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PRESSURE MODULAION ON MICRO-MACHINED PORT FUEL INJECTOR PERFORMANCE

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ABSTRACT−An experimental study was carried out to characterize the spray atomization process of micro-machined port fuel injectors with a piezoelectric atomization device, which can generate pressure pulsations through vibration of a piezoelectric transducer. In this study, several types of micro-machined arrays such as 30~200-microns of hole arrays were tested. Both a dual-stream and a central-port injectors with micro-machined arrays were tested and compared with normal port fuel injectors. The spray visualization was conducted to characterize overall spray structure and phase Doppler particle analyzer (PDPA) system was used to quantify the droplet size and velocity. In addition, the pressure history was recorded by using digitized signal from pressure transducer. The results showed that modulation is effective to the spray atomization for tested injectors and atomization performance depends on injector design factors, orifice sizes, and frequency and power of the modulator. A number of resonance frequencies of the modulator was modified by injector parameters and temperature. In addition, our results suggested that design of sufficient space among holes is critical to avoid droplet coalescence in the multi-hole micro-machined injectors.

KEY WORDS : Pressure modulation, Micro-machined port fuel injector, Spray visualization

1. INTRODUCTION

In general, combustion processes require fine atomization of fuel droplets to produce optimal combustion efficiency and to satisfy stringent emission regulation. In automotive port-fuel-injection (PFI) engines, the injector is used primarily as a fuel meter during closed-valve injection under warm-up condition. The atomization performance of the injector is not as critical as targeting performance (aiming at the hot inlet valve for improving the fuel vaporization and mixing with air). Under cold starting or open-valve injection conditions, however, improved atomization is very critical for engine combustion stability and emissions. Poor atomization results in wall wetting on port combustion chamber surfaces, which in turn demands over-enrichment and significantly increases engine-out hydrocarbon emission (Zhao *et al.*, 1995). Under cold starting conditions, these initial engine-out unburned hydrocarbons cant be consumed in the catalytic converter, which is not yet lighted off. Therefore, a device capable of modifying the atomization (Berger, 1985) and targeting characteristics corresponding to different engine operation conditions is very desirable. Micro-machined technology has been shown to have the advantage of improved manufacturing quality control and enhanced atomization performance for multi-hole director-plate type PFI (Amer *et al.*, 1995a, 1995b; Lai *et al.*, 1994). Therefore, an experimental study was carried out to characterize the spray atomization process of micro-machined injectors in conjunction with a piezoelectric atomization device.

Most of the studies carried out to evaluate the pressure-modulated sprays were done on pressure swirl simplex nozzle and with water as working fluid (Chung *et al.*, 1997; Ibrahim *et al.*, 1996; Takahashi *et al.*, 1996; Takahashi *et al.*, 1997). Zhao *et al.* (1996) used a port fuel injector with surrogate fuel (Viscor 16-B) as the working fluid. It was found that the spray behavior strongly depends on the driving frequency and power of the pressure modulator and the injector design. In this study, similar approach is taken, but different multiple-hole micro-machined director-plates were adapted to PFI injector body. The operating characteristics of the modulator were established, and the pressure modulated PFI spray structure is analyzed using pressure history, spray structure, and spray visualization and phase Doppler techniques.

2. EXPERIMENTAL SETUP

The schematic of the experimental setup is shown in

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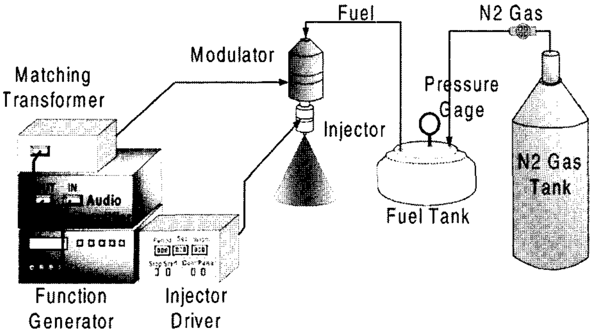

Figure 1. Schematic of experimental setup.

Figure 1. A piezoelectric modulator is mounted upstream of the injector. Similar to previous study (Dressler, 1991, 1993; Zhao *et al.*, 1996), the modulator working principles is as follows: (a) piezoelectric transducer that receives electrical signal from some external source, and converts it into longitudinal mechanical motion. (b) A resonant mechanical structure that amplifies the motion produced by the transducer. (c) A pump that converts the mechanical motion into a pressure perturbation in the working fluid. The pumping action is produced in the narrow fluid passage between the housing and the pump. (d) An orifice that creates a fluid stream whose velocity is modulated by pressure perturbation.

