EPA/AA/TDG/94-03

Technical Report

High-Speed/High-Resolution Imaging Of Fuel Sprays From Various Injector Nozzles For Direct Injection Engines

by

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MEMORANDUM

SUBJECT: Exemption From Peer and Administration Review

FROM: Karl H. Hellman, Chief *KH*
Technology Development Group

TO: Charles L. Gray, Jr., Director
Regulatory Programs and Technology Division

The attached report entitled "High-Speed/High-Resolution Imaging of Fuel Sprays from Various Injector Nozzles for Direct Injection Engines," (EPA/AA/TDG/94-03) describes the results of our continuing in-house investigation to quantify the transient fuel spray properties from new concept injectors and technology for engine applications. A high-speed laser sheet imaging system and a laser diffraction technique were used to integrate the visual observations with the droplet size measurements from various injector nozzles.

Since this report is concerned only with the presentation of data and its analysis, and does not involve matters of policy or regulations, your concurrence is requested to waive administrative review according to the policy outlined in your directive of April 22, 1982.

Concurrence:

Charles Gray
Charles L. Gray, Jr., Director, RPT

Date: *10-10-94*

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I. Summary

A high-speed/high-resolution imaging technique and analysis were applied to study fuel injector spray timed evolution in ambient air and in a motored single-cylinder engine. Alcohol fuel was injected from a low- and mid-pressure fuel injection systems. The two injection systems with various nozzles were designed for use in the EPA/NVFEL program to develop clean and efficient engines that use alternative fuels.

A 15W copper vapor laser with a fiber optic delivery system synchronized with a high-speed drum streak camera was utilized to expose films at 5,000 frames per second (fps). The spray characteristics were investigated at injection pressures of 0.68 MPa (100 psi) and 15.0 MPa (2,200 psi) and injection duration range of 3-5 ms. A sequence of successive frames was selected from the films to examine the influence of the injector parameters and the valve lift on the atomization process. The spray penetration was quantified by analyzing the high-speed films. The mean droplet size distributions from the nozzles were measured by using the Malvern particle sizer.

This report is part of an ongoing investigation to obtain information on the transient spray properties from new concept injectors and technology for direct injection engine applications. Experimental results indicated that the low-pressure injectors yielded large droplet and the mid-pressure injectors generated small droplet on the average of 10 microns (μm). This is due to the spray convergence and droplet coalescence in the low-pressure injector and to the high fuel jet momentum, and consequently, the good atomization in the mid-pressure injector. The visual observations provided valuable information about the spray features and are used to interpret the droplet size measurements.

II. Introduction

An important area for successful further development of the internal combustion engine involves convenient control of the fuel-air mixture at the time that combustion is initiated to promote fuel efficiency, reduce exhaust emissions, and provide flexibility of operation in a broader range of speeds and loads. The use of advanced fuel injection systems appears to be an attractive approach that could improve the engine combustion process and reduce emissions. The emphasis in this effort is to provide in a systematic approach the needed experimental data on the spray dynamics, including atomization, vaporization and mixing, from low- and mid-pressure direct cylinder fuel injection systems. By better understanding the simultaneous effects of the injector controlling design parameters, it is hoped that this work will assist the ongoing fuel injection and engine development at the Environmental Protection Agency's National Vehicle and Fuel Emissions Laboratory (EPA/NVFEL).

The advent of high-pressure fuel injection systems has led to a large number of system arrangements, like the dual-injector, sequential injection and the two-stage injector systems. With these arrangements there have been several studies concerned with the injection system performance. Many important aspects of the spray events were tested under various ambient pressure conditions utilizing different imaging techniques. Savey, et al. [1]* used stroboscopic flash photography to visualize the spray characteristics of a unit injector operating with water injection into the ambient air. The photographic evidence used in conjunction with dynamic laser attenuation measurements allowed the estimation of the spray penetration distance and cone angle. A shadowgraphic technique was employed by Kato, et al. [2] for the analysis of non-evaporating fuel spray characteristics. Fuel was injected into a high pressure nitrogen-filled chamber where spray events were captured with a high-speed camera. Spray droplet diameter and equivalence ratio were analyzed using shadow photographs. In-cylinder tests of the injection process were also conducted, but these did not include any visualizations. Katsura, et al. [3] photographed the impingement of a diesel spray on a flat wall in a high-pressure chamber with both transmitted and scattered light. The effect of ambient density was studied and it was found that the spray droplet size decreases with increasing ambient density. The synchronization of a copper vapor laser sheet with a high-speed camera was employed by Hamady and Morita. [4,5] Experiments were performed by injecting jet-type fuel through a single-hole nozzle at high-injection pressure into atmospheric air and in a direct injection rotary engine. Several event-to-event variations in the injection process were observed that had not previously been noted.

Engine studies using pressured chambers with air flow were considered to simulate in-cylinder flow situations. Hiroyasu, et al. [6] used high-speed Schlieren photographs to observe spray vaporization and analyze diesel spray behaviors. A repetitive micro-flash used with a drum camera allowed Yoshikawa, et al. [7] to observe spray behavior. They also conducted in-engine studies and utilized emission measurements to optimize the injection conditions. In a firing engine, Werlberger and Cartellieri [8] used the endoscopic high-speed combustion photography technique to study wall jet development, the role of swirl, and the effect of the pilot injection on mixture formation and combustion.

With advances in measuring techniques, other optical systems were developed and applied, namely, laser diffraction and laser sheet illumination [9-11] for determining the droplet size distributions, spray

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* Numbers in brackets designate references at end of report.

penetration, and cone angle. Phase Doppler anemometry [12,13] was used for examining the dynamic behaviors of the fuel jet such as velocity and particle size. Laser induced exciplex fluorescence [14,15] and laser induced Rayleigh scattering [16] were also devised to provide planar information on the spray characteristics, including vapor and liquid phases and fuel vapor concentration, of the fuel-air mixture.

In view of the above discussion of various methods to quantify the spray structures, high-speed/high-resolution imaging is needed to describe the fuel injection process and to integrate the visual observations with the quantitative measurements. For instance, spray regions of interest can be identified and examined for their transient behavior. In this investigation, emphasis was placed on the analysis of the injector's controlling parameters which influence the fuel spray structures. Several nozzles of different designs were manufactured to achieve injection of different spray patterns. High-speed imaging and laser diffraction systems will be devised to examine and quantify the spray features of interest. On the basis of the spray analysis, the information will be used to suggest design changes which will enhance atomization, spray formation, and the droplet size distributions. Information of this type is not only important, but provides a valuable database for the development and evaluation of concepts that exploit fluid dynamic instabilities or other approaches to enhance atomization.

III. Experimental Facilities

A. Engine Assembly

For this work, an OH160 Tecumseh single-cylinder air-cooled engine was modified by bolting an extension on the original piston top. The extended piston is contained within a cylinder which has three mounts to support quartz windows for imaging and droplet size measurements. The retrofitted piston with a cylindrical bowl cut into it is equipped with a quartz insert to allow optical access through the piston. An adjustable mirror holder including a mirror is located inside the extended piston to provide optical access into the combustion chamber through the piston. The Tecumseh cylinder head was replaced by an in-house custom-fabricated cylinder head to adapt different types of injectors. Figure 1 shows that a fuel injector can be centrally positioned so that its centerline coincides with the cylinder axis.

The spark plug is mounted close to the injector tip. The valves were driven by extending the push rods from the base engine with the same stock timing. Standard piston rings and intake and exhaust manifolds were used in this assembly. Table 1 shows the specifications of the modified

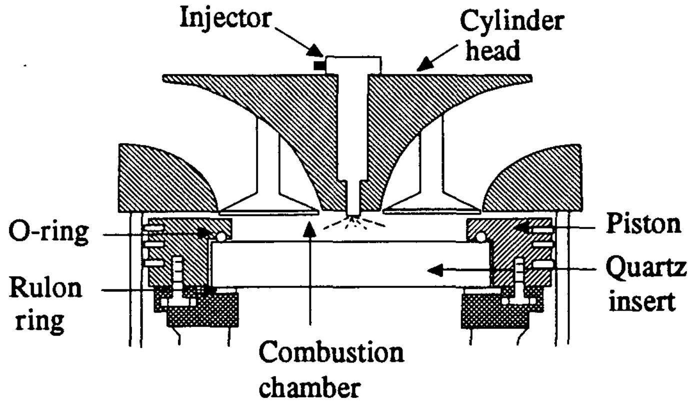


Figure 1 Engine modified cylinder head assembly

engine. The engine assembly was constructed to allow easy changing of the engine head, piston and quartz. The assembly was mounted onto a heavy steel plate along with an 11.2 kW (15 hp) variable-speed electric motor coupled to the engine crankshaft. An IC5460 engine electronic control unit was used to control the ignition timing and fuel injection operation.

Table 1 Modified engine specifications

Bore x Stroke (mm)	88.9 x 73.0
Displacement (cm^3)	453.3
Diameter of piston bowl (mm)	60.0
Depth of piston bowl (mm)	10.0
Compression ratio	12.0
Number of valves	2

B. Fuel Injection Systems

Two fuel injection systems were used in this investigation, The first operating at 0.68 MPa and the second at 15.0 MPa fuel pressure. The first system is equipped with a nozzle having an outward opening spring-loaded poppet valve which is operated by an electronically controlled integral solenoid. The outward opening uses the cylinder pressure to hold the valve against its seat to improve closure process. Due to the low-injection pressure the injection events will occur during the intake and early part of compression stroke. The nozzle assemblies are shown in Figure 2.

In the mid-pressure system, two injector types were used. The first injector is equipped with a nozzle having an outward opening spring-loaded poppet valve which is operated by the fluid hydraulic pressure.

