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DYNAMIC RESPONSE OF FUEL NOZZLES FOR LIQUID-FUELED GAS TURBINE COMBUSTORS

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BREAK

ABSTRACT

To imitate resonances that might occur in the fuel delivery system of gas turbine combustors, the incoming liquid streams of two pressure swirl nozzles were perturbed using a piezoelectric driver. Frequencies of perturbations examined were from 3 to 20 kHz, and water was used as the test fluid. A video camera and a Phase Doppler Particle Analyzer (PDPA) were used to study the effect of perturbations on the mean flow quantities of the sprays. Various lighting arrangements were used for the video photography: back lighting, front lighting, a strobe synchronized with the input to the piezoelectric, and a laser sheet oriented along the midplane of the sprays.

The study showed that the piezoelectric drive had an effect on the spray system at discrete frequencies. At these particular frequencies, by increasing the input voltage, it was found that the piezoelectric drive affected the atomization in the following ways: (1) the mean flow rate decreased, (2) the spray cone angle decreased, (3) the break up length decreased, (4) the peak of the spatial distribution of the mean droplet size decreased, and (5) the mean droplet sizes and velocities increased near the spray center line and decreased in the outer region of the spray. A hysteresis effect of the drive frequency on the spray cone angle was observed. The results indicated that more fundamental research is needed to gain an in-depth understanding of the physical processes induced in the spray by the piezoelectric drive.

INTRODUCTION

Recent concerns of NO_x emissions from advanced gas turbines and operation at higher pressure ratios and temperatures have changed the constraints on combustor designs. Combustors are being designed to push the envelope of stable operation.

Combustion instabilities occur when the unsteady heat release from the flame is in phase with the acoustics of a combustion chamber, and there is insufficient damping in the system. The unsteady heat release can be caused by several factors, including hydrodynamic instabilities, perturbations in the fuel delivery system, variations in chemical kinetics, or perturbations in the air supply (Oyediran et al., 1995).

In a liquid fueled system, perturbations in the fuel delivery affect the atomization pattern of the spray, which in turn has an impact on the distribution of the dynamic heat release in the system. Thus, the effect of fuel perturbations on sprays is an important link in the dynamic mechanisms of instabilities in liquid fueled combustors; this effect has been modeled extensively for liquid rocket instabilities (Schöyer, 1993).

There are two fuel atomization concepts: 1) injecting the fuel under high pressure into a relatively slow moving gas, and 2) utilizing high velocity air to disintegrate the liquid sheet or jet. The simplex nozzle, the subject of this paper, fits in the first category. This type of nozzle, also known as the pressure-swirl type, employs a single swirl chamber to produce a well-atomized spray of wide cone angle. Several investigations have been made in order to obtain some of the details of the performance of these atomizers. These investigations have been almost exclusively experimental and focused on obtaining the Sauter mean diameter (SMD) and range of drop sizes in the spray (McDonell and Samuelsen, 1991).

The main factors that govern the atomization quality of pressure-swirl atomizers are: fuel properties, properties of air (or gas) in which the fuel is injected, fuel injection pressure, and atomizer dimensions. Despite all the efforts made, our knowledge of this type of atomization is still unsatisfactory for the following reasons: 1) the physics of spray formation are not well understood, 2) the available data and correlations are of questionable validity, 3) there is little

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agreement between the various investigators as to the exact relationships between liquid properties, nozzle dimensions, and mean drop size (Lefebvre, 1989).

It is generally accepted that the dimension of most importance for simplex atomizers is the thickness of the liquid sheet emanating from the nozzle (Lefebvre, 1983). Previous studies have shown that the liquid sheet is normally disturbed by aerodynamic effects, causing fragments of liquid to break off the wavy sheet (Fraser et al., 1962, Dombrowski and Hooper, 1962, and Dombrowski and Johns, 1963). Surface tension forces tend to restore disturbances in the liquid surface, while the aerodynamic forces tend to amplify disturbances. Under certain conditions, aerodynamics forces exceed the interfacial tension and cause the formation of unstable waves with exponentially increasing amplitude.

A comprehensive fuel nozzle model has been recently developed (Rizk, 1994). This model involves the integration of a fuel injection model, and a combustion model with two-step reaction mechanism (McDonell and Samuelsen, 1991). The fuel injection model includes spray dynamic calculations (it address airflow characteristics of the atomizer and the droplet turbulent dispersion), and spray evaporation (considering heat-up and steady state stages). A recent investigation by Dumouchel et al. (1990) involved the fluid mechanics of the viscous flow within the nozzle to provide a means of determining the spray angle. However, this analysis was done for very low inlet Reynolds number and showed disagreement by a factor of 2 between the experimental and computational spray angle.

Non-uniformities in fuel delivery can cause local hot spots which will be the site of excess NO_x production and could provide dynamic heat release rates sufficient to trigger combustion instabilities. In fact, active control of fuel delivery has been suggested as a means to eliminate combustion instabilities. Thus, the need to understand and predict the dynamic behavior of fuel nozzles has increased dramatically for gas turbines. The study presented in this paper was concerned with the effect of perturbations in the liquid delivery system on sprays for gas turbine combustors.

