Internal Structure of the Transient Full-Cone Dense Diesel Sprays

Ö.L.Gülder, G.J.Smallwood and D.R.Snelling
National Research Council Canada
Combustion & Fluids Engineering
Combustion & Fluids, Bldg. M-9, Ottawa, Ontario, K1A 0R6
Canada

ABSTRACT

Two-dimensional laser light scattering and transmission techniques were used to investigate the internal structure of the unsteady full-cone dense diesel sprays. The experiments were conducted at maximum injection pressures ranging from 19-32 MPa using an electronic diesel injector with a single hole nozzle. The experiments involved the imaging of the unperturbed structure of the dense core region of a full cone intermittent diesel spray on photographic film at high resolution, and the simultaneous measurement of laser sheet transmission along the centerline of the spray by an array consisting of 2048 diodes. At all injection pressures, line-of-sight laser sheet transmission measurements showed that the dense core region is fragmented very near to the nozzle exit, about 25-30 nozzle diameters downstream, and perhaps much closer. Further downstream from this location, the transmission measurements and simultaneous 90° scattering images revealed that the structure has an intermittent appearance with pockets of dense spray separated by relatively void regions. Two-dimensional images displayed a highly atomized spray structure beyond 50 nozzle diameters downstream, with no indication of an intact liquid core for the range of injection pressures studied.

INTRODUCTION

An understanding of the transient diesel spray structure is required to achieve a reasonably detailed description of the diesel combustion process [1]. However, there is a lack of knowledge regarding the mechanics of transient spray formation and the influence of the operating and design parameters [2-4]. As a result, optimizing diesel engine performance and reducing pollutant emissions is achieved by using lengthy iterative testing and development procedures. To reduce this development effort, multi-dimensional numerical codes are being used as a design tool to simulate different aspects of diesel engine operation. Although modelling efforts to understand the dynamics of the dense clusters of droplets are progressing rapidly [5], the lack of experimental data that describes the internal structure of unsteady sprays limits the development of physically sound spray submodels required for numerical codes [6].

There exist a large number of unsteady spray studies devoted to describing the external features and peripheral structures of the spray, many of which have been reviewed recently [1,4] A less studied area is the internal structure of full-cone transient diesel sprays. Due to the very high optical density of these sprays, the internal features have been considered in the past to be non-visible [7]. Thus, efforts to experimentally determine the internal structure of diesel sprays have been confronted with toilsome challenges.

The interest in the internal structure in general, and the nature of an intact liquid core in particular, has several causes. The geometry and the dynamics of the core is a result of the jet break-up process, which controls the initial droplet size and velocity [7]. Also, the existence of a very dense or intact liquid core region may favor higher soot formation rates due to rich mixtures and minimal air penetration. Although the presence of an intact liquid core in unperturbed intermittent diesel sprays has never been visualized directly, correlations describing the intact core length or break-up length using data obtained by conductivity probes have been reported [4,8], indicating distances comparable to diesel engine combustion chamber dimensions.

The presence of an intact liquid core has also been inferred from data representing spray tip penetration as a function of time [9]. This data indicated that the jet is divided into two regions, a developing region from the nozzle orifice to transition, and a fully developed region beyond the transition point. By applying jet disintegration theory developed for continuous liquid jets, expressions were derived for the data showing that the tip of the fuel plume moves at an almost constant velocity during the initial portion of the injection period, followed by a sharp transition to decelerating motion. The transition was interpreted to be that from an intact liquid core to an atomized spray.

Other reports on the nature of the intact core are based on observations made with direct photography and shadowgraphy which produce line-of-sight images [10,11]. Due to the high obscuration by these sprays, it is difficult to obtain sufficient information related to the internal structure of full-cone transient diesel sprays from the line-of-sight averaged photographs. Even by slicing the spray with a slit as small as 1 mm width it was impossible [10] to distinguish between tightly packed droplets, ligaments, or an intact liquid core in a dense spray due to high obscuration. A valid approach is to observe Mie scattering from laser sheet illumination, which has shown results that are inconsistent with the presence of a long intact liquid core in intermittent diesel sprays [12-14].