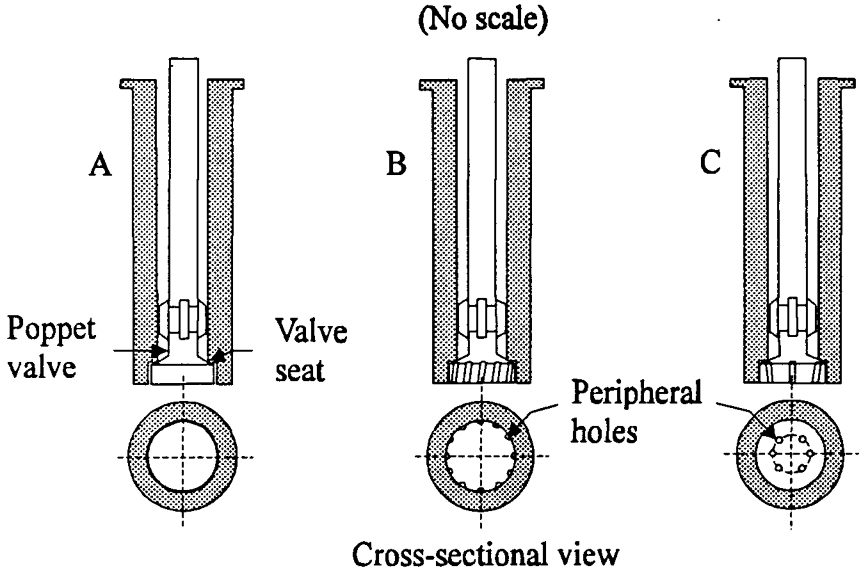


Figure 2 Low-pressure injector nozzle assemblies

The nozzle assembly is shown in Figure 3. The nozzles and springs can be varied to study different injector concepts.

The second injector has an inward opening needle valve actuated by the pressure acting against spring force. The fuel injection system has full electronic control of the solenoid valve. Initially, the second fuel injector nozzle tip design incorporated a cruciform slot geometry. The fuel spray from this nozzle utilized the swirling effect imparted to the fuel as it

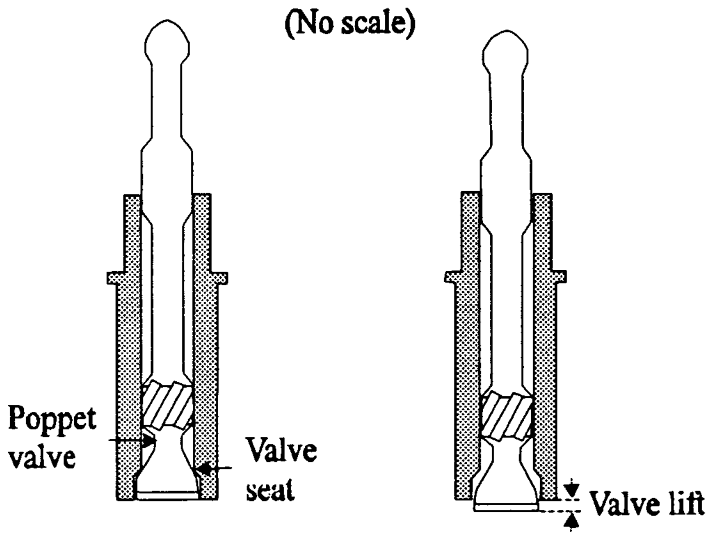


Figure 3 Mid-pressure injector poppet type nozzle assembly

passes through angular slots on the nozzle needle. As shown in Figure 4, a set of different nozzle designs have been used, in an attempt to improve the droplet size distributions.

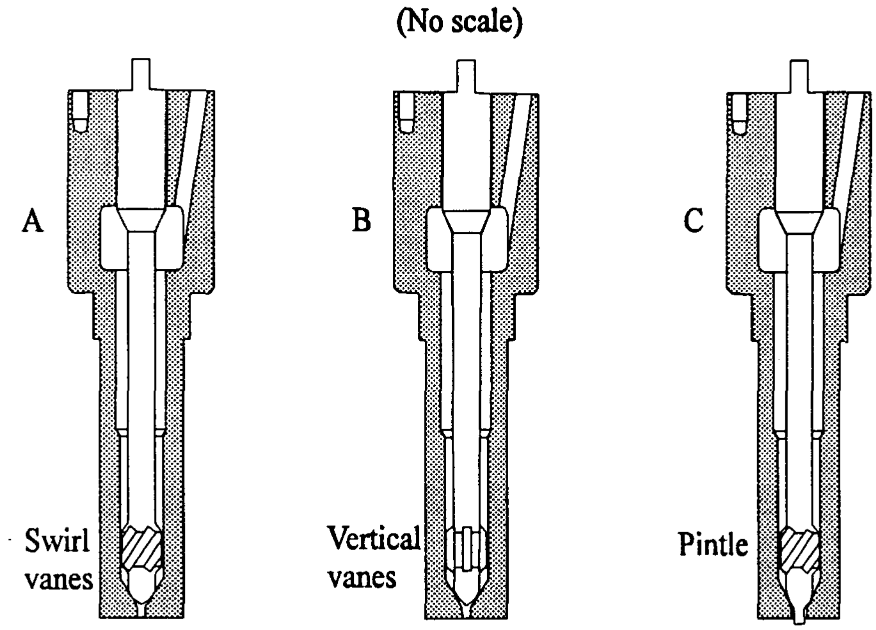


Figure 4 Mid-pressure injector nozzle assemblies

C. High-Speed/High-Resolution Imaging System

The high-speed imaging system is shown schematically in Figure 5. It consists of a copper vapor laser, fiber optic delivery system, light sheet forming optics, laser drum streak camera, and a laser 'n' shot controller.

The copper vapor laser (CVL) Model CU15-A, is a gas discharge device of 15W average output power manufactured by Oxford Lasers. It emits short pulses of 5-30 kHz at pulse energy 2.75 (max.) in the green and yellow regions of the visible spectrum at wavelengths of 511 and 578 nm. The pulse duration is approximately 20 ns and pulse jitter is ± 2 ns. The laser main components are a plasma tube, high-voltage DC power supply and pulsed discharged system (thyratron driver and thyratron). The thyratron driver is a high-voltage, high-repetition pulse generator which provides trigger pulses to the thyratron. The driver can be operated using an internal oscillator or by applying the external pulse to the trigger select.

The laser beam (25 mm in diameter) can be directed toward the region of interest by the fiber optic delivery system. The fiber diameter used is 600μm. The fiber has a standard mount adapter (SMA) termination at both ends. Overall injection transmission efficiencies are in excess of 70 percent for fiber diameters greater than or equal to 600 μm.

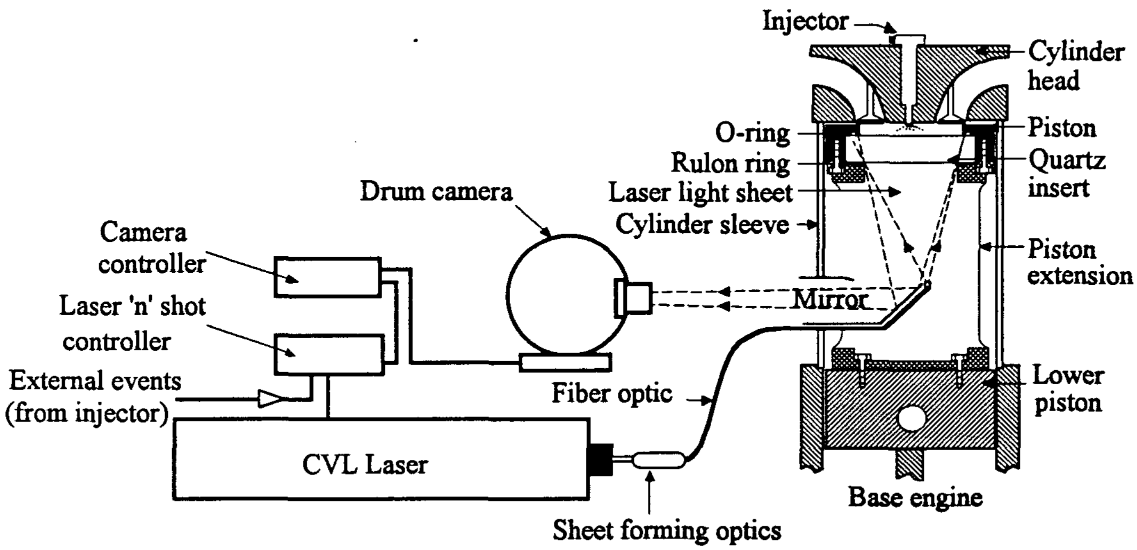


Figure 5 High-speed/high-resolution imaging system and optical engine assembly

The camera is a Cordin Model 321 laser drum camera, which exposes a streak/frame record of 25 mm wide and 1,000 mm long at a maximum rate of 0.30 mm/μs on a standard 35 mm, 400 ASA color negative film and has an effective aperture of f/3.2. It is designed for framing use with the CVL pulsed laser at 35,000 frames per second (max.). The film is loaded and recovered with a single-shot, daylight cassette. The camera has a reflex viewer to simplify focus. The camera housing is evacuated to at least 20 mm Hg absolute pressure during operation. This reduces image aberrations from density variations in the air and thermal effects of friction. The camera operational parameters are controlled by its controller Model 447A.

The laser 'n' shot controller is used to switch the thyratron driver of the CVL from internal to external modes. In the external mode, the pulse generator of the controller triggers the laser the number of pulses at the frequency desired during the filming process. At the end of the film, the controller switches the laser back to the internal mode. The controller can also be used to synchronize fuel injection events and ignition timing with the camera. Operation of the system can be used to study time-resolved fuel sprays during single-injection events and to study individual engine combustion events.

D. Malvern Particle Sizer

The Malvern particle sizer is an optical system which uses line-of-sight measurement through the spray. It is applied to measure the ensemble characteristics of the spray like the droplet size distributions. The system measures simultaneously the intensity of the forward diffracted light at several angles as the laser beam passes through the spray.

The Malvern software can provide calculated information such as the Sauter mean diameter (SMD) and other derived parameters including volume concentration and specific surface area. More details on the accuracy and limited applications of the Malvern system are found in references [18-20].