There are several ways the fuel spray may be altered to affect the heat release rate: (1) liquid fluctuations can alter the mean quantities, i.e. spray cone angle, particle size distribution, or atomization length which affects the distribution of both the mean and dynamic heat release rates; (2) liquid flow fluctuations can affect the spray in a dynamic manner, i.e. it can cause periodic fluctuations in cone angle, droplet distribution, and flow rate which can lead to periodic changes in the heat release rate and its location; (3) the spray may be affected by other dynamics in the system, such as perturbations in the incoming air stream or perturbations in the pressure of the combustion chamber itself. This paper describes the results of a study of the first of these effects - the effect of liquid flow perturbations on mean quantities of the spray.

Perturbations in the liquid flow through nozzles are known to affect the overall spray in many ways (Lefebvre, 1989). These perturbations can affect the mean spray distribution, atomization, and cone angle from a pressure atomizer. In fact, this has been used in the medical community to improve distribution of sprays for inhalation of medicine (Topp and Eisenklam, 1972). Also, this effect is being exploited to improve atomization performance of fuel nozzles for many applications from simplex nozzles for jet engines (Dressler, 1993a), to fuel injectors for internal combustion engines (Zhoa et al., 1995). Recently, Takahashi et al. (1994) conducted an investigation to examine the effect of the piezoelectric driver on atomization using orifice plates with circular or rectangular holes. More recently, the same authors (Takahashi et al., 1995), investigated the effect of the piezoelectric driver on a Delavan pressure-swirl atomizer. In both investigations, the atomization processes were characterized using flow visualization and phase Doppler anemometry techniques.

In this paper, a similar piezoelectric driver was utilized to study (1) a Delavan pressure-swirl atomizer (for comparison with the previous work) and (2) a Parker Hannifin pressure-swirl atomizer. Also, in this investigation, flow visualization and phase-Doppler anemometry techniques were used to characterize the atomization. While the main goal of the previous investigations were improving the atomization at the low flow rate range (i.e., increase the turndown ratio), the goal of this study was to utilize the piezoelectric drive to imitate resonances that might occur in the fuel delivery system.

FACILITY DESCRIPTION

Tests for the dynamic response of fuel nozzles for liquid-fueled gas turbine combustors were carried out in test cell SE-5 of the Engine Research Building at NASA Lewis Research Center. Test cell SE-5 is dedicated to testing of fuel nozzles under atmospheric, non-reacting conditions. The facility has adequate plumbing to supply liquid and air to either airblast or pressure atomizers. The fuel nozzles were mounted horizontally and the piezoelectric driver was connected upstream. Fuel injector spray was collected downstream using a 0.30 m ID PVC pipe that dumped into a drain basin. Ambient temperature water was used as the test fluid. The water was contained in a 0.085 m^3 tank that was pressurized with 862 kPa air to provide water flow to the test nozzles. The water was filtered by a 25 μm filter to remove any particulates that could plug up the test nozzle orifices. For these tests, water flow rates ranging from 0.41 g/s to 5.4 g/s were provided. A schematic of the facility can be seen in Fig. 1.

Water flow to the nozzle was initiated by supplying air to the top of the water tank. The water flow rate was controlled by adjusting the tank pressure and the pneumatic control valve setting on the nozzle supply line. The water flow rate was measured using a venturi meter. A Keithley 500 Series Data Acquisition system was used for pressure and temperature measurements, as well as valve control.

Interrogation of the various nozzle flow fields was accomplished using a 2-component Phase Doppler Particle Analyzer. Mean and fluctuating velocities, mean drop sizes, volume flux, and number density were measured using the PDPA. Theory of the PDPA operation is well documented in the literature (Bachalo and Houser 1984). Receiving optics located 30° off-axis collect the refracted light from drops passing through a probe volume formed by the intersection of four laser beams. The PDPA attempts to measure each drop as it passes through the probe volume. The system was configured to provide a probe volume diameter of 230 μm and the receiver slit width was 100 μm. The resulting measurement size range was 3.5 to 177 μm.

To characterize the entire spray, the probe volume was traversed throughout the flow field. The spray symmetry was checked by passing the probe volume across several diameters of the spray. The mean drop sizes and velocities agreed to within 20% for any given radial location; therefore, the sprays were determined to be fairly symmetrical, and only a radius of the spray was measured for most tests.

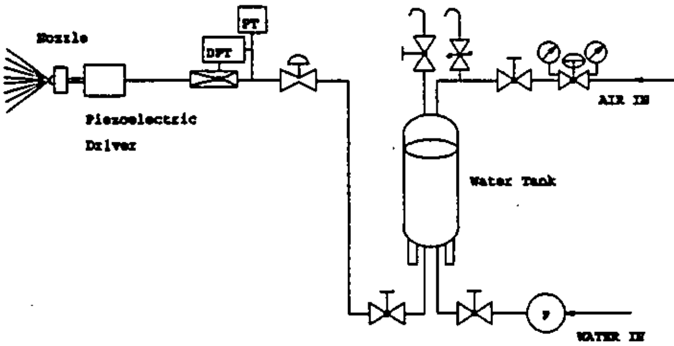

Figure 1 Facility schematic.