Cavaliere et al. [13] performed two-dimensional laser light scattering measurements to investigate the atomization and dispersion processes of unsteady diesel sprays. In this seminal paper [13], it was demonstrated that the fuel jet is already fragmented at the nozzle exit during the needle lift. One of the major conclusions was that the main part of the liquid, including the inner region of the jet, is fragmented at a distance from the nozzle notably shorter than that measured in similar but steady sprays [13]. Similar observations regarding the length of the intact core have been reported in [12] and [14].

We report here experimental data obtained on an intermittent diesel spray produced by an electronic diesel injector. Measurements were carried out using Mie scattering from laser sheet illumination to determine the velocity, and combined with the sheet transmission, to observe the structure in the dense core region of a transient diesel spray.

EXPERIMENTAL METHODOLOGY

Optical Apparatus

Laser sheet illumination has been applied to provide detailed structural information at planar cross-sections parallel to the spray centerline at different time delays after the start of injection. The factors affecting image quality appeared in a recent review of experimental considerations regarding the use of photography in imaging of sprays [15], thus only the unique aspects of the experimental layout shown in Fig. 1 are described here.

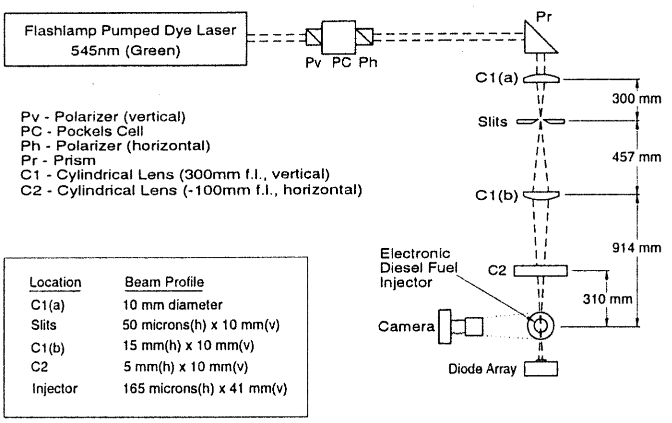

Fig.1 Top-view schematic showing optical layout for Mie scattering and transmission measurements of the dense core region in diesel sprays.

The dense core visualization imagery was achieved using the output of a flashlamp pumped dye laser, which was shortened by external Pockels cells to create a pulse of 50 ns duration. This was done to eliminate blurring in the image due to high velocities present in the spray. The laser beam was geometrically filtered through 50 μm slits to reduce the divergence, resulting in a maximum sheet width of 165 μm FWHM (as measured by a beam profiler) over the field-of-view of the camera. The laser sheet intersected the spray centerline axis, and a camera recorded Mie scattering from the spray normal to the laser sheet. To reduce secondary scattering (multiple scattering) from spray outside of the laser sheet, the energy was attenuated to 0.08 mJ for these photographs. The spray was imaged on Kodak Gold 100 photographic film using a Nikon F-801 camera with a Micro-Nikkor 105 mm lens and an extension ring to achieve a magnification of 1.14. The field-of-view of the camera was 31 mm in the spray axis direction, and the laser sheet extended 41 mm in this direction.

For the laser sheet transmission measurements, a Princeton Instruments PDA-2048 unintensified linear photodiode array was placed 120 mm past the spray axis on the path of the laser sheet. The laser sheet was 1.5 mm thick at this position and was centered on the 2.5 mm length of the photodiodes. The array consisted of 2048 diodes, each 25 μm wide, extending for 50.8 mm parallel to the spray axis direction. The magnification from the spray axis to the diode array was 1.22, so that each diode represented a 20 μm region of the spray axis. The signal on the photodiode array was digitized at 16 bits to give sufficient dynamic range for the measurement of transmission.

For the spray tip velocity measurements, the same optical apparatus was used, except that a second laser was added producing two-color double exposures on the film. Two colors were blue (= 454 nm) and green (= 545 nm). The lasers were triggered sequentially, with the delay between the laser pulses in the range of 10-50 μs. The energy after the slits was 1.05 mJ for the blue laser and 0.65 mJ for the green laser.