IV. Results and Discussion

This section presents an analysis of alcohol fuel sprays from a low- and mid-pressure injection systems injected in ambient air at atmospheric pressure and in-cylinder at engine speed of 1,000 rpm. High-speed imaging of the spray events were taken at 5,000 fps in axial planes along the nozzle axis. From the flow visualizations, important spray features were identified and integrated with the droplet size measurements and injector controlling parameters to quantify spray properties.

In the first phase of experiments, sprays from ten different geometric configurations of nozzle "A" (see Figure 2) of the low-pressure injection system were examined. The nozzle tip configurations were based on flush-closed and flush-open between the poppet valve and nozzle body. Figure 6 shows successive frames of the entire injection event from nozzle "A" with a flush-open configuration. This figure demonstrates clearly the detrimental effect of spray convergence and droplet coalescence on the atomization process and, consequently, further in the event formation of large droplets dominated the spray pattern. The visual observations from the other nine nozzles showed similar phenomena prevailing the spray structures; therefore, photographs will not be presented.

To quantify the spray features described in Figure 6, droplet size measurements were conducted along the spray axis. Figure 7 presents the variation in droplet size at 2.5 and 5.0 cm from the nozzle exit. From the measurements large droplets were found to exist through the end of

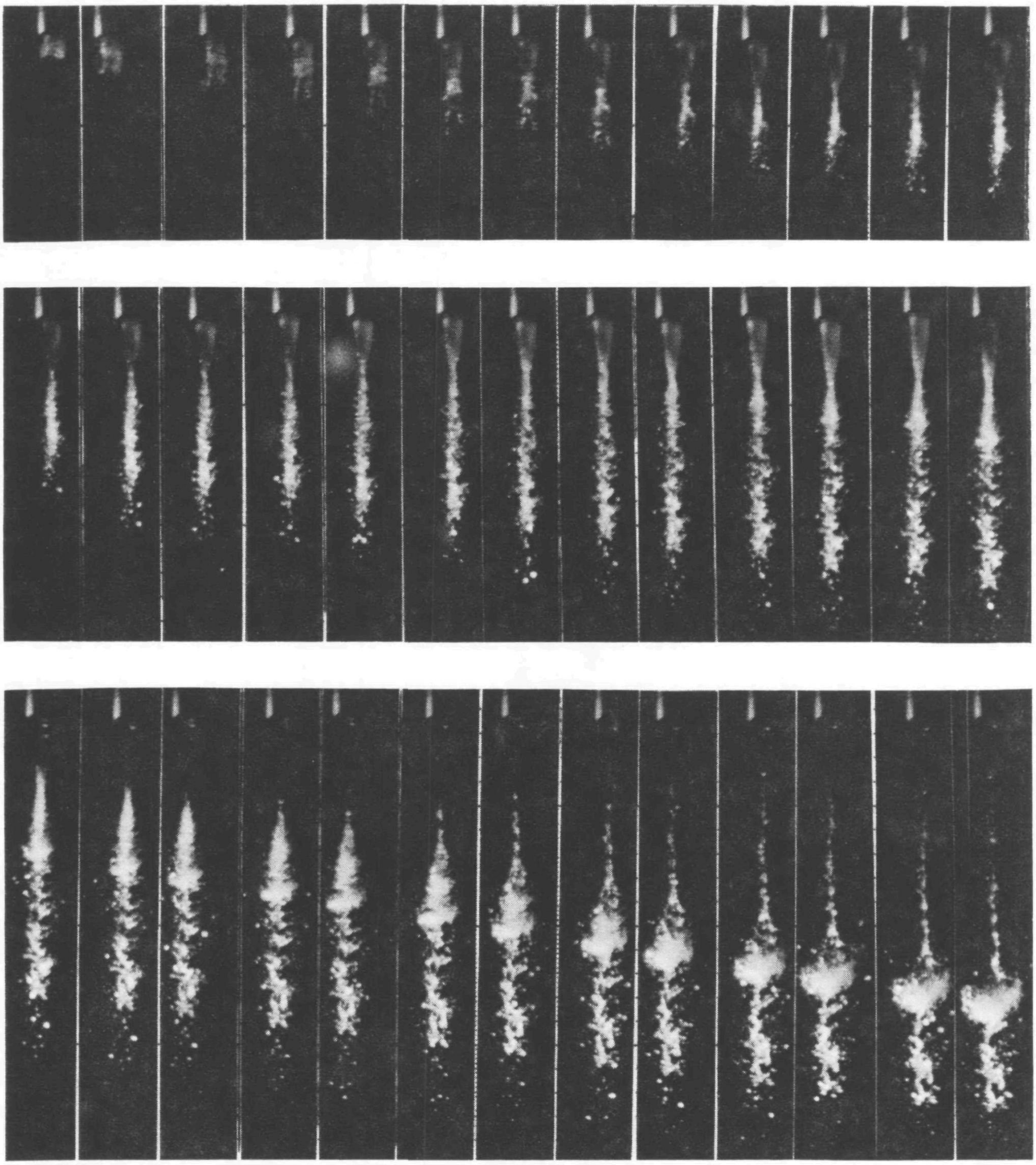


Figure 6 Successive frames of one injection event injected from the low-pressure injector (nozzle "A") into the atmosphere at 0.68 MPa injection pressure and 5000 fps