The purpose of this system is to introduce pressure perturbation to liquid inside nozzle cavity, to enhance instability of liquid film and to modify the liquid breakup process.

The instrumentation for the modulation system includes a function generator (Hewlett Packard 33120A), power amplifier (Denon PA-2200), matching transformer, and piezoelectric modulation device. Adjusting the voltage of the function generation, with 5 Volts corresponding 100% driving power controls the power of the modulations. The voltage supplied to the atomizer was measured using a digital multi-meter (Micronta) and the current was measured by connecting the atomizer in series with Tektronix TM. The test instrumentation is as follows: The upstream pressure history of the injectors was measured using miniature Kulite pressure transducers (model XT-123 B-100SG) and recorded using a strain-gage indicator and recorder. The global spray structure was quantified by planar laser Mie scattering technique (Lai *et al.*, 1998) (Nd:YAG laser as a light source with images captured by 35 mm still camera) and back-lighted microscopic visualization using spark light source with short light duration (50 ns). The drop size and velocity were measured by phase Doppler interferometry (two-component Aerometric RSA system). The measurement locations to get droplet size and velocity were on the spray axis at 76 mm from the tip. The injection pressure was fixed at 270 kPa.

In addition to a conventional two-hole dual-stream (DS) PFI injector and an outward-opening central port injection (CPI) injector, different micro-machined injectors are tested. Two-dimensional arrays of small orifices are laser-drilled on automotive director plates. The 2-D arrays are drilled with a 10° inclination angle, with respect to the bisecting symmetry plane, to simulate a dual-stream injector with a 20° divergence angle. These plates are either mounted directly on the modulator (micro-machined plates, MMP30 and MMP60) or retrofitted on a PFI body (micro-machined injector MM30, MM60, MM100) downstream of the modulator. PFI body has built-in filter, solenoid, needle, seals, and the associated flow passage and fluid volume, which could cause dissipation and dispersion of the pressure modulation. The resultant Reynolds numbers of the flow at these orifices are all very small, mostly less than 500, indicating a laminar flow condition at the exit. Another linear array of 200-micron sharp-edged holes with 1mm spacing between the holes was made using photochemical bimetal etching techniques. Since the flow rate of this plate is significantly larger than those needed for automotive application, it is only used for microscopic visualization.

Table 1. Specifications of the injectors tested.

Injector	Hole Φ (μm)	Spacing (μm)	Hole # (Array)
CPI	500		1
DS	200		2
MM100	100	500	2×(3×4)
MM060	60	300	2×(4×8)
MM030	30	150	2×(15×8)
MMP200	200	1000	40*
MMP60	60	600	2×(3×5)
MMP30	30	300	2×(5×8)

*Bi-metal etched 1-D array

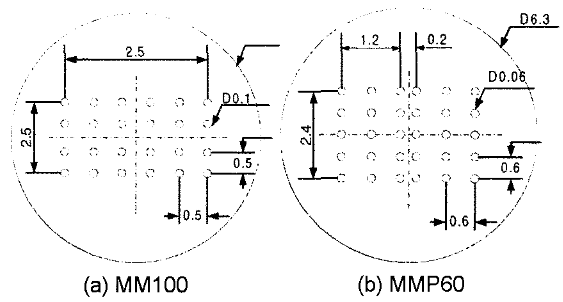

Figure 2. Geometry of the MM100 and MMP60 injectors.

The specifications of the injectors are summarized in Table 1. The geometry of plates of the MM100 injector and the MMP60 injector are shown in Figure 2.

3. RESULT AND DISCUSSIONS

Figures 3~8 show that the spray characteristics depend on the driving frequency and power of the pressure modulation, and fluid property. The dependency, however, differs with injector design. The central port injection injector shows the most dramatic changes with different

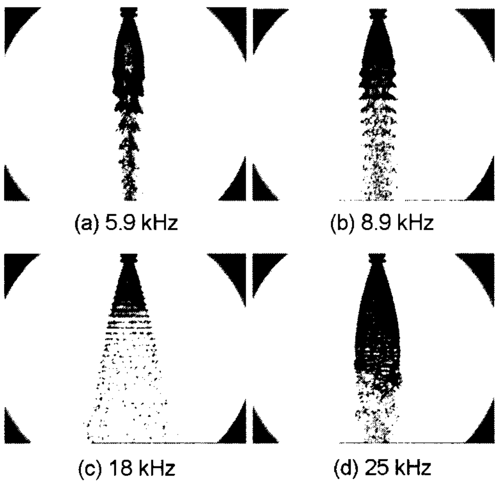

Figure 3. Frequency dependent modulation characteristics of CPI (Water) at 20% power.