Injection System

Measurements were made on a transient spray produced by an electronically controlled, single hole, accumulator type diesel injector manufactured by BKM, Inc. A nozzle tip of 0.34 mm hole diameter and 0.9 mm hole length was used with the electronic injector. The measurements were made at maximum injection pressures of 19, 27, and 32 MPa, with fuel delivery of 11, 23, and 34 mg/injection, respectively. All measurements were made at atmospheric backpressure and room temperature. The liquid used for these experiments was No. 2-D diesel fuel. The injector was fitted with pressure transducers to measure both the rail and accumulator pressures. The illumination of a helium-neon laser, which was directed past the tip of the nozzle onto a photodiode, was scattered by the fuel during injection. This caused a decrease in the diode signal, which was used to determine the injection duration of 3.5 ms. The injection characteristics for a pulse at 27 MPa are shown in Fig. 2.

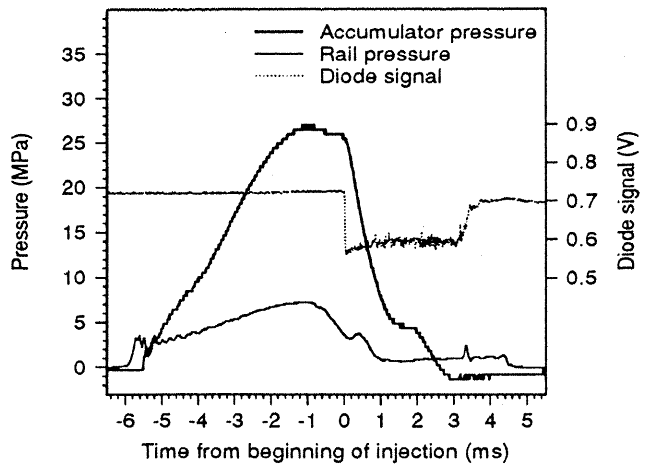

Fig.2 Injection pressure signals for 27MPa pulse. Drop in diode signal indicates presence of spray

To put the operating regime of this injector into perspective with respect to previous work dealing with break-up length, the break-up length was estimated from published information [5] for the experimental conditions listed above. The estimated break-up length was several hundred hole diameters. At higher backpressures and temperatures, such as those found in an operating diesel engine, the effects of fluid mechanics and vaporization should be accelerated, causing the atomization process to occur more quickly, and over a shorter distance.

RESULTS

Spray Tip Velocity Measurements

The spray tip velocity was measured using two-color, double-pulse, laser sheet illuminated double exposure photography. For these photographs, excessive laser energy was used to deliberately induce enough secondary scattering so that all the liquid present was imaged onto the film. Thus, even if the spray tip was not in the plane of the laser sheet, it would appear due to the secondary scattering. The velocity was determined by measuring the distance between the tips of the blue and green images, and dividing this by the time separation between the two laser pulses. Measurements were made for maximum injection pressures of 19, 27, and 32 MPa. The delay from beginning of injection varied from 10 μs to 700 μs, and the resulting tip penetrations were from 1 mm to 100 mm (3 to 300 hole diameters). The results shown in Fig. 3 clearly indicate that the spray tip velocity varied during injection. There was strong acceleration of the spray tip for the first 200 μs, with the peak velocity reached at 300-500 μs, followed by deceleration to lower velocities. As the maximum injection pressure increased, the peak velocity also increased, and the time to reach the peak velocity was reduced. There was no constant velocity region in any of these sprays. Inspection of Fig. 3 does not reveal behavior that would indicate a sharp transition from an intact liquid core to an atomized spray.

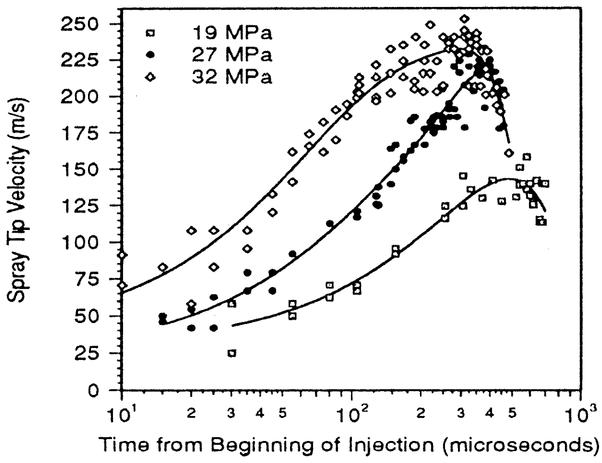

Fig.3 Spray tip velocity as a function of time from beginning of injection at typical diesel maximum injection pressures.