Eight thousand drops were measured at each traverse location. At each location no more than 25% of the droplet measurement attempts were rejected by the Doppler Signal Analyzer (DSA) based on various validation criteria. Signals from the receiver were filtered, digitized and processed by the DSA using the discrete Fourier Transform. A probe volume correction was used to account for the variation of the effective probe volume diameter with droplet size. The coordinate system used for the tests can be seen in Fig. 2.

A video camera was used to photograph the spray coming from a Delavan swirl atomizer and a Parker Hannifin research simplex atomizer. The Delavan nozzle used was a Model WDA 1.0, with a 60° spray angle and a design flow rate of 1.0 g/s. The Parker Hannifin research simplex atomizer had a 82° spray angle and a design flow rate of 2.0 g/s. Video photography was used to study the effect of perturbations on the mean spray flow field. Various lighting arrangements were used for the video photography: back lighting, front lighting, a strobe synchronized with the input to the piezoelectric, and a laser sheet oriented along the midplane of the spray.

Figure 3 shows the piezoelectric driver used to perturb the liquid flow (Dressler, 1993b). The driver is composed of four functional elements: (1) the piezoelectric transducers that receive the electrical signal and convert it to longitudinal 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 hollow-cone fluid sheet whose velocity is modulated by the pressure perturbation. The velocity modulation system includes a function generator, power amplifier, matching transformer, and piezoelectric transducers. A sinusoidal driving signal with peak-to-peak voltage, V_{pp}, and frequency, f, is applied to the center electrode of the piezoelectric transducers. The peak-to-peak current I_{pp} depends on the crystal response. Both V_{pp} and I_{pp} are measured by an oscilloscope.

RESULTS AND DISCUSSION:

Flow visualizations was used for both the Delavan and Parker Hannifin pressure atomizers. The regular video photography showed the changes in characteristics of the atomization with the piezoelectric drive on and off. One significant observation was that the effect of the piezoelectric drive on the atomization process takes place at discrete frequencies (resonant frequencies). These frequencies were dependent on the type of nozzle tested (Delavan or Parker Hannifin). Also, measurements of mean flow quantities were conducted for the Parker Hannifin nozzle; these included mean flow rate as well as droplet distribution data obtained using the Phase Doppler Particle Analyzer.

It was observed that the mean liquid flow rate through the nozzle changed when the piezoelectric drive was turned on. Figure 4a shows the relationship between pressure drop across the nozzle and the flow rate through the nozzle, with and without exciting the piezoelectric driver (for the Parker Hannifin nozzle driven at 10.00 kHz). Figure 4b shows this same data, plotted as discharge coefficient C_D versus Reynolds number Re_D.

$$C_D=\frac{Q}{A\sqrt{2\Delta p/\rho}} \quad , \qquad Re_D=\frac{4m}{\pi\mu D}$$

where Q and m are the fluid volumetric and mass flow rate, respectively, A is the cross-sectional area based upon the atomizer orifice diameter D, Δp is the pressure drop and ρ and μ are the fluid density and kinematic viscosity, respectively. From Fig. 4a it can be seen that for a given pressure drop, there was as much as a 10% reduction in the mean flow rate. This is true for higher pressure drops, while at low pressure drops (100 kPa or less) the effect of the piezoelectric driver on the mean flow rate is almost negligible. As a result, it was not possible to hold both the liquid flow rate and nozzle inlet pressure constant as the flow perturbations were changed. The following discussion includes both situations when the inlet pressure was held constant (and the flow rate varied) and when the flow rate was held constant (by varying the inlet pressure). From Fig. 4b the nozzle discharge coefficient, for no excitation, drops monotonically from 0.47 to a flat value of 0.4 as the Reynolds number increases

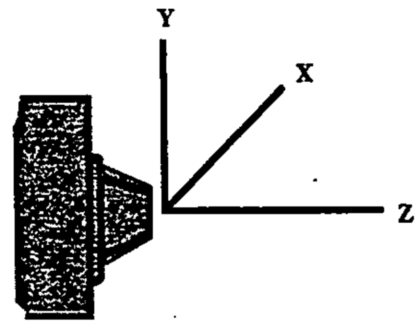

Figure 2 Coordinate system used for PDPA system

from 3000 to 7500. With the piezoelectric on, the discharge coefficient drops, also monotonically, as the Reynolds number increases for 300 and 850 V, but does not change in a monotonic manner for 600 V.