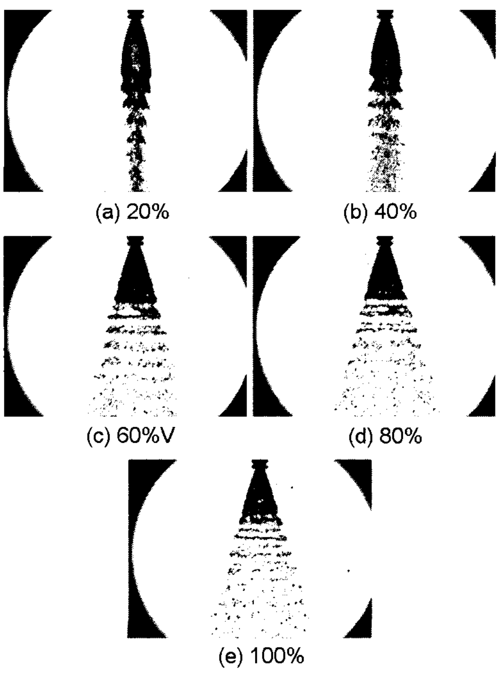

Figure 4. Amplitude dependent modulation injection characteristics of CPI (Water) at 5.9 kHz.

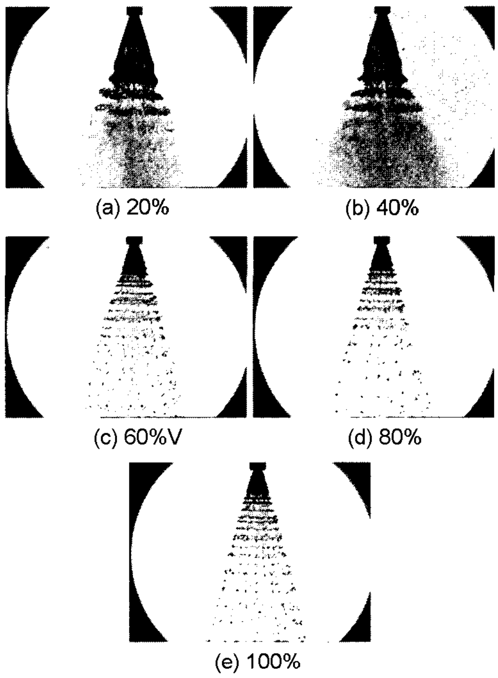

Figure 5. Amplitude dependent modulation injection characteristics of CPI (Viscor 16B) at 5.9 kHz.

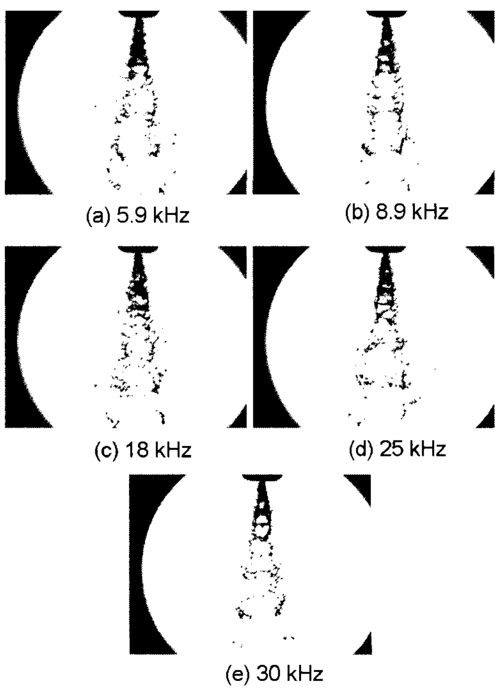

Figure 6. Modulation injection of DS Injector using Viscor 16B at 100% driving power.