Direct Visualization

Photographic direct visualization of the dense spray region has been considered difficult, because the primary scatterers were obscured by a contiguous field of relatively uniform illumination produced by secondary scattering [10]. For the experiments discussed here the technique applied, outlined below, was developed by Gülder *et al.* [14]. All spray components intersected by the laser sheet, defined as primary scatterers, were in focus. This was because the sheet width of 165 μm was less than the depth-of-focus of the camera lens, which ranged from 250 μm at f/2.8 to 3 mm at f/16. There was a dense spray field between these primary scatterers and the camera lens. This spray, not intersected by the laser sheet, and mostly outside of the in-focus region of the camera lens, caused secondary (or multiple) scattering. Since the secondary scattering was from out-of-focus spray, the blurring caused the image of the scattered radiation to spread over a larger area, and to have a more uniform, less intense distribution of energy than an in-focus image would have.

The effects of secondary scattering were reduced by closing the aperture on the camera lens by 2-3 stops. The reason that this was effective was that the secondary scattering was less intense than the primary scattering, since the secondary scattering results from primary scattering radiation being rescattered by liquid outside of the light sheet. Most of the secondary scattering was from out-of-focus sources, thus enlarging the image area and reducing the energy density striking the film. Thus, by closing the aperture, the energy density from the secondary scattering was reduced below the gross fog level of the film, while the primary scattering was still able to produce an exposure. It should be noted that in bracketing these exposures, one f-stop more exposure did result in visible secondary scattering on the film, while one f-stop less exposure resulted in nothing appearing on the film, not even the illumination from primary scatterers.

The results (Fig. 4) displayed a high level of atomization in the probed region of 50 to 140 hole diameters from the injector tip, with no indication of an intact liquid core. This held true over a range of peak injection pressures from 19 MPa to 32 MPa, as observed in Figs. 4(a) - 4(c). Images were recorded at delays ranging between 50 μs and 3.5 ms from the beginning of injection. The detail was observed more clearly in an enlarged view of a portion of Fig. 4(b), centered 70 hole diameters downstream, reproduced as Fig. 5(a). The image in Fig. 5(a) was processed to eliminate the secondary scattering present by applying a low-pass filter and then subtracting this filtered image from the original image. The result of this image processing (Fig. 5(b)) illustrated that the illumination emanated from randomly spaced point sources, which were interpreted as droplets. There was no evidence of extended sources which would have indicated an intact core, ligaments, or large blobs of fuel. The number density distribution of droplets did not seem to be homogeneous since the point sources of illumination were unequally distributed, with dark regions indicating the absence of droplets. It should be noted that the sheet thickness was equal to only a few droplet diameters, and thus the presence of regions without droplets was reasonable, even for a dense spray.

Transmission Measurements

The transmission of the laser sheet through the centreline of the spray was measured relative to the laser sheet intensity in the absence of spray, as a function of distance downstream of the nozzle tip. Direct visualization photographs were taken simultaneously. A typical example, at 1 ms from the beginning of injection and 27 MPa maximum injection pressure, is shown in Fig. 6.