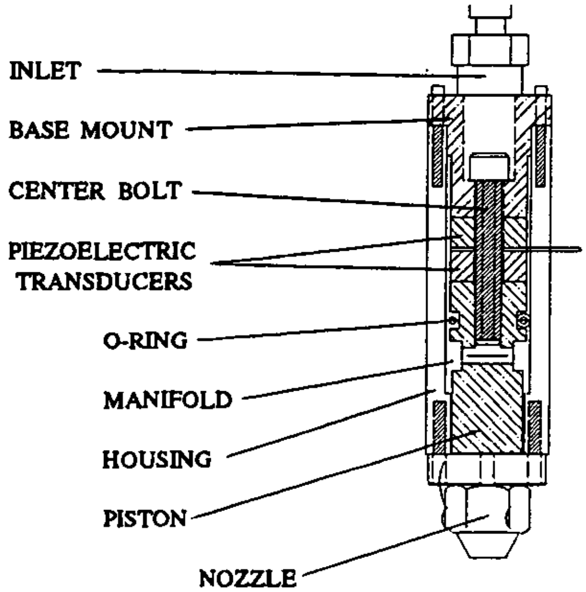

Figure 3 Piezoelectric drive, used to imitate fuel system resonances.

Delavan Nozzle

Table I shows the different cases, discussed in this section, that were examined visually for the Delavan nozzle using regular video photography.

Figures 5a and 5b show still pictures taken from the video for the Delavan nozzle (flow rate of 0.5 g/s and inlet pressure of 414 kPa) driven at 6 kHz (30 volts peak-to-peak) and without the drive, respectively. The flow field was illuminated using a strobe synchronized with signal input to the piezoelectric driver (6 kHz for both figures). The figures show clearly how the breakup length of the liquid sheet was shortened by the perturbations in the liquid flow. Figures 5c and 5d show the same flow conditions and driving frequency. However, in this case the illumination was done using a continuous laser sheet at the midplane of the nozzle. These two figures show additional effects of the liquid perturbations on the nozzle atomization. The overall cone angle of the spray was smaller when the liquid flow was being perturbed (Fig. 5c) than when there was no excitation (Fig. 5d). In addition, the cone seemed less hollow, i.e. more particles filled the center of the spray cone, when the piezoelectric drive was on. These observations are consistent with similar results obtained by Takahashi et al. (1995).

Parker Hannifin Nozzle

Table II shows the different cases, discussed in this section, that were examined visually for the Parker Hannifin nozzle using regular video photography.

Figures 6a and 6b show still pictures taken from the video for the Parker Hannifin nozzle (1.22 g/s flow rate and 391 kPa inlet pressure) with the piezoelectric drive on (10.00 kHz, 560 V) and off, respectively. The flow field was illuminated using a continuous laser sheet at the midplane of the nozzle. Qualitatively, these figures show a similar effect of the piezoelectric device on the atomization process. As seen above for the Delavan nozzle, the overall spray cone angle was reduced and more particles are seen to fill the center of the spray cone when applying perturbations in the liquid flow.

Figures 7a shows a still picture taken from the video of the Parker Hannifin nozzle with a flow rate of 1.63 g/s (454 kPa inlet pressure) and without excitation. The flow field was illuminated using continuous back lighting and the shutter time of the camera was decreased to 0.1 ms. Figures 7b-d show similar pictures with the piezoelectric drive at 10.00 kHz and input voltages of 300 V, 600 V and 960 V respectively. The figures show similar effects of the liquid perturbations on the atomization process as described above. In this case, the mean pressure was not adjusted to maintain the mean flow, thus the mean flow dropped when the driver was turned on (as shown in Fig. 4). It is evident from the pictures that the effect of the drive became more pronounced as the applied voltage was increased; the cone angle was decreased as the voltage was increased. However, the filling-in of the center of the spray cone is not obvious, as it was when illumination was done using a laser sheet at the midplane of the nozzle.

This visualization is valuable to understanding the qualitative effects of liquid perturbations on the sprays. However, the spray looked very different depending on the lighting (strobe versus laser versus continuous backlighting) and shutter speed of the camera. It was obvious that conclusions might be altered depending on how the spray was observed. Also, if we are to learn how the liquid perturbations will affect the distribution of the mean and dynamic heat release rates in a combustor we need more than qualitative observations. Thus, it was obvious that these visual observations needed to be substantiated and quantified. The PDPA was used to quantify the effect of the piezoelectric drive.

Table III shows the different cases examined for the Parker Hannifin nozzle using the PDPA. Figure 8a shows results for the Parker Hannifin nozzle using the PDPA at 1.27 cm distance downstream from the nozzle tip. In this figure, the Sauter mean diameter (SMD) is plotted versus the radial position for an inlet pressure of 454 kPa (flow rate of 1.63 g/s when the driver was off), frequency of 10 kHz, and voltages of 300 V, 600 V and 960 V. The figure shows an increase in the mean particle size in the center of the nozzle from about 10 μm (no excitation) to about 20 μm (excitation at 10 kHz, 960 V). On the other hand, the figure shows that the excitation resulted in a decrease of the mean particle size in the outer region of the spray cone from about 75 μm (no excitation) to about 55 μm (excitation at 960 V).