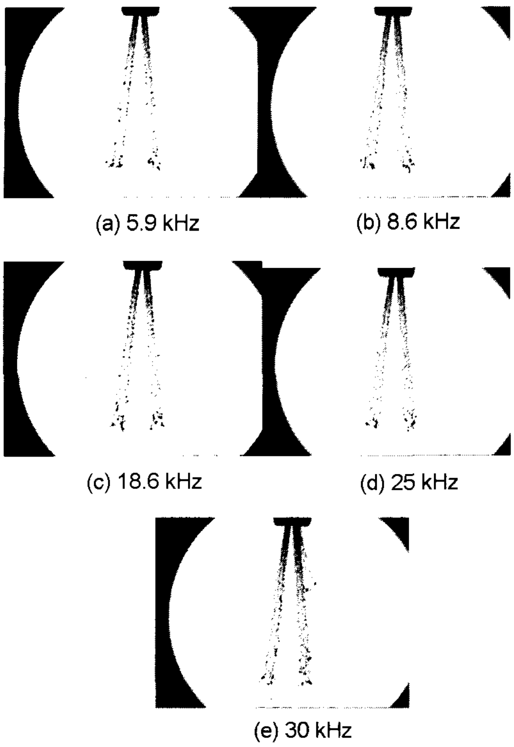

Figure 7. Modulation injection of MM60 Injector at 100% driving power.

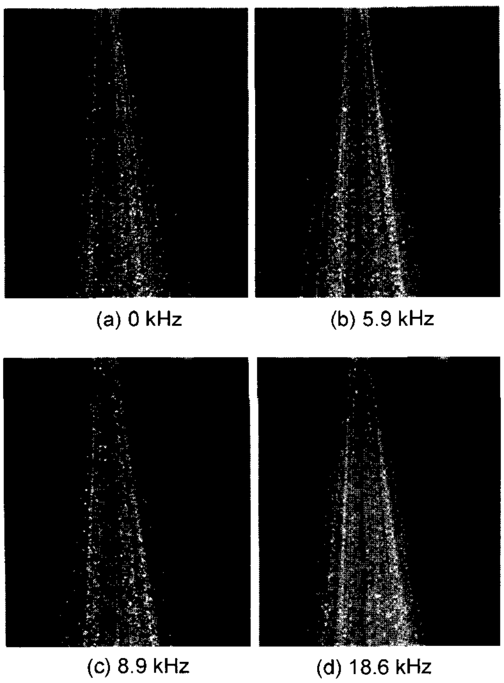

Figure 8. Modulation injection of MMP30 at 25% driving power.

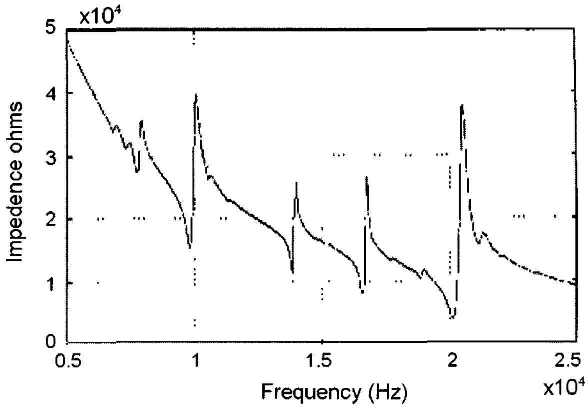

Figure 9. Terminal characteristics of piezoelectric pressure modulater.

driving parameters and fluid property, while the micromachined injectors do not show significant variation in the macroscopic spray visualization results. Since the pressure perturbation can be damped by the injector body, simple internal design such as the CPI injector shows better atomization improvement by pressure modulation