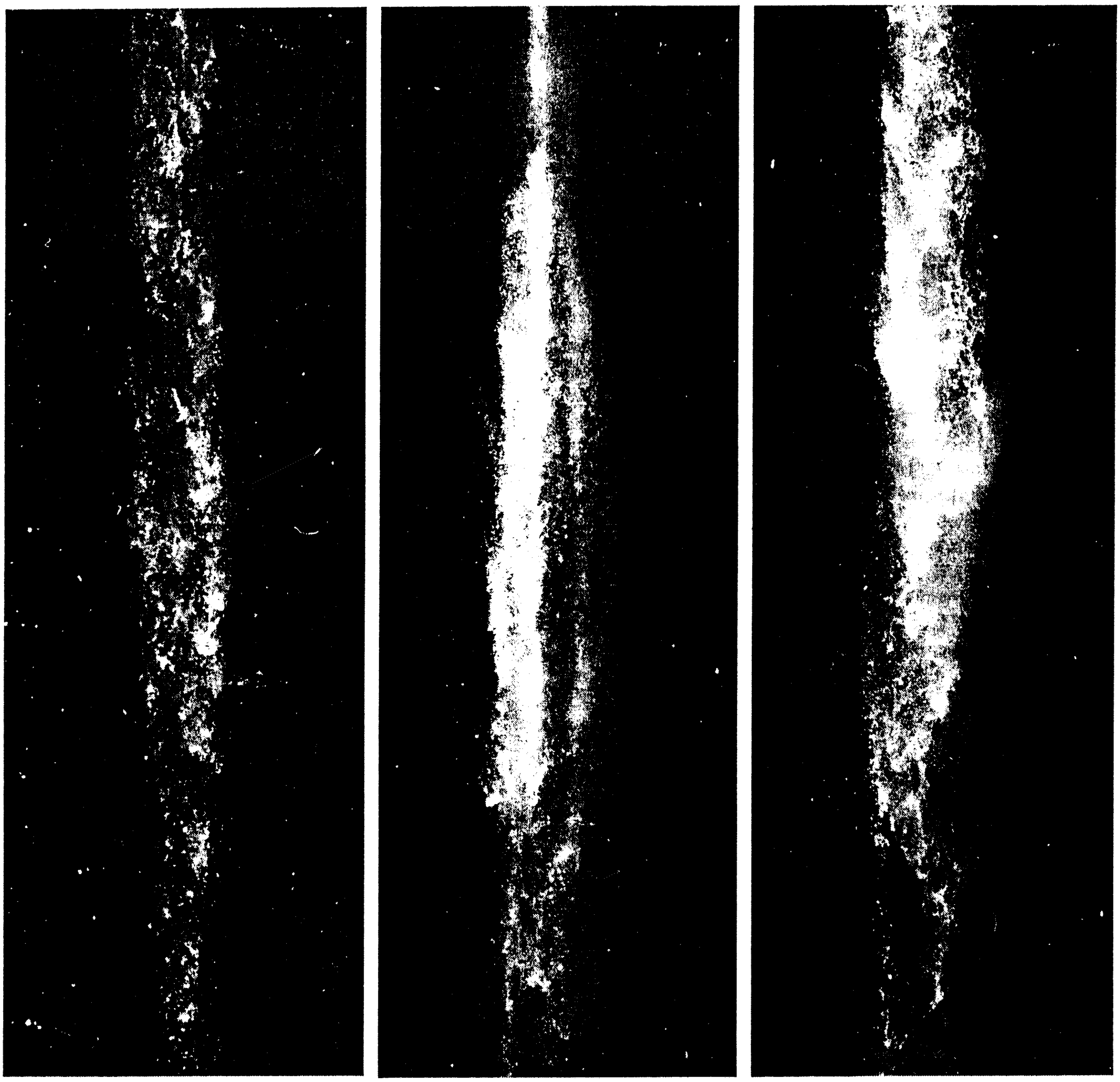

Fig.4 Dense core region of diesel spray showing complete atomization and no evidence of an intact liquid core. Maximum injection pressure: (a) 19 MPa, (b) 27 MPa, (c) 32 MPa.

The spray in the region from the nozzle exit to 24 mm (70 hole diameters) downstream is shown in the photograph. The scattering intensity was too great to resolve detail in the dense core region, from near the tip to 9 mm (25 hole diameters) downstream, where the intensity had decreased to a level at which individual droplets were observed. Further downstream from this location, the structure appeared intermittent, with pockets of dense spray separated by relatively void regions. There was less than 1% transmission of the laser sheet from 0.7 mm to 8.5 mm, followed by oscillations in the transmission from 1% to 5% at locations further downstream.

As observed in Fig. 6, the line-of-sight transmission was inversely correlated with the degree of scattering observed normal to the laser sheet. For repeated experiments, the line-of-sight transmission continued to show correlated behaviour, although there was pulse-to-pulse variation in the distance to the first void and the subsequent intermittent structure. The high level of attenuation combined with the high scattering intensity observed in the dense core region before the first void indicates that there was a large number of air/liquid interfaces. This implies that the liquid is fragmented, entraining a substantial air fraction, in this region. The radius of curvature of these interfaces was presumably small (i.e. droplets or fine wrinkles) since large radii interfaces scatter predominately in the forward direction and would have contributed to the transmission.

