video lecture series, explains how waves propagating along a cylindrical jet of liquid are mathematically similar to waves propagating in a compressible gas. One can therefore look at a cylindrical liquid column as analogous to a compressible gas, with the pressure-density relationship for the gas replaced by a pressure-radius relationship for the jet.

Several papers describe the application of large perturbations to liquid jets and the atomization resulting from the steepening of the pulse front. By dropping a weight, Dunne and Cassen [9] probably were first in creating what may be described as a shock on a cylindrical jet and creating a spray. Others have used magnetic drivers to improve the shock forming process [10,11].

For our approach to atomization, we reverse the control process used in the earlier research and apply a drive signal in space and time to make the fluid jet unstable. Our temporal drive signal is sufficiently large that the pulse steepens into a discontinuity that atomizes the jet. We can drive the fluid cylinder unstable in the higher modes which Rose showed to be unstable on a cylindrical plasma.

**DROP GENERATOR CONSTRUCTION** The key development of this project has been the design of the piezoelectric driver which produces large velocity perturbations on the liquid jet [12].

The high-amplitude velocity-modulation atomizer assembly, shown in Figure 1, and described in detail [13], consists of a piezoelectric crystal driver in a circular fluid manifold with an orifice plate across the end of the manifold. The model of the current atomizer contains four functional elements:

- (1) the piezoelectric transducers which receive the electrical signal and convert it to mechanical motion,
- (2) a mechanical structure that amplifies the motion produced by the transducers,
- (3) a pump that converts the amplified mechanical motion to a pressure perturbation in the working fluid, and
- (4) a nozzle that creates a fluid stream whose velocity is modulated by the pressure perturbation.

The mechanical structure is a resonant device which can exhibit large mechanical deflections at specific resonant frequencies. At these resonant frequencies, the current and voltage to the piezoelectric transducer are in phase; thus, energy loss is minimized. Unlike other ultrasonic atomizers that have fluid manifolds designed to be resonant at the operating frequency, the pump in this device does not have a resonance at the operating frequency.

**NOZZLE CONSTRUCTION** We use a photofabrication process to form nozzles of practically any shape or size. We have made circular nozzles as small as 12 microns in diameter. We have also made rectangular nozzles which contain width perturbations. Better atomization is obtained if the nozzle perimeter has perturbations placed on it.

These perturbations provide initial conditions for the high-order modes which can then be driven to create the jet instabilities.

**QUANTITATIVE TESTS** Takahashi has made quantitative measurements of the sprays produced by photofabricated nozzles [14] and also from a commercial cone nozzle [15]. He found that with a round nozzle, the spray had a Sauter mean diameter less than half the jet diameter. Less electrical power was required to create sprays from a rectangular nozzle than from a circular nozzle. The range of flow rates which gave acceptable atomization from a commercial nozzle was extended and the spatial distribution of the spray was expanded.

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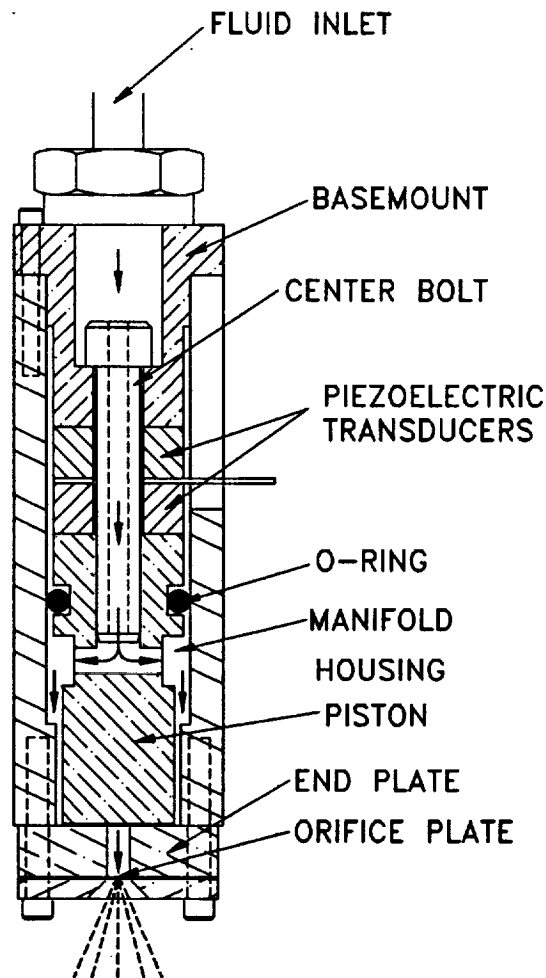


Figure 1: Schematic of the high-amplitude velocity-modulation atomizer.