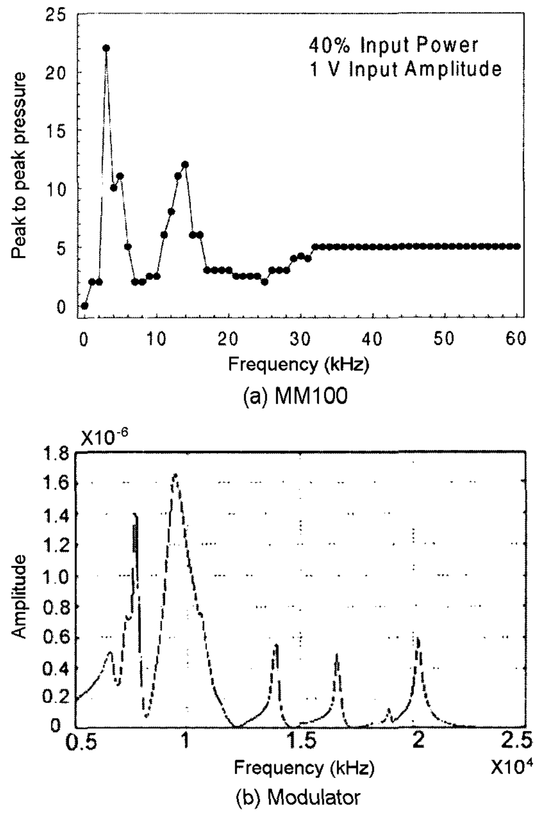

Figure 10. Peak to peak pressure.

techniques.

The terminal characteristics of the piezoelectric modulator are shown in Figure 9 in terms of the frequency response of impedance and displacement. In general the impedance is inversely proportional to frequency, with the resonance behaviors shown as peaks at different frequency. However, the terminal characteristics change with the operation temperature, which in addition to the injector and injection parameters, makes it even more

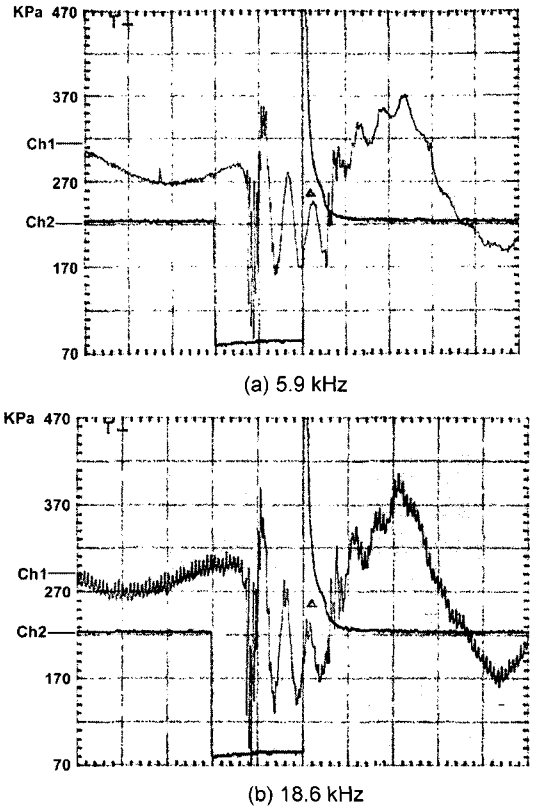

Figure 11. Pressure history upstream of DS injector at 40% driving power 40%.

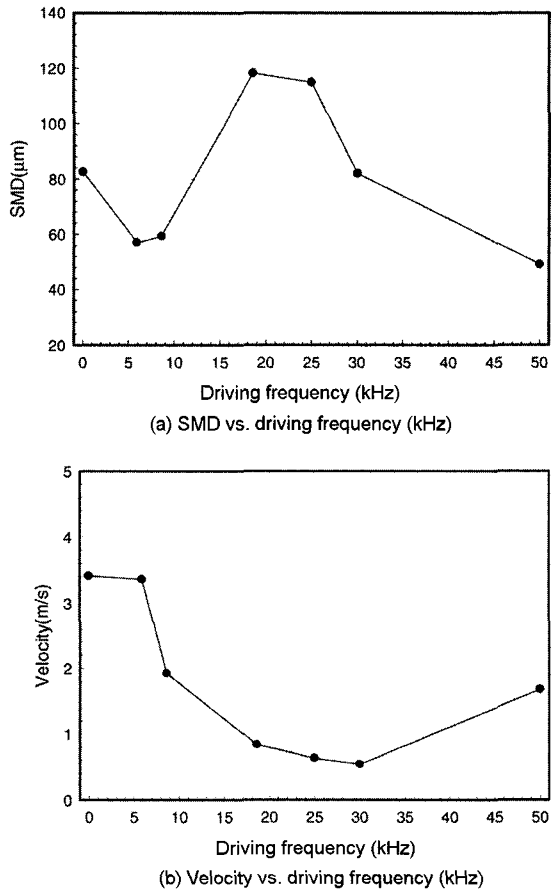

Figure 12. Droplet size and velocity of micro machine plate injector (MMP060) at 40% driving power.