Five sets of transmission data were averaged at each time interval (from 50 μs to 3 ms) to produce the results displayed in Fig.7, which shows the variation of the transmission behaviour as a function of time as well as the downstream location. For the data at 50, 100, and 250 μs, the spray tip was within the field-of-view, indicated

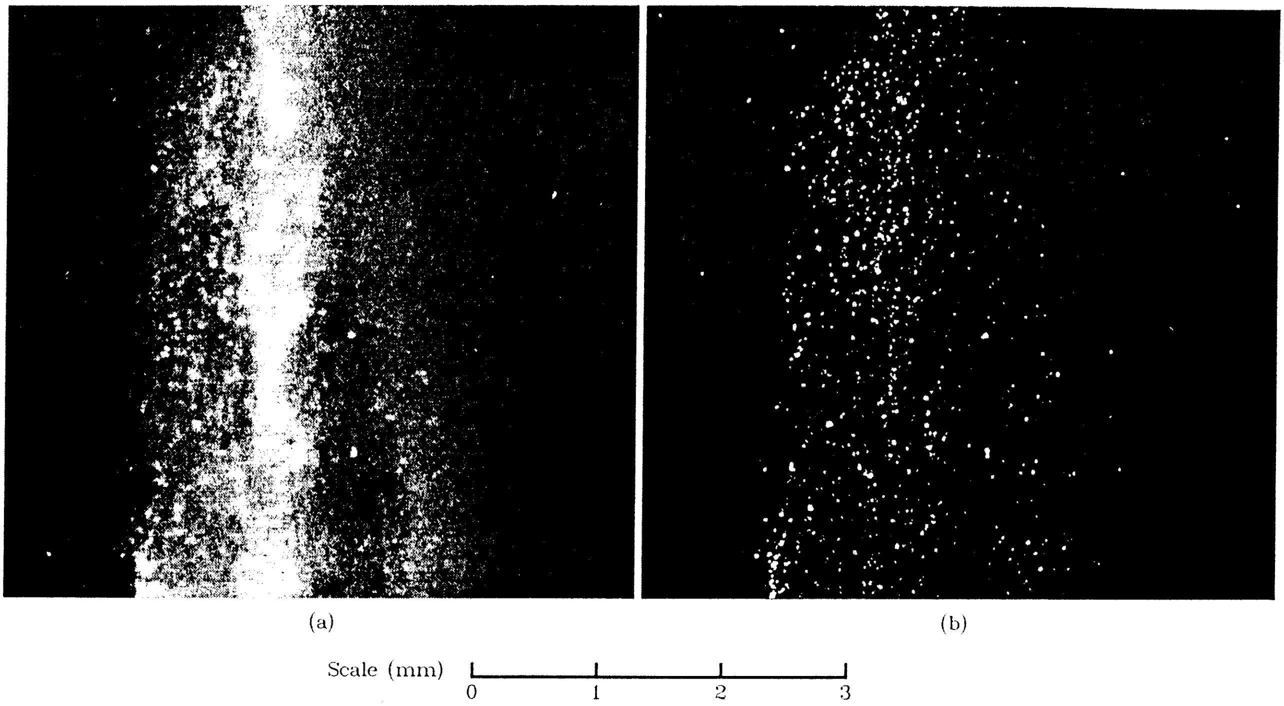

Fig.5 (a) Enlargement from Fig. 4(b) centered 24 mm (70 nozzle diameters) from the nozzle. (b) Result of image processing of Fig. 5(a).

by the regions of 100% transmission. From 1 ms to 3 ms, the transmission is increasing at all locations, rising to well above 10% for most of the spray beyond 10 mm at 3 ms. The region of maximum attenuation extends the furthest at 250 μs, where it extends almost 15 mm. This region becomes continually shorter in length at all later time intervals.

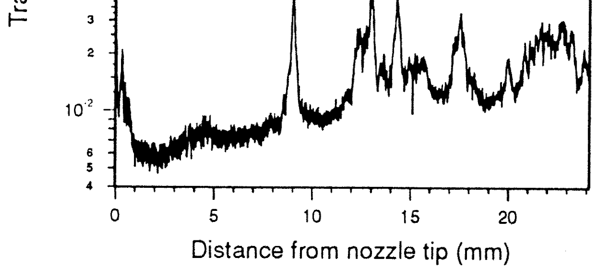

Fig.6 Transmission versus downstream distance, with the simultaneously recorded scattering. Maximum injection pressure 27 MPa, delay time 1 ms.