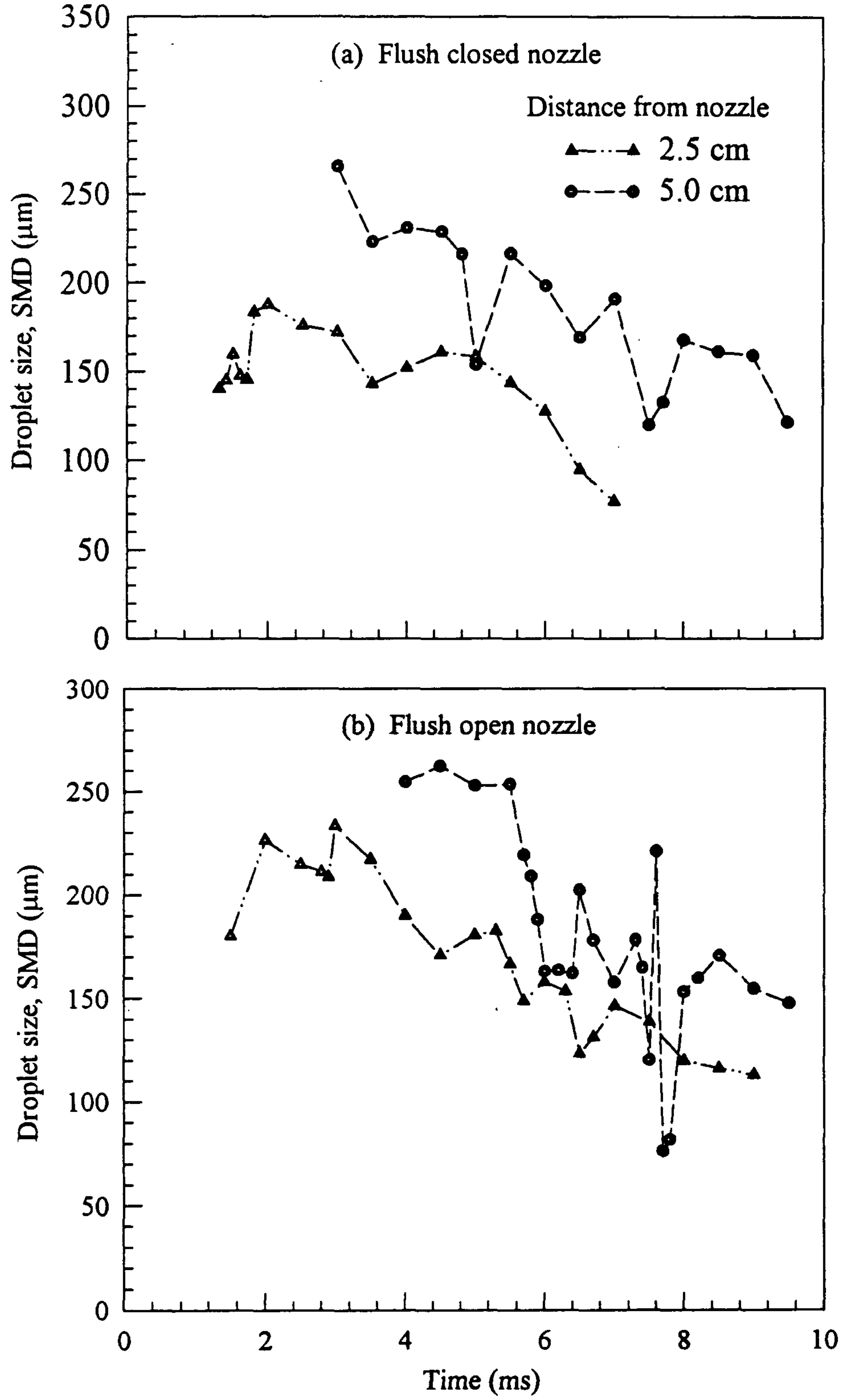


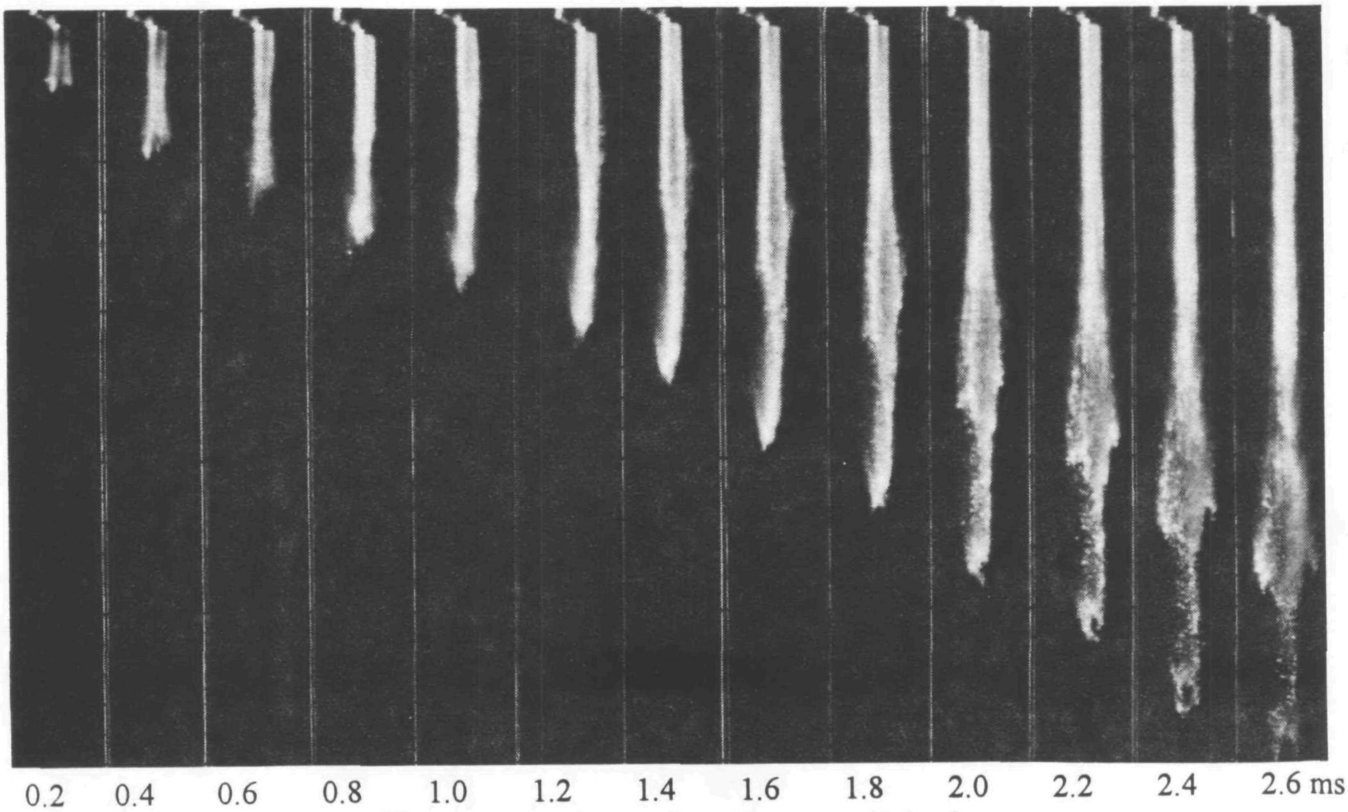
Figure 7 Variation of droplet size with time from the start of injection for the low-pressure injector

injection. It was also apparent from the experiments that the atomization was influenced by the inconsistent performance of the injector solenoid valve design, plunger travel, and dynamic response. Due to these adverse effects of the spray convergence and injector performance on the atomization process, limited results are presented in this report. However, further injector developments and modifications to promote the atomization are underway.

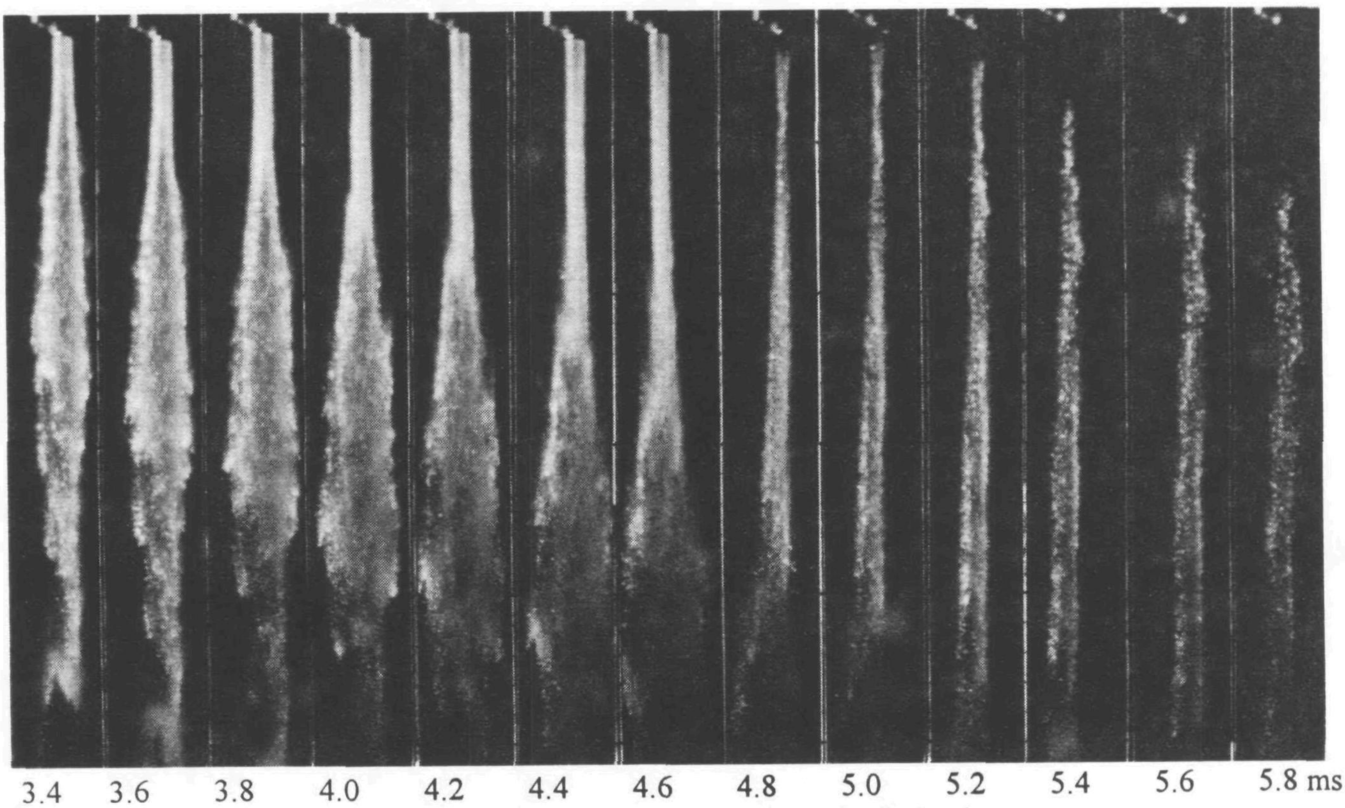
In the second phase of experiments, sprays from the mid-pressure injectors were analyzed. For poppet valve injector depicted in Figure 3, a sequence of successive frames were selected to demonstrate the spray development in ambient air at 0.7 mm valve lift. At the start of injection, Figure 8 shows a narrow cone-shaped spray formed at the nozzle exit. In the early stage the fuel jet moved outward from the nozzle, where the leading edge traveled with a high-penetrating velocity before dissipating. After reaching the breakup length the spray penetration velocity decreased significantly. This spray behavior is a consequence of the aerodynamic interaction between the fuel jet and the ambient air, which usually leads to enhancement of the fuel atomization and fuel-air mixing process. As the injection event proceeds the fuel jet continues to penetrate the ambient air but at a lower rate. At the outer surface of the jet the mixing region grows in breadth and the liquid core disintegrates into droplets. Between 2.2 and 4.6 ms, Figure 5 demonstrates these features of the fuel jet divergence and the decrease in penetration velocity. In the final stage of the injection event (after 4.6 ms) large droplets can be observed due to valve closing and droplet coalescence. Experiments were also conducted for valve lift of 0.3 mm. The general spray features resemble those described previously; however, photographs indicated a better atomization process as displayed in Figure 9.

From the high-speed films, the spray penetration distances were measured and plotted for two poppet valve lifts in Figure 10. It is important to note that after 2 ms the slopes of these curves start to decrease, quantifying the visual observation of liquid core breakup. The figure also indicates that by limiting the valve lift from 0.7 to 0.3 mm the corresponding penetration distances are increased. This can be attributed to restricting the nozzle exit which elevates the pressure differential at the valve seat and consequently the fluid speed.

The spray mean droplet sizes represented by SMD were measured along the spray axis at different distances from the nozzle exit for 5 ms pulse duration. The droplet size distribution profiles in Figures 11(a) and 11(b) show a decrease in the droplet size with the measurement delay times from the start of injection, and an increase near the end of injection event. The large droplet formation at the start of injection is caused by