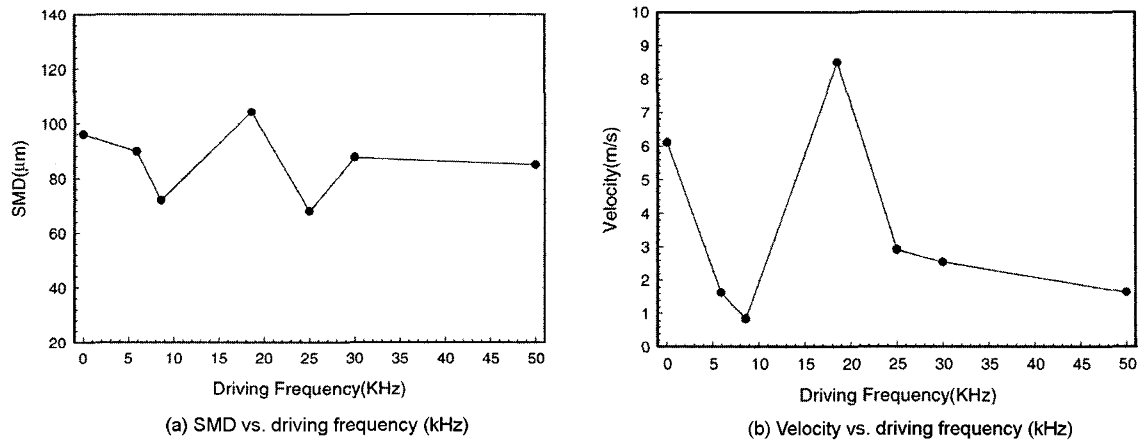

Figure 13. Droplet size and velocity of micro machine mlate injector (MMP030) at 40% driving power.

complicated to define the optimal operation condition.

Peak *to* Peak pressure of *MM100* injector *and* Modulator itself are shown in Figure 10. Figure 10(a) is on MM100 *and (b)* is on *modulator itself in* air. Amplitude of displacement has resonance in air. Pressure modulation with casing and fluid was changed. It shows that pressure modulation depends upon injector design.

Figure 11 shows typical pressure traces of DS injector at 4 ms injection duration. The pressure oscillations are much lower than those in CPI injectors, which shows that the downstream injector design can significantly change the characteristics of the pressure modulation.

Figures 12 and 13 show variation in SMD and velocity with driving frequency for the MMP injectors, which have double the hole spacing and do not have the artifacts of a PFI body. With modulation, the SMD and velocity is *mostly decreased except at a few frequencies*, which may correspond to resonance. However, the effect of modulation is quite complicated, as the atomization enhancement may be offset by the agglomeration effects.

To illustrate, the microscopic visualization of 1-D-array *MMP200* injector in Figure 14 shows different breakup regimes corresponding to different flow and driving *frequency. The pulse steeping* effect causes the breakup to occur at roughly the same downstream locations for

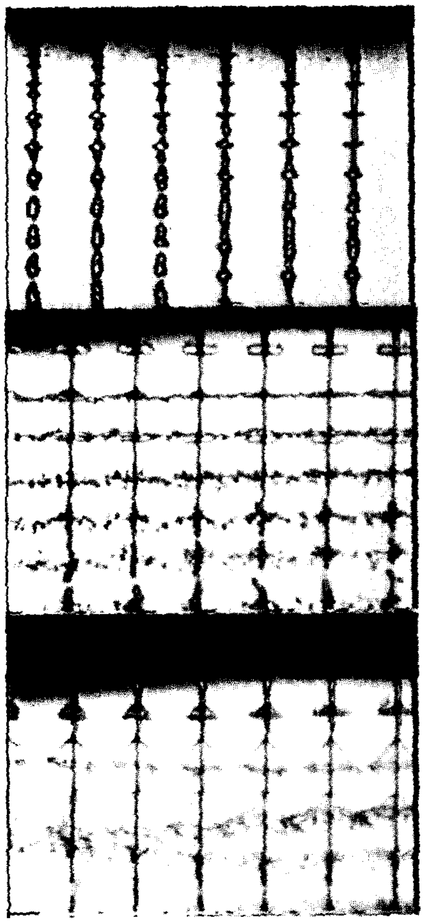

Figure 14. Pressure modulation of water sprays from a linear nozzle plate (200um hole with 1mm separation) as *frequency changes* 5 kHz through 18 kHz showing different break up regions and collisions.