DISCUSSION

In *steady* pressure-atomized sprays, the dense spray region consists of an intact liquid core (similar to the potential core of a single phase turbulent jet) surrounded by a dispersed flow region that begins at the injector exit. The atomization progresses by primary breakup forming droplets through stripping from boundary layers on the liquid core surface, followed by a secondary breakup of ligaments and large drops. In analogy with this picture of the steady spray atomization mechanism, the highly transient and intermittent diesel sprays were thought to have a similar structure.

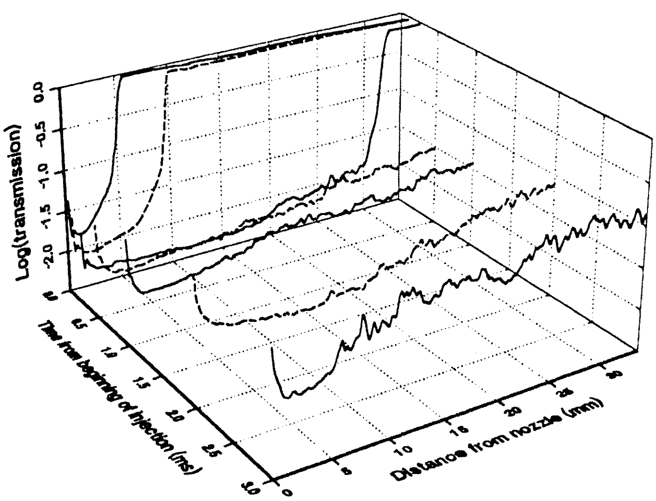

Fig.7 Transmission versus both time from beginning of injection and downstream distance. Delay times of 50, 100, 250, and 500 μs and 1, 2, and 3 ms.

An unsteady diesel spray is a fully pulsed jet (i.e. no mass flow between pulses). Previous studies of single phase fully pulsed jets showed significant differences between steady and pulsed jets. The entrainment in fully pulsed jets was much higher than the steady or partially pulsed jets [16]. Also, the velocity profile spreading and volume flow rate were increased in pulsed jets in the near field [17,18]. These studies indicate that steady jet characteristics are recovered only when a certain downstream location is reached, and the near field is greatly altered [19].

Recent measurements by Cavaliere *et al.*[13] and Yule and Salters [20] support the view that unsteady diesel sprays do not behave like steady ones. The unsteady fluid dynamics of the liquid jet plays an important role in the atomization. The fuel injected when the injector needle is fully lifted is fragmented some millimeters downstream of the nozzle exit. In contrast, the break-up length for steady diesel sprays is evaluated to occur much later (some centimeters downstream) [13]. By using an improved conductivity probe, it was inferred that the intact core or break-up zone in unsteady diesel sprays is not a simple liquid column, but probably consists of a distributed chaotic assembly of sheets and ligaments disintegrating into droplets, with a very high void fraction (about 99%) within it [20].

The results presented herein indicate that, if there is an intact liquid core in diesel sprays, its length is of the order of 30 nozzle diameters or less. Beyond that position, the spray displays a highly atomized flow field. The description by Yule of the break-up length, consisting of disintegrating sheets and ligaments with a very significant void fraction [20], also implies that an intact core is not present in diesel sprays.

CONCLUSIONS

1. Two-dimensional images displayed a highly atomized spray structure beyond 50 nozzle diameters downstream, with no indication of an intact liquid core for the range of injection pressures studied. After eliminating the secondary scattering present by applying a low-pass filter and subtracting the filtered image from the original image, it was demonstrated for enlarged views of the spray that the scattering is from randomly spaced point sources, which were interpreted as droplets, rather than liquid columns, ligaments, or large blobs of fuel.

2. At all injection pressures, line-of-sight laser sheet transmission measurements showed that the dense core region was fragmented very near to the nozzle exit, about 25-30 nozzle diameters downstream, and perhaps much closer. Further downstream from this location, the transmission measurements and simultaneous 90° scattering images revealed that the structure has an intermittent appearance with pockets of dense spray separated by relatively void regions.

3. It is apparent that pressure-atomized and fully pulsed round liquid sprays have a significantly different near-field structure than their steady counterparts. Our findings, along with the recent work of others, are inconsistent with the existence of a long (on the order of 100 nozzle diameters or more) intact liquid core in unsteady diesel sprays.