Figure 8b shows the volume flux plotted versus radial location in the spray for the same conditions as those described in Fig. 8a. The minimum validation rate for the study was only 75%, hence the volume flux data can not be used in any quantitative sense. Qualitatively, Fig. 8b agrees with the flow visualization observations (Fig. 6 and 7), specifically that the spray cone angle was reduced by applying the liquid perturbations and that the reduction was more significant as the applied voltage increased.

Figure 8c shows the mean axial velocity versus the radial position in the spray for the same conditions. The figure indicates that perturbing the liquid flow results in an increase in particle velocities near the center line of the spray and a decrease in particle velocities near the outside of the spray.

As stated earlier, the effect of the piezoelectric driver on the spray is a function of the driving frequency. There are sudden changes in the character of the spray as the frequency is varied and the system shifts from one mode to another. In fact, the dominant mode was observed to be a function of excitation frequency as well as the frequency history. An example of such hysteresis is shown in Fig. 9. Figures 9b and 9d both show the spray being driven at 9 kHz and 900 Volts with the same liquid flow rate and both were filmed using continuous back lighting. However, the sprays look significantly different. The difference between the sprays in Fig. 9b and 9d was caused by their different histories. In fact, Fig. 9a-d are in sequential order. First, the spray was driven at 10 kHz and 900 Volts (Fig. 9a). Then the frequency of the perturbation was slowly reduced to 9 kHz (Fig. 9b) while the piezoelectric driver remained on. Then, the driver was simply turned off (Fig. 9c) and then turned back on (Fig. 9d) at the same, 9 kHz, frequency. The difference between sprays in Fig. 9b and 9d shows the non-linear effect of the system on the atomization resonances.

Of the frequencies tested which did not exhibit hysteresis, 9.35 kHz was found to have the greatest visible effect on the spray when the driver was turned on and off. Figures 10a and 10b show the spray with a flow rate of 1.63 g/s (inlet pressure of 454 kPa when the driver was off) being driven at 9.35 kHz and 850 Volts and with no driving, respectively. The flow field was illuminated using continuous back lighting. Again the figures confirm earlier observations made that the cone angle was reduced by perturbing the liquid flow. The PDPA results for this case are discussed below.

Figure 11a shows results for the Parker Hannifin nozzle using the PDPA at 1.27 cm downstream of the nozzle tip. In this figure, the Sauter mean diameter (SMD) is plotted versus the radial position in the spray for a flow rate of 1.63 g/s, frequency 9.35 kHz, and voltage of 850 V. As shown in previous cases, this figure shows an increase in the particle size in the center of the nozzle from about 10 μm (no excitation) to about 15 μm (excitation at 9.35kHz, 850 V). On the other hand, the figure shows that the excitation resulted in a decrease of the particle size in the outer region of the spray cone from about 80 μm with no excitation to about 60 μm with excitation. Figure 11b shows the volume flux plotted versus the spray radius for the same conditions described in Fig. 11a. Qualitatively, the figure agrees with the flow visualization observations (Fig. 10a,b), specifically that the spray cone was reduced by applying the perturbations. Figure 11c shows the mean axial velocity plotted versus the radial position in the spray for the same conditions described in Fig. 11a and 11b. As before, the figure indicates that these perturbations increased the particle velocity near the center line of the spray and decreased the particle velocity in the outer region of the spray.

In addition, measurements were taken at distances further from the nozzle exit. The variations of the spray in the axial direction were observed for a driving frequency of 14.2 kHz, which represented another discrete resonant frequency. Figure 12 shows variations in (a) Sauter mean diameter (SMD), (b) volume flux, and (c) axial velocity from PDPA measurements taken at 1.27 cm, 2.54 cm and 3.81 cm downstream of the nozzle edge tip, using the Parker Hannifin simplex atomizer. The experiment was conducted for a liquid flow rate of 1.63 g/s, driving frequency of 14.2kHz and voltage of 600 V. The figures show the parameters plotted across the spray diameter; asymmetry is noticed from the data collected. The figures show an increase in the maximum value of the Sauter mean diameter (SMD) as one travels downstream. The maximum SMD = 86.5 μm at $z = 1.27$ cm, 89 μm at $z = 2.54$ cm, and 98.7 μm at $z = 3.81$ cm. The data show slight differences in the maximum volume flux between 1.27 cm and 2.54 cm downstream; then a dramatic drop in the maximum volume flux at 3.81 cm downstream of the nozzle. Finally, the maximum of the radial distribution of the mean axial velocity decreased in the downstream direction.

It should be noted that the present results are in general agreement with earlier work (Takahashi et al., 1995); however, direct comparisons are difficult to make because of: 1) differences in the type of nozzle used (geometry and design); 2) differences in the flow rate (or the nozzle inlet pressure).