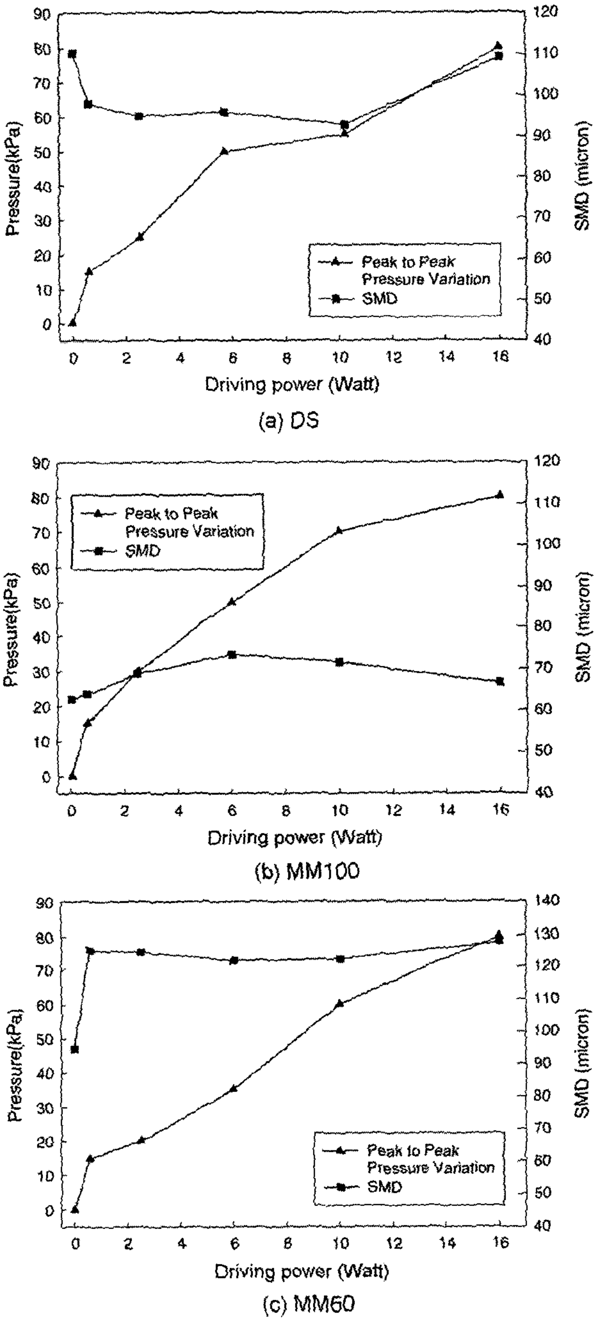

Figure 15. Variation in peak-to-peak pressure and SMD with driving power at 3.5 kHz.

streams from different orifices. As a result, advantage of breakup enhancement by pressure modulation can be easily offset by droplet collision and coalescence in the lateral direction. However, more investigation is required to clarify the pressure modulation effect, including the effect of spacing in micro-machined injectors.