ACKNOWLEDGEMENTS

The work reported herein was supported by DND, PERD Program 1.5 and the internal research funds of the National Research Council. We thank Y. Coté, M. F. Baksh, D. Gareau, and S. M. Aval who helped to set up the experimental rigs.

REFERENCES

1. Kamimoto, T. and Kobayashi, H., "Combustion Processes in Diesel Engines", Prog. Energy Comb. Sci. Vol.17, pp.163-189, 1991.
2. Bracco, F. V., "Structure of High-Speed Full-Cone Sprays", Recent Advances in the Aerospace Sciences (C. Casci, ed.), Plenum Press, New York, p. 189, 1985.
3. Chigier, N. A., "The Physics of Atomization", Fifth International Conference on Liquid Atomization and Spray Systems (ICLASS-91), pp.1-15, 1991.
4. Hiroyasu, H., "Experimental and Theoretical Studies on the Structure of Fuel Sprays in Diesel Engines", Fifth International Conference on Liquid Atomization and Spray Systems (ICLASS-91), pp.17-31, 1991.
5. Bellan,J.,and Harstad,K.,"The Dynamics of Dense and Dilute Clusters of Drops Evaporating in Large, Coherent Vortices", Twenty-Third Symposium (International) on Combustion, The Combustion Institute, pp. 1375-1381, 1990.
6. Takagi,T.,Fang,C.Y.,Kamimoto,T., and Okamoto,T., "Numerical Simulation of Evaporation, Ignition and Combustion of Transient Sprays", Comb. Sci. Technol. Vol.75, pp.1-12, 1991.
7. Chehroudi, B., Chen, S.-H., Bracco, F. V., and Onuma, Y., "On the Intact Core of Full-Cone Diesel Sprays", SAE Paper No. 850126, 1985.
8. Yule, A. J., and Filipovic, I., "On the Break-Up Times and Lengths of Diesel Sprays", Int. J. Heat and Fluid Flow, Vol.13, pp.197-206, 1992.
9. Hiroyasu, H., Kadota, T., and Arai, M., "Fuel Spray Characterization", Combustion Modelling in Reciprocating Engines (J.N. Mattavi and C. A. Amann, eds.), Plenum Press, New York, p.369, 1980.
10. Ishikawa, M. and Murakami, T., "Characteristics of Intermittent Sprays Generated by an Orifice Atomizer", Second International Conference on Liquid Atomization and Spray Systems (ICLASS-82), pp. 85-92, 1982.
11. Balles, E. N. and Heywood, J. B., "Spray and Flame Structure in Diesel Combustion", J. Eng. Gas Turb. Power, Vol.111, pp.451-457, 1989.
12. Bower, G. R. and Foster, D. E., "Investigation of the Characteristics of a High Pressure Injector", SAE Paper No. 892101, 1989.
13. Cavaliere, A., Ragucci, R., D'Alessio, A., and Noviello, C., "Analysis of Diesel Sprays Through 2-Dimensional Laser Light Scattering", Twenty-Second Symposium (International) on Combustion, The Combustion Institute, pp. 1973-1981, 1988.
14. Gülder, Ö. L., Smallwood, G. J., and Snelling, D. R., "Diesel Spray Structure Investigation by Laser Diffraction and Sheet Illumination", SAE Paper No. 920577, 1992.
15. Chigier, N., "Optical Imaging of Sprays", Prog. Energy Comb. Sci., Vol.17, pp.211-262, 1991.
16. Bremhorst, K., and Hollis, P. G., "Velocity Field of an Axisymmetric Pulsed, Subsonic Air Jet", AIAA Journal, Vol.28, pp.2043-2049, 1990.
17. Favre-Marinet, M., and Binder, G., "Structure des Jets Pulsants", J. Mechanique, Vol.18, pp.355-394, 1979.
18. Crow, S. C., and Champagne, F. H., "Orderly Structure in Jet Turbulence", J. Fluid Mechanics, Vol.48, pp.547-591, 1971.
19. Kouros, H., Medina, R., and Johari, H., "Spreading Rate of an Unsteady Turbulent Jet", AIAA Journal, Vol.31, pp.1524-1526, 1993.
20. Yule, A. J., and Salters, D. G., "An Improved Technique for Measuring the Break-Up of Diesel Sprays", Proc. ILASS-Europe 92, Amsterdam, Sept. 1992.