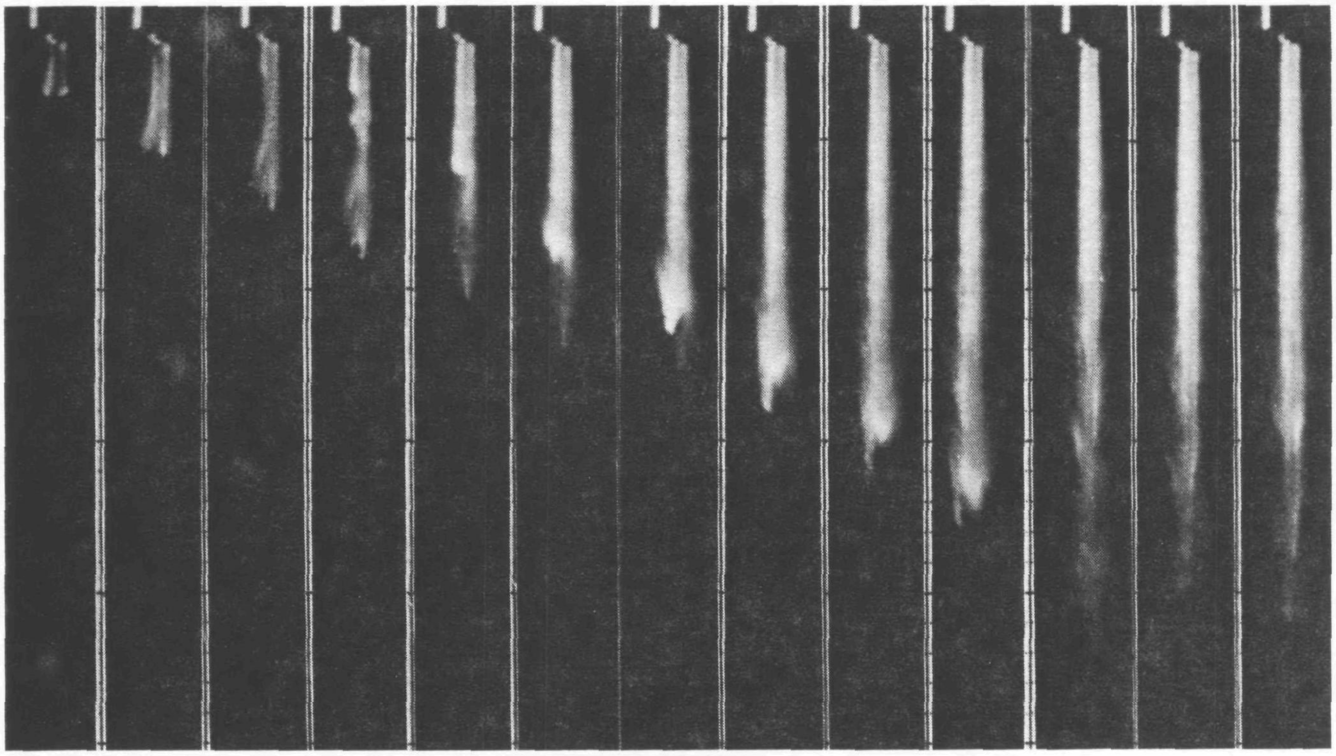


(a) Successive frames from the start of injection



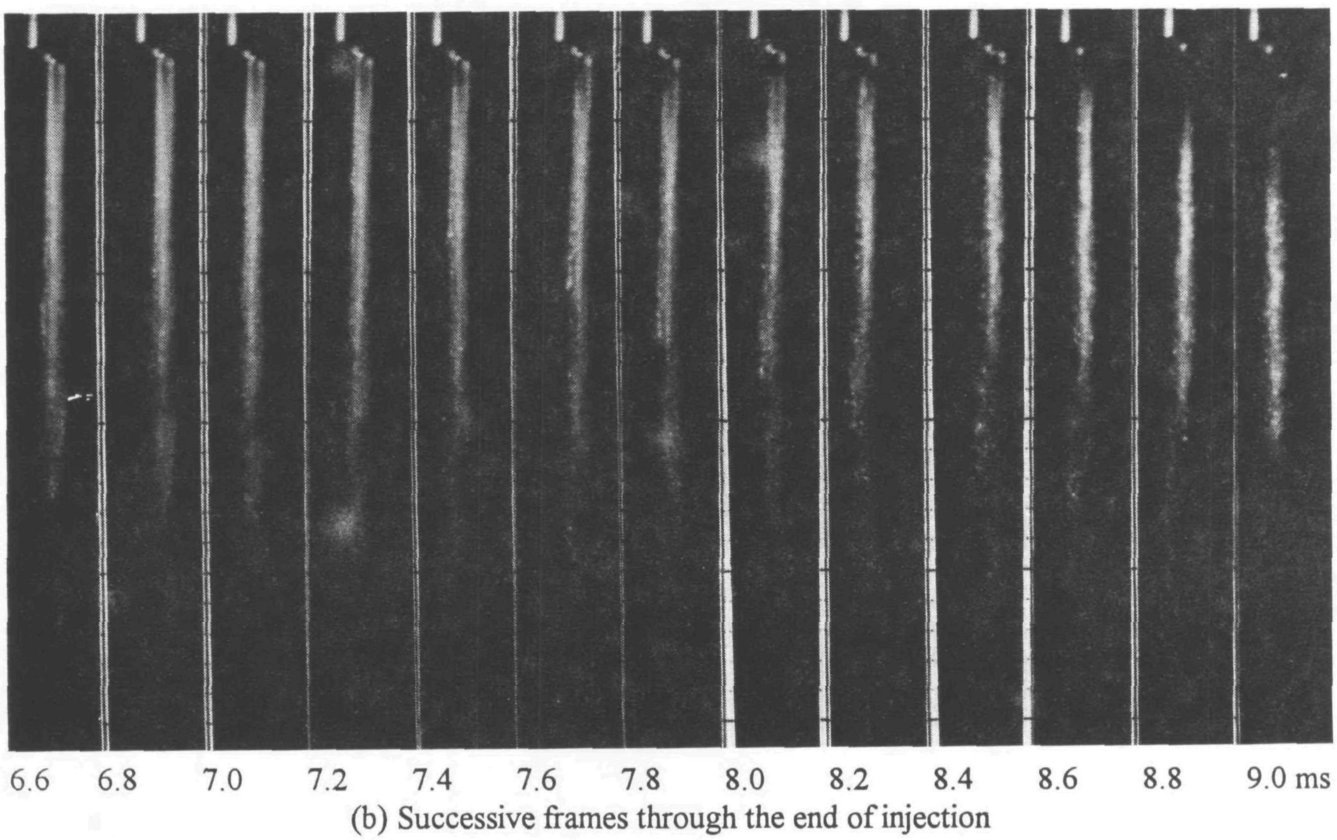
(b) Successive frames through the end of injection

Figure 8 Selected frames of one injection event injected into the atmosphere from the mid-pressure poppet valve injector at 15MPa injection pressure (0.7 mm valve lift and 5000 fps)



0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 ms

(a) Successive frames from the start of injection



6.6 6.8 7.0 7.2 7.4 7.6 7.8 8.0 8.2 8.4 8.6 8.8 9.0 ms

(b) Successive frames through the end of injection

Figure 9 Selected frames of one injection event injected into the atmosphere from the mid-pressure poppet valve injector at 15MPa injection pressure (0.3 mm valve lift and 5000 fps)

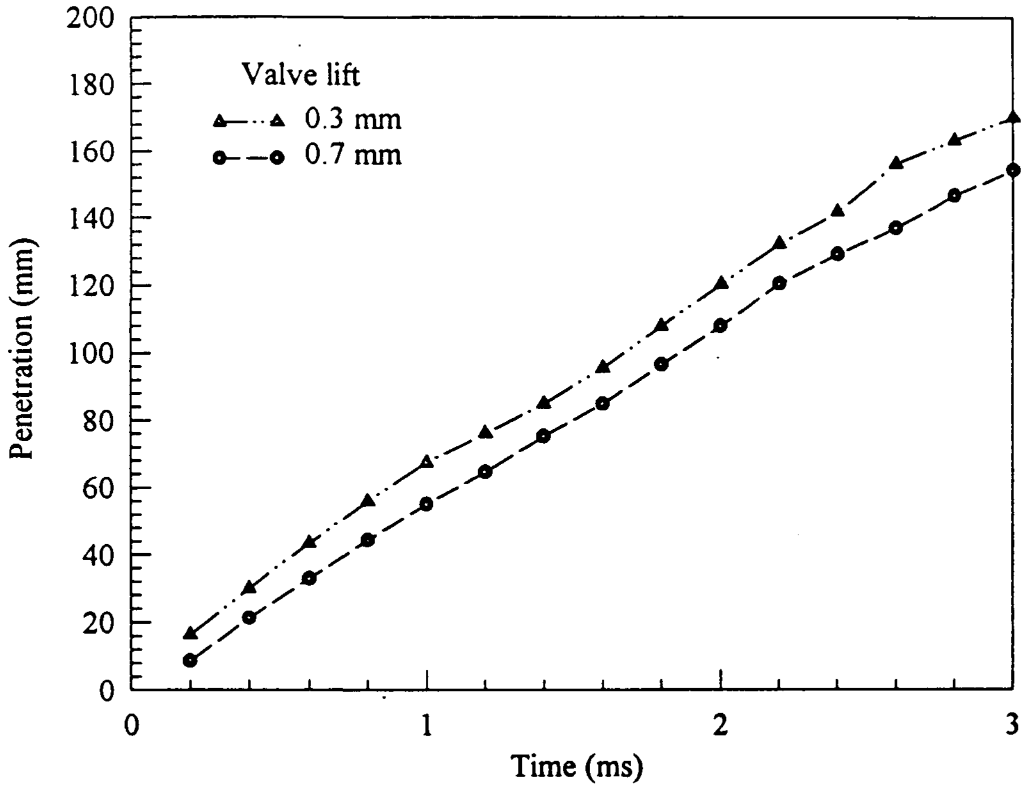


Figure 10 Valve lift effect on the spray penetration for the mid-pressure poppet valve injector

the relatively lower liquid jet momentum and its lower energy to atomize the fuel. As the injection process continues, the momentum of the liquid jet attains its maximum value, which in turn breaks the liquid stream into fine droplets. This eventually leads to the atomization process demonstrated in the figure after delay time of 2 ms, where smaller droplets become to dominate the spray region. After 6 ms, it is evident that the droplet size starts to increase again. This can be attributed to the nozzle valve closing and the coalescence of the droplets in the spray trailing region where the fuel jet energy is dissipated. Figure 12 shows a comparison of the valve lift effect on the droplet size distribution. This figure indicates 30 percent reduction in droplet size with decreasing the valve lift from 0.7 to 0.3 mm on the average. It is important to mention that with a smaller valve lift the spray fluctuations are minimized due to less mechanical instabilities in the injector. In addition, the measured flowrates at the 0.7 and 0.3 mm valve lifts are respectively 75 and 79 mm^3/injection for 5 ms pulse duration. In a direct injection engine a droplet size of 20 μm or less is desired for faster vaporization. The spray droplets produced by the 0.3 mm lift nozzle approach this value.