SUMMARY AND CONCLUSIONS

In the present study, a Delavan swirl atomizer and a Parker Hannifin research simplex atomizer have been examined. Water was used as the liquid for the nozzles. Before entering the nozzle the liquid flow was perturbed using a piezoelectric driver. This was used to simulate resonances that might occur in the fuel delivery system. Frequencies of perturbations examined were from 3 to 20 kHz. Regular video photography and PDPA were used to study the effect of perturbations on mean flow spray quantities. Different lighting arrangements were used for the video photography: back lighting, front lighting, a strobe synchronized with the input to the piezoelectric, and a laser sheet oriented along the midplane of the spray. The following conclusions were drawn from this study based upon the Parker Hannifin nozzle (with which most tests were conducted).

General Effects

The measurements made using a venturi flow meter, flow visualization techniques and the PDPA showed that the piezoelectric drive (at certain resonant frequencies) affected the simplex atomizer such that: 1) the mean flow rate decreased, 2) the spray cone angle decreased, 3) the break up length decreased, 4) the peak of the spatial distribution of the mean droplet size decreased, 5) the droplet size increased near the spray center line and decreased in the outer region of the spray, 6) the axial velocities increased near the center and decreased in the outer region and 7) the results from the PDPA showed that the sprays were radially symmetric.

Specific Effects

Geometry Effects: One significant observation made in this study was that the effect of the piezoelectric drive on the atomization process takes place at discrete frequencies (resonant frequencies). These frequencies were dependent on the type of nozzle tested (Delavan or Parker Hannifin). As for the Delavan nozzle, it did resonate at generally lower frequencies than those for the Parker Hannifin nozzle. Therefore the piezoelectric effect on the liquid atomization is highly geometry dependent, as expected.

Frequency Effects: The measurements made using regular video photography and PDPA showed the following: (a) The effect of the piezoelectric device takes place at discrete frequencies. (b) It appears from the flow visualization that the effect of driving was more pronounced at 9.35 kHz than that at 10 kHz. However, the PDPA results indicate that there is little difference (if any) between the two cases. (c) A non-linear effect was observed from the flow visualization at certain frequencies (9 kHz) on the spray pattern depending on whether this frequency was reached from a higher or a lower level.

Voltage Effect: The measurements made using video photography and the Phase Doppler Particle Analyzer (PDPA) showed that the effects described above were more pronounced as the driving voltage increases.

Downstream Variations: The measurements made using the PDPA showed the following: (a) The maximum value of the Sauter mean diameter increased in the downstream direction, this may be attributed to either (i) the presence of larger droplets of non-spherical shapes (will not be detected by the PDPA system) at the nozzle exit; these droplets will break up as they travel downstream, or (ii) the coalescence of smaller droplets as they travel down stream, (b) The maximum value of the volume flux showed little difference between $z = 1.27$ cm and 2.54 cm downstream from the nozzle exit, and then dropped dramatically at $z = 3.81$. (c) The maximum value of the radial distribution of mean velocity decreased in the downstream direction.

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TABLE I. FLOW VISUALIZATION - DELAVAN NOZZLE

Flow Parameters		Driving Parameters		Diagnostic
Liquid Flow Rate [g/s]	Inlet Pressure (gage) [kPa]	Frequency [kHz]	Voltage [V] peak-to-peak	Type of Illumination
0.50 (Fig. 5a)	410	6	30	Synchronized Strobe
0.50 (Fig. 5c)	410	6	30	Laser Sheet at Nozzle Midplane

TABLE II. FLOW VISUALIZATION - PARKER HANNIFIN

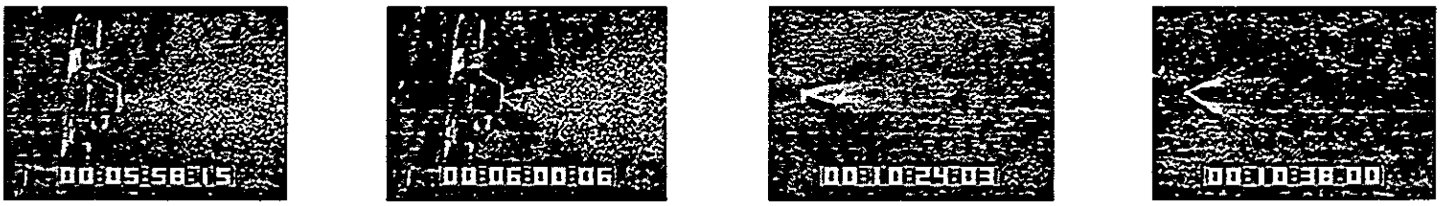
Flow Parameters		Driving Parameters		Diagnostic
Liquid Flow Rate [g/s]	Inlet Pressure (gage) [kPa]	Frequency [kHz]	Voltage [V] peak-to-peak	Type of Illumination
1.22 (Fig. 6b)	390	none	0	Laser Sheet at Spray Midplane
1.20 (Fig. 6a)	390	10	560	
1.63 (Fig. 7a)	450	none	0	Continuous Back Lighting
1.63 (Fig. 7b)	450	10	300	
1.54 (Fig. 7c)	450	10	600	
1.45 (Fig. 7d)	450	10	960	
1.45 (Fig. 9a-d)	450	10 to 9	900	
1.45 (Fig. 10a)	450	9.35	900	