Figures 15 shows variation in peak-to-peak pressure

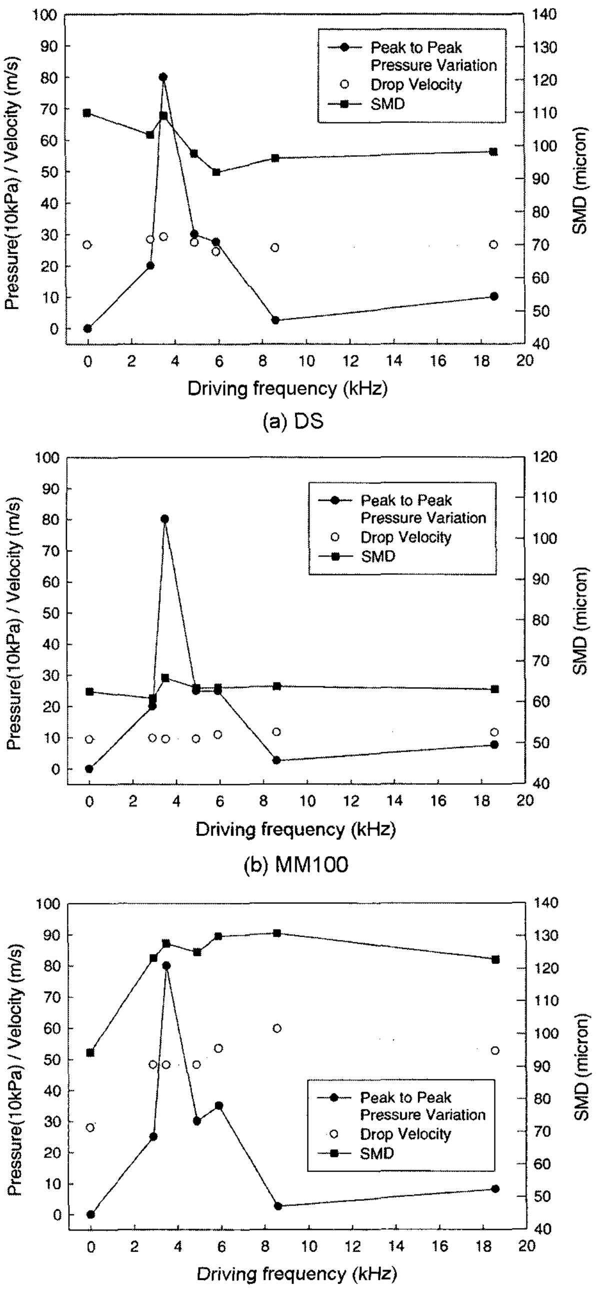

Figure 16. Variation in peak-to-peak pressure, SMD, and velocity with driving frequency.

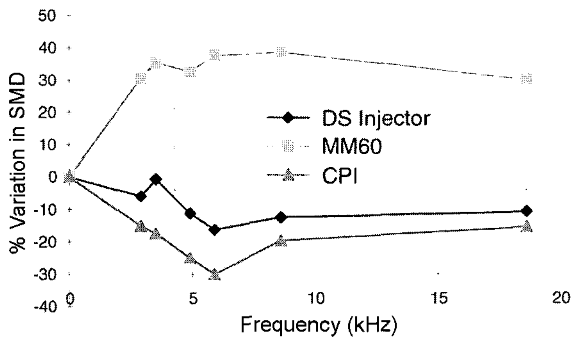

Figure 17. Percentage variation in SMD with modulation for different injectors.

oscillation and SMD with driving power. The pressure variation is proportional to driving power. The SMD decreases with driving power for DS injector except at maximum power where SMD suddenly increases. The MM100 shows increasing tendency with power. MM060, however, shows sudden increase of SMD with modulation and then decreases with driving power.

Figure 16 shows variations of peak-to-peak pressure, SMD and averaged velocity with driving frequency. It is evident that the amplitude of pressure modulation is dependent on frequency and independent of the injectors tested, as long as a PFI injector body is used. It is also noticed that velocity is mostly positively correlated with SMD. Droplet size and velocity increase further due to droplet collision and coalescence.

Figure 17 shows the opposite effect of micro-machined injector as compared with other PFI injectors. Micro-machined injector has more possibility to have droplet coalescence and collision generated by pressure perturbation due to distance of hole-to-hole. While PFI injectors have the effect of decreasing SMD at conditions of resonant frequencies (up to 30%), droplet size of micro-machined injector is getting bigger up to around 40% with compare to condition of baseline spray. The net result of pressure modulation is generally shown on atomization enhancement which is negated by droplet coalescence and collision.

4. CONCLUSION

In this study, it was found that atomization strongly depends on injector design, orifice size, and driving parameters (frequency and power) and the atomization characteristics of automotive PFI injector spray are improved significantly by the pressure perturbation generated inside fuel line over a wide range of fuel flow rate. Some important findings are summarized as follows;
(1) Pressure Modulation affects on SMD, velocity and

spray behaviors (spray angle and penetration length).

(2) The fuel spray is more uniform in space by the pressure modulation technique with compare to condition of baseline spray.

(3) There are decreasing effects of SMD up to 30% on PFI injectors and increasing effect of SMD up to around 40% on micro-machined injector with compare to condition of baseline spray.

(4) Sufficient hole-to-hole separation appears to be critical in avoiding droplet coalescence in the multiple-hole micro-machined injectors.

In addition, more detailed study is necessary to find out the relationship between orifice size and hole-to-hole spacing with pressure modulation.

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