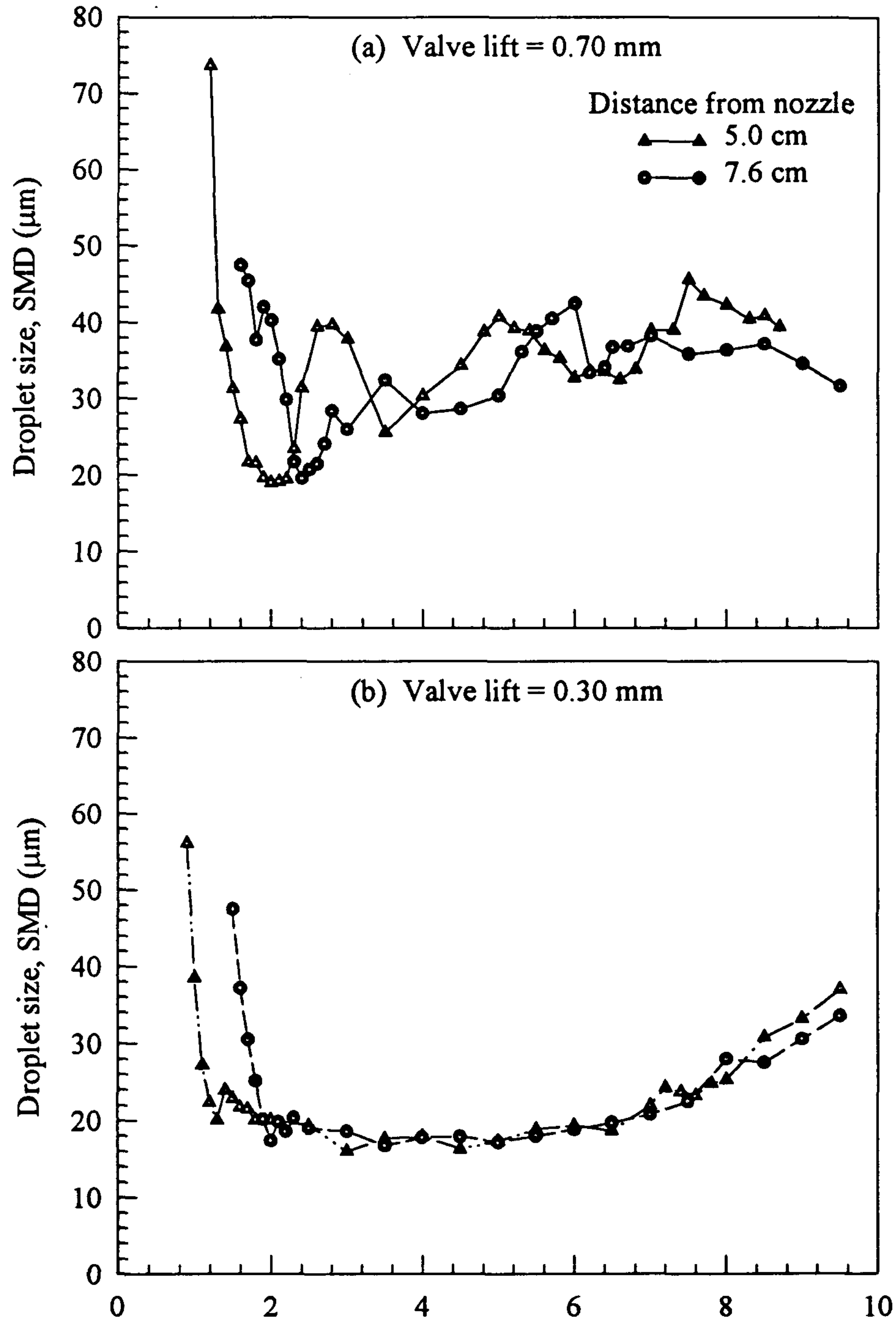


Figure 11 Variation of droplet size with time from the start of injection for the mid-pressure poppet valve injector

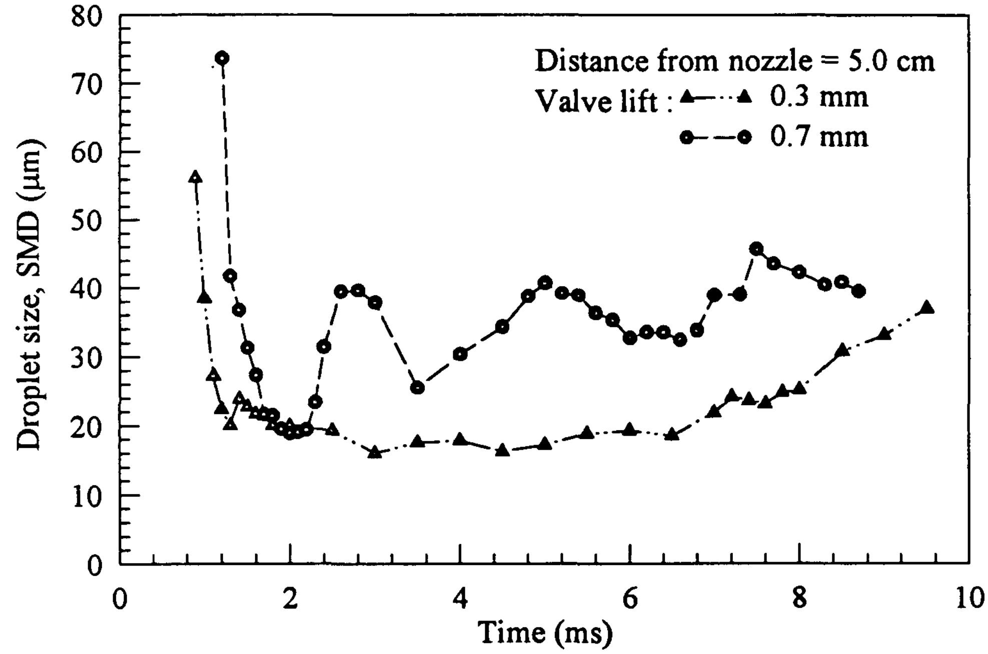
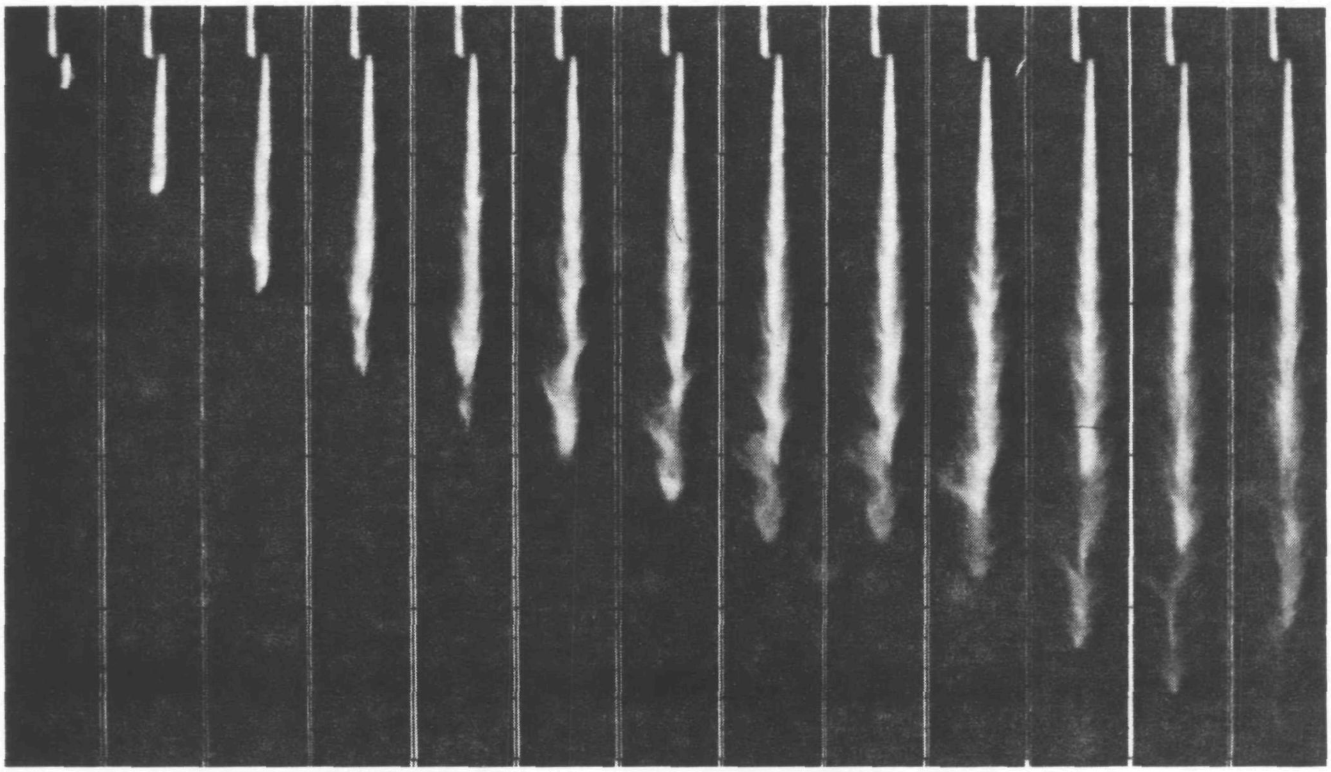


Figure 12 Valve lift effect on the droplet size distribution for the mid-pressure poppet valve injector

In this part of the experiments, high-speed imaging was applied to characterize the sprays from three different nozzle assemblies "A", "B" and "C" as shown in Figure 4. Nozzle "A" has swirl vanes and a single hole of length to diameter ratio of 2 (l/d = 2, d = 0.2 mm), Nozzle "B" has vertical vanes and a single hole of l/d = 4 (d= 0.6 mm) and nozzle "C" has swirl vanes and a pintle valve. For nozzle "A", Figure 13 displays one injection event in ambient air at 15 MPa fuel injection pressure. In this figure spray development is analogous to that described in Figure 9. However, photographs indicate better atomization during the early stage of injection due to nozzle geometry, fluid velocity and valve opening. In addition, this spray pattern combined with the fluid droplet air interaction continued to promote the atomization process during the entire injection event. At the valve closing relatively small droplets can be observed.