TABLE III. PDPA MEASUREMENTS - PARKER HANNIFIN

Flow Parameters	Driving Parameters		Diagnostic
Liquid Flow Rate [g/s]	Frequency [kHz]	Voltage [V] peak-to-peak	Distance Downstream of Nozzle Exit [cm]
1.63 (Fig. 8a,b,c)	none	0	1.27
1.63 (Fig. 8a,b,c)	10	300	1.27
1.54 (Fig. 8a,b,c)	10	600	1.27
1.45 (Fig. 8a,b,c)	10	900	1.27
1.54 (Fig. 12a,b,c)	14.2	600	1.27
1.54 (Fig. 12a,b,c)	14.2	600	2.54
1.54 (Fig. 12a,b,c)	14.2	600	3.81
1.63 (Fig. 11a,b,c)	9.35	850	1.27

(a) (b)

Figure 4 Effect of piezoelectric drive on (a) mean mass flow rate, and (b) discharge coefficient for an excitation frequency of 10.00 kHz.

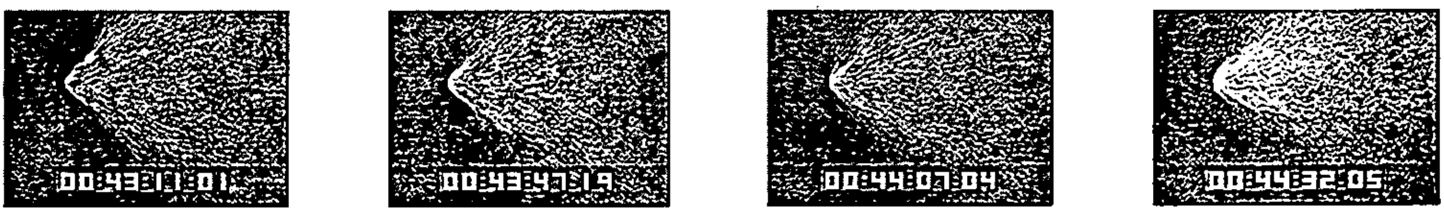


(a) (b) (c) (d)

Figure 5 Delavan pressure atomizer, liquid flowrate 0.50 g/s; (a) and (b) strobe syncronized with function generator; (c) and (d) continuous laser sheet at midplane of nozzle; (a) and (c), piezoelectric driven at 6 kHz; (b) and (d), no piezoelectric drive.

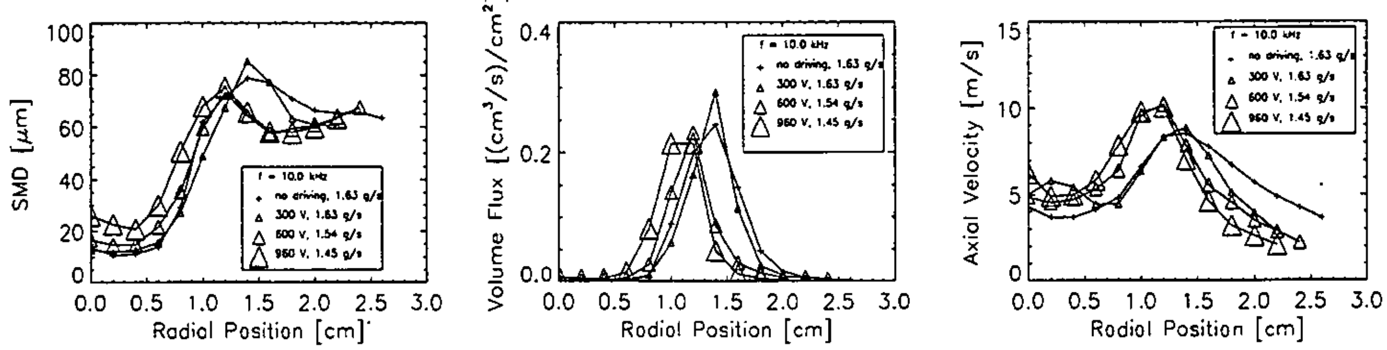
(a) (b)

Figure 6 Parker Hannifin Research Atomizer, illimunated by a continuous laser sheet along midplane of spray: (a) piezoelectric drive at 10 kHz, (b) no piezoelectric drive.



(a) (b) (c) (d)

Figure 7 Parker Hannifin research atomizer with continuous back lighting of spray and piezoelectric driven at 10 kHz: (a) 0 Volts (no drive), (b) 300 Volts, (c) 600 Volts, (d) 960 Volts.



(a) (b) (c)

Figure 8. The effect of driving voltage on the distributions of (a) Sauter mean diameter (SMD), (b) volume flux, and (c) axial velocity, at a distance of 1.27 cm from the nozzle exit, for a driving frequency of 10.0 kHz. The mean inlet pressure was kept constant, so the mean flow was affected by the piezoelectric device.

Figure 9 Hysteresis in oscillating flow, (a) started at frequency of 10 kHz, (b) reduced frequency to 9 kHz without turning off the piezoelectric drive, (c) turned off drive, (d) turned piezoelectric drive on at same frequency (9 kHz), did not return to same spray angle as in (b).