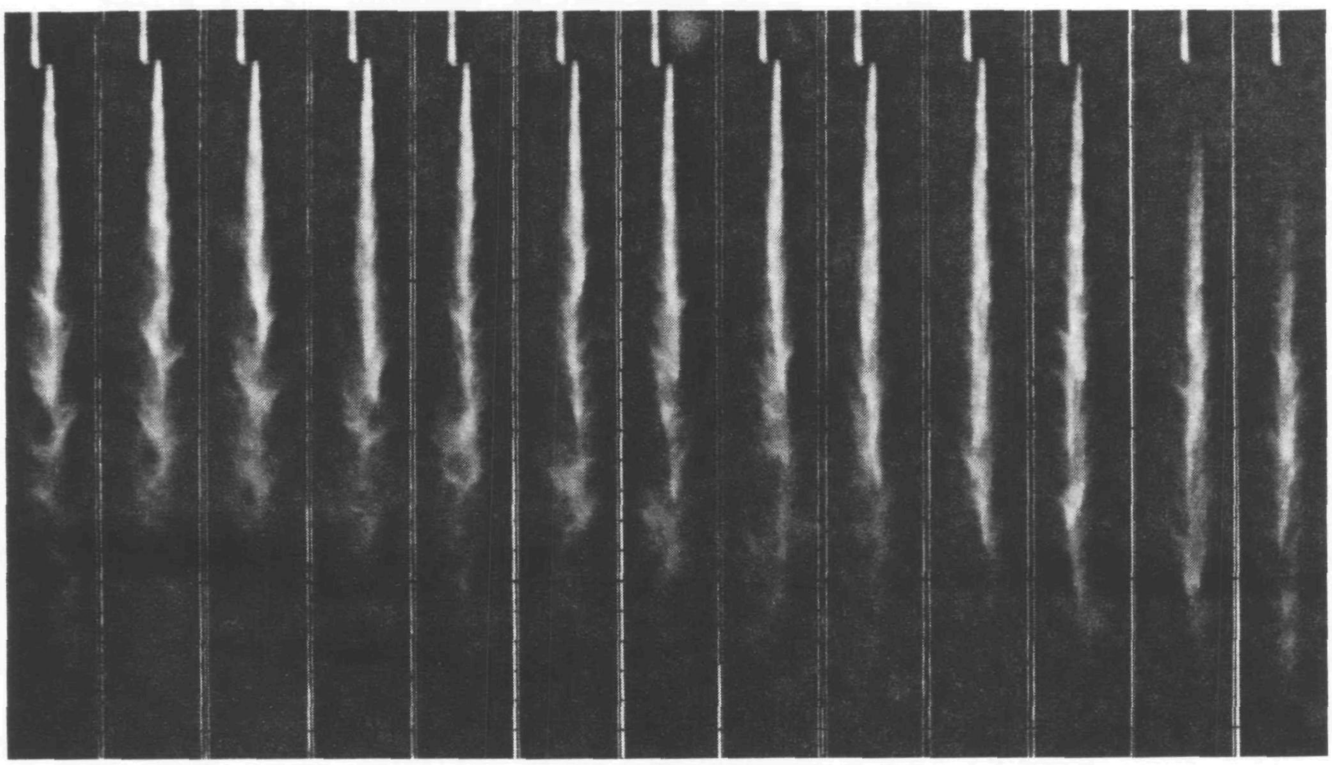
Under similar conditions, high-speed imaging was performed to describe the spray patterns from nozzles "B" and "C". Photographs from both nozzles showed resemblance to the general spray features from nozzle "A". Quantitative description of the spray penetration distances and droplet size measurements are presented below.

Figure 14 presents a comparison of penetration distances from the three nozzles. It is important to note that nozzle "A" has a larger



0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 ms

(a) Successive frames from the start of injection



7.4 7.6 7.8 8.0 8.2 8.4 8.6 8.8 9.0 9.2 9.4 9.6 9.8 ms

(b) Successive frames through the end of injection

Figure 13 Selected frames of one injection event injected from the mid-pressure single hole nozzle (nozzle "A") into the atmosphere at 15MPa injection pressure (5000 fps) penetration in the early stage of the injection process and consequently higher velocity. This phenomenon led to better fuel atomization as illustrated in Figure 13.

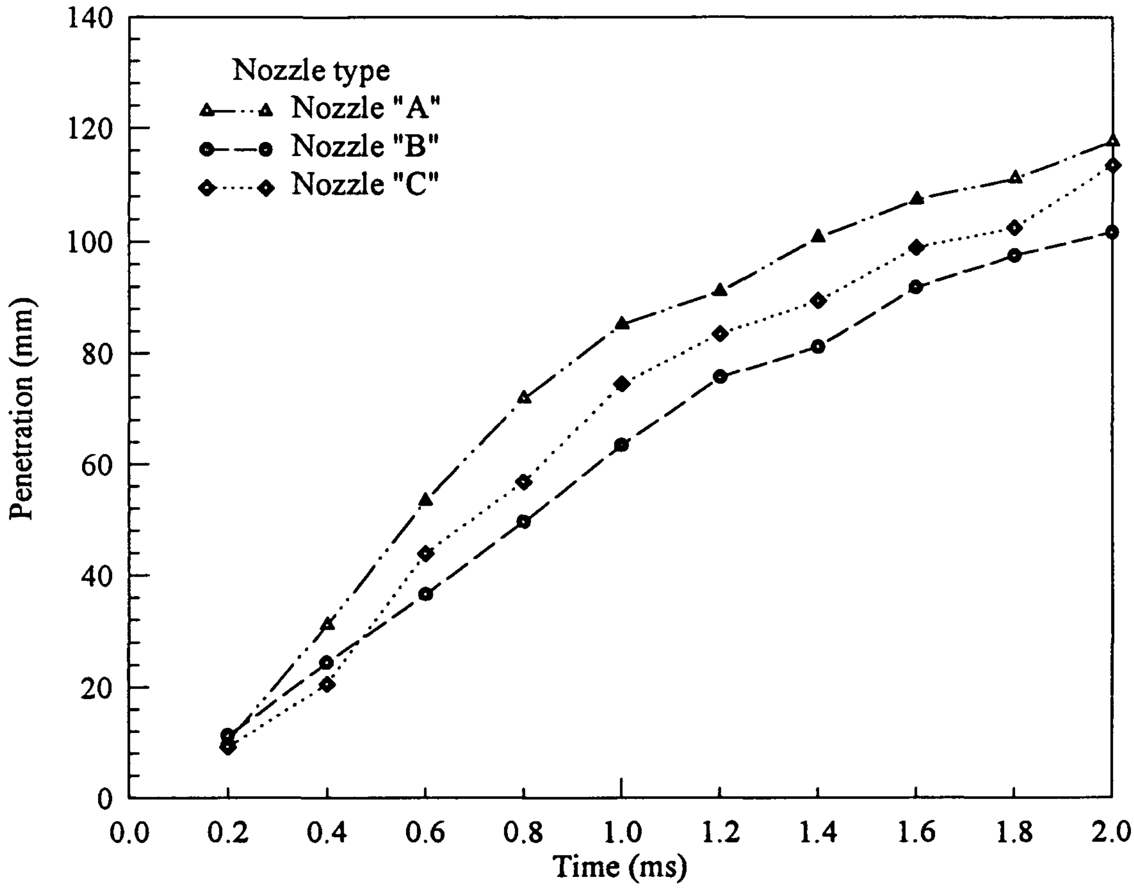


Figure 14 Comparison of the spray penetration at 15 MPa fuel injection pressure for the mid-pressure single hole injectors

Figure 15(a) displays the droplet size measurements from nozzle "A", along the spray axis for two different distances from exit. The average droplet size in this figure is under 8 µm which shows agreement with a subjective evaluation of the spray quality obtained from examination of the images. Good atomization can be observed from the start of injection. Axial distributions of droplet size from nozzle "B" are presented in Figure 15(b). Data show that there is a general increase in the droplet size compared to nozzle "A". Figure 15(c) illustrates the variation of the droplet size from the pintle-type injector. It is apparent from this figure that smaller size droplets are found relative to nozzle "B". The corresponding measured flowrates from the three nozzles for 5 ms pulse duration are 44, 55 and 65 mm^3/injection, respectively.