Figure 10 Change in mean cone angle for spray driven at 9.35 kHz. Parker Hannifin research atomizer back lit continously: (a) piezoelectric drive on, (b) drive off.

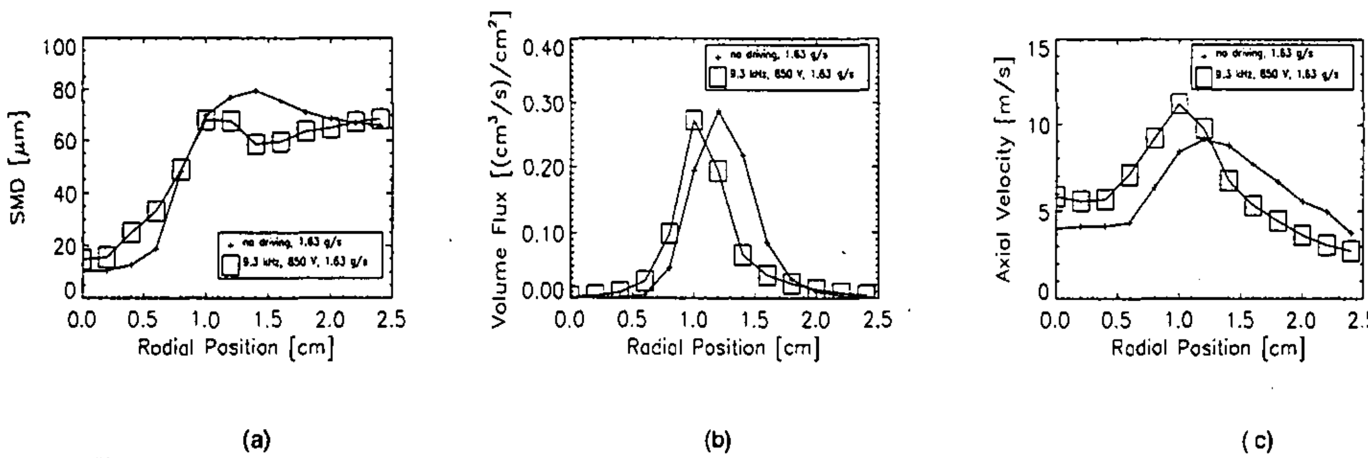


Figure 11 Effect of 850 V, 9.35 kHz piezoelectric drive on the distributions of (a) SMD, (b) volume flux, and (c) axial velocity, at a location 1.27 cm downstream of the nozzle exit. The mean inlet pressure was ajusted such that the mean flowrate would remain constant with and without the drive.

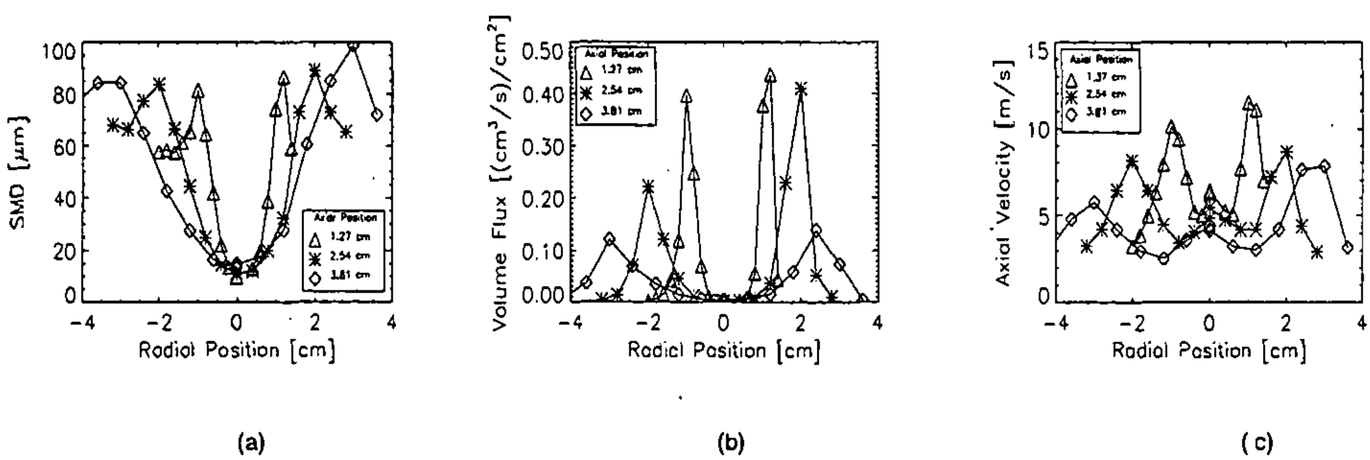


Figure 12 Distributions of (a) SMD, (b) volume flux, and (c) axial velocity, for various axial locations from the nozzle tip. The flow is being driven at 14.2 kHz and 600 V, with a mean liquid flowrate of 1.54 g/s.