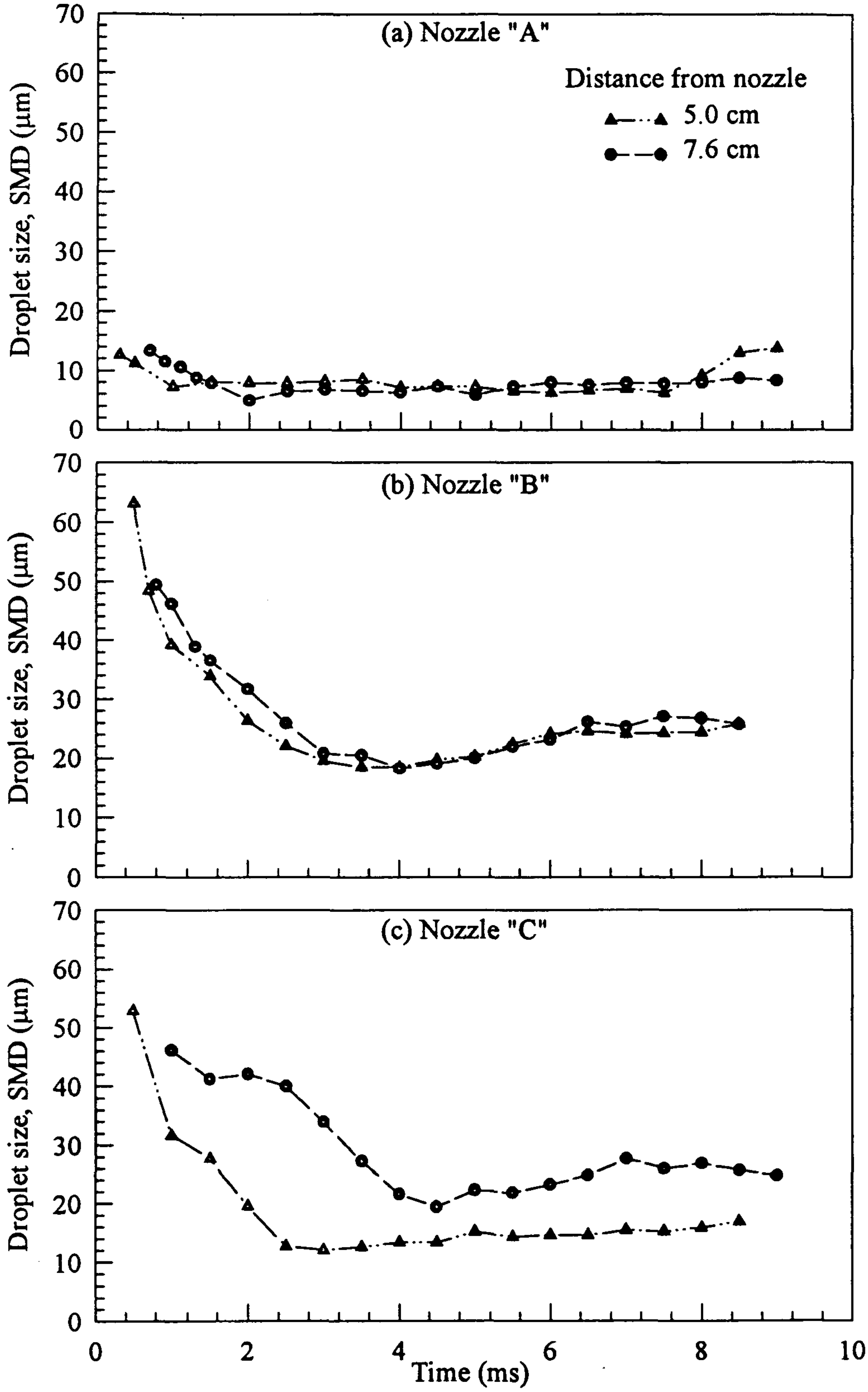


Figure 15 Variation of droplet size with time from the start of injection for the mid-pressure single hole injectors

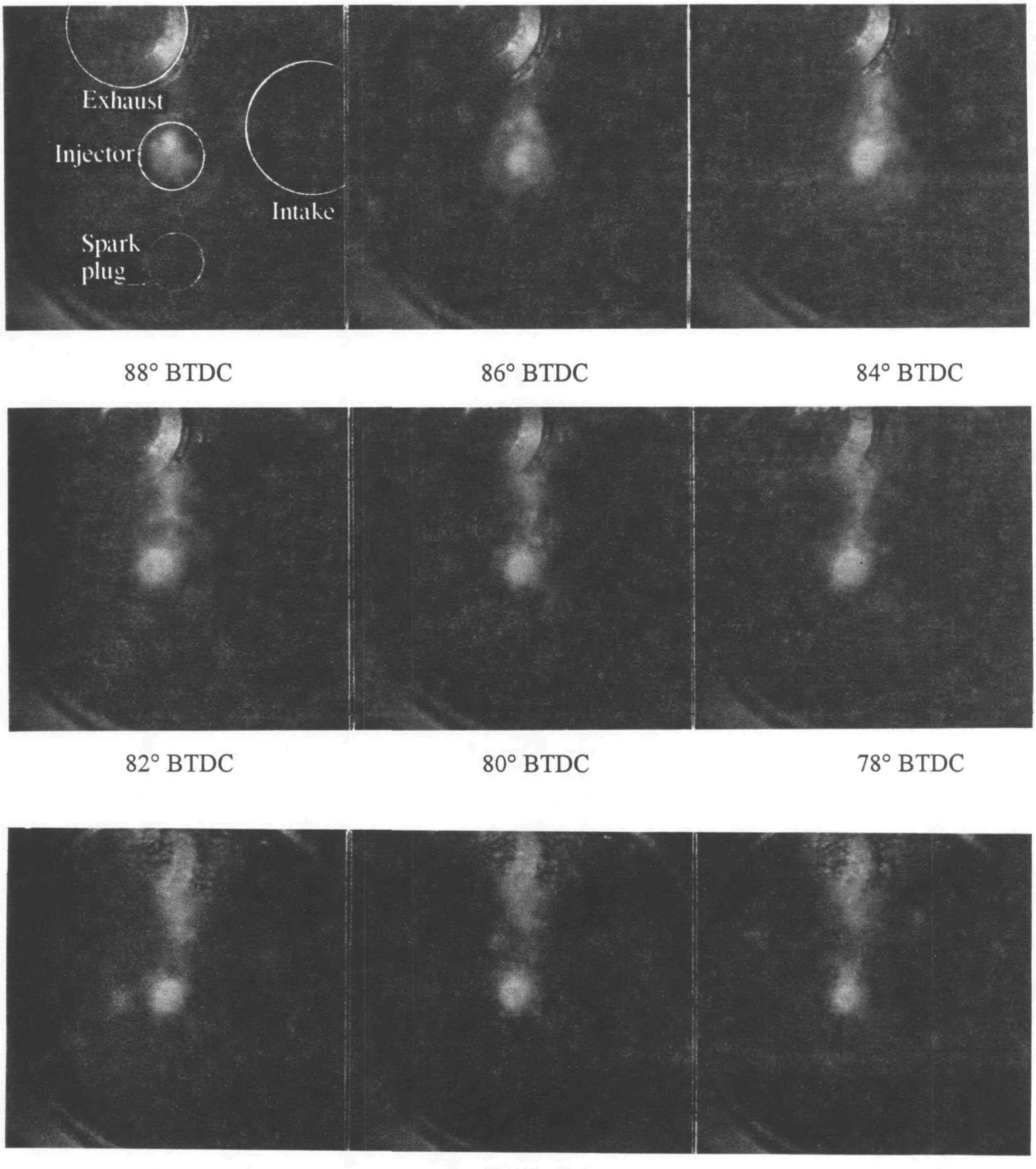


Figure 16 Selected frames of one injection event at 5000 fps and injection pressure of 15MPa from a poppet valve injector during compression in a motored single-cylinder engine at 1000 rpm

In the present study, observation of the spray characteristics in the engine is limited to the poppet-type mid-pressure fuel injection system. The high-speed films were taken by using the optical engine assembly shown in Figure 5. Selected photographs of the injected fuel are displayed in Figure 16 at 15.0 MPa from the start of injection at about 88° CA BTDC. In this set of photographs, the impinged fuel jet diffuses symmetrically in a disk-shaped flow structure originating at the center of the combustion chamber. It is also apparent from 72 to 60° CA BTDC that the fuel distribution is uniform and diffuses symmetrically as the compression proceeds. In this case, a combustion chamber with strong squish flow could be used to enhance fuel-air mixing, improve dilution tolerance and combustion stability. Consequently, a cylinder head with high flow rate and reduced intake air resistance caused by high swirl motion could be used to replace a conventional high swirl direct injection cylinder head. Further development is currently underway at the NVFEL lab to identify, evaluate, develop and utilize advanced injector technologies in direct injection engine applications.

V. Conclusion

The spray characteristics of a low- and mid-pressure fuel injection systems injected into the atmosphere and in-cylinder have been described by analyzing high-speed films of the process. In addition to the qualitative description of the sprays the films were used to measure fuel penetration and give more physical aspects to the laser diffraction droplet size measurements. Comparison of the spray features from the different nozzle configurations provided useful information on the injector parameters and its effect on the sprays. The following concluding remarks can be made:

1. The high-speed imaging system developed at the EPA/NVFEL offers an efficient method to test injectors and study transient spray behaviors. This is to ensure that new concepts are adequately assessed for feasibility and successful design.

2. From the low-pressure injector, the spray convergence and droplet coalescence adversely influenced the atomization and, consequently, contributed to the formation of large droplets.

3. For the poppet valve nozzle of the mid-pressure injector, the penetration distances and droplet sizes were significantly influenced by the valve lift. Smaller droplets were generated by decreasing the valve lift without markedly altering the fuel flowrate.

4. The ensemble characteristics of the spray from nozzle "A" of the mid-pressure injector showed a high level of atomization. This phenomenon is clearly demonstrated in the high-speed photographs, and the droplet size measurements which yielded on the average SMD values of under 8 μm.

5. The penetration distance and droplet size measurements from the three nozzles ("A", "B" and "C") of the mid-pressure injector were consistent with the visual observations. Spray features were significantly influenced by the nozzle design.

6. In an engine the spray from a centrally located mid-pressure injector diffuses symmetrically and shows uniform distribution of the fuel. Accordingly, combustion chamber with relatively strong squish can be used to promote fuel-air mixing and flame propagation.

Finally, progress has been made in demonstrating the effects of various nozzle configurations on the spray patterns and droplet size distribution. In addition, the high-speed images have contributed greatly to the physical understanding of the transient spray characteristics.

VI. Recommendations and Future Efforts

To avoid the spray convergence and its adverse effect on the atomization in the low-pressure injection system, the following design modifications should be made: (a) replace the vertical slots with swirling vanes on the valve stem, (b) use tapered nozzle tip, and (c) restrict the diametral clearance between the valve and the nozzle body.

In the mid-pressure injection system fine atomization was achieved from some nozzle designs; however, the bouncing in the other injectors influenced significantly the spray characteristics. In this case, modifying the accumulation volume or the spring in the injectors is required.

The continuing efforts of the Technology Development Group of the Office of Regulatory Programs and Technology at the EPA/NVFEL lab will focus on fuel spray characterization and combustion analysis in a direct injection engine. New injector concepts and technology will be tested using both high-speed imaging and laser diffraction techniques. Results will be incorporated into automotive engine developments to promote clean combustion and reduced emissions for future generation engines.

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