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Optical Diagnostics and Direct Injection of Liquid Fuel Sprays

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***Abstract*:** The research described here addresses the problem of a paucity of high quality data on the full field structure of high pressure liquid fuel sprays for gasoline direct injection, GDI, engines. The paper describes the application of phase Doppler anemometry, PDA, and single-shot laser sheet Mie imaging to the study of GDI sprays and discusses the methodologies adopted for the experimental systems and the optimisation of the techniques. Experimental data is presented which defines the spray structure in terms of PDA vector and scalar fields and single-shot CCD digital images. The work demonstrates the essential complementary nature of the single point and planar optical diagnostics for spray studies.

***Keywords*:** spray, GDI, PDA, laser sheet, visualisation.

1. Introduction

Gasoline Direct Injection (GDI) technology has been demonstrated to offer lean burn fuel economy benefits of between 20 to 40% and reduced emissions (Iwamoto et al., 1997; Tomoda et al., 1997; Harada et al., 1997). The problem facing the automotive engineer is the lack of detailed fundamental and development data on GDI fuel sprays and their interaction with the in-cylinder flow dynamics. In order to ensure that GDI technology is applied to its best advantage an understanding of gasoline fuel atomisation and detailed, precise data of the spray dynamics are essential. Two different injector technologies are evolving for GDI applications, high-pressure single-fluid systems and low-pressure dual-fluid systems. The former relies on gasoline injection pressures of between 50 and 120 Bar to achieve atomisation while, for the latter case, gasoline at a more normal fuel line pressure of up to 7 Bar, is atomised with the assistance of an air blast at pressures up to 10 Bar. The fuel injection period is short with full load fuel delivery of order milliseconds.

For the fundamental scientific understanding of the processes involved in fuel atomisation data are required under all environmental conditions while, from the engineering point of view, the injection systems have to be studied under typical engine operating conditions. The primary data required must be able to characterise the full field spatial and temporal distribution of the fuel state, i.e. liquid, droplets and vapour as well as the air state.

Optical diagnostics and image processing provide a whole suite of tools which are playing a leading role in providing this understanding fuel atomisation, (Berckmueller et al., 1996; Comer et al., 1998; Evers, 1994; Fujikawa et al., 1998; Ikeda, 1997; Le Coz, 1998; Parrish and Farell, 1997). In the short term, it will be used to guide engine design and development work and, in the near future, will feedback into improving both injector and combustion system designs. The optical techniques to be applied in this work on GDI fuel spray characterisation and analysis are:- the single point techniques of laser Doppler anemometry (LDA) and phase Doppler anemometry

(PDA) together with the single shot planar Mie imaging technique which provides a view of the structure and temporal development of the spray. However, to be able to acquire a consistent and high quality database that advances scientific understanding and yet provides engineering data within the time scales of an engine development programme these diagnostics and data processing methods have to be specifically configured to match this application of liquid fuel spray atomisation.

This paper discusses the methodologies adopted for the experimental hardware, the optimisation of the optical techniques and presents full field data relating to the atomization and spray development for one GDI fuel injector, a single-fluid pressure-swirl atomizer operating under full load fuel delivery conditions.

2. Optical Diagnostics

2.1 Laser and Phase Doppler Anemometry (LDA and PDA)

The PDA diagnostic is the general form of Laser Doppler Anemometry (LDA) and yields simultaneous information about not only the droplet velocity vector but also its size as it passes through a highly localised measurement volume. As such PDA belongs to the single point, single particle counting class of techniques and in realising this it helps to establish criteria for the correct specification and operation of the PDA instrumentation relative to the droplet velocity, size and concentration. The above description on gasoline direct injection indicates that these fuel sprays are likely to be highly transient, dense and with the high injection pressures providing a high degree of penetration and atomisation. The measurement problem is therefore one of the detection of small, high speed droplets inside a dense cloud of surrounding droplets. Furthermore, under engine conditions, with high in-cylinder temperatures, the temperature, density and therefore refractive index of the droplet will be unknown.

These requirements are satisfied by specifying an LDA/PDA transmitter system with a high laser power and a small measurement volume, in conjunction with a large aperture, high gain receiver system placed at a large scattering angle to the transmitter to minimise the measurement volume length and sensitivity to refractive index changes. A new generation LDA/PDA transmitter system has been designed to meet the criteria of high power and high spatial resolution. It is based on an advanced Bragg cell design offering much improved laser power handling capabilities and symmetrical beam splitting of the shifted and unshifted beams at high Bragg angles. The Bragg cell is integrated with a laser beam expander to produce a simple, elegant high power LDA/PDA transmitter that offers a variable beam separation with a high beam expansion ratio (Wigley et al., 1998). In two component form two transmitters, one for each wavelength, are paralleled as shown in Fig. 1.

The separation of the two pairs of beams at the focusing lens (9) is adjusted by a translation of the Bragg cells (6) along the optical axis, followed by a small refocus of lenses (4) and (7) to achieve re-collimation of the beams. Since independent transmitters are used for the two velocity components the beam separation and hence velocity range or resolution can be optimised for any given application. For the measurements of the axial and radial velocity components, laser wavelengths 514 and 488 nm respectively, the beam separations were set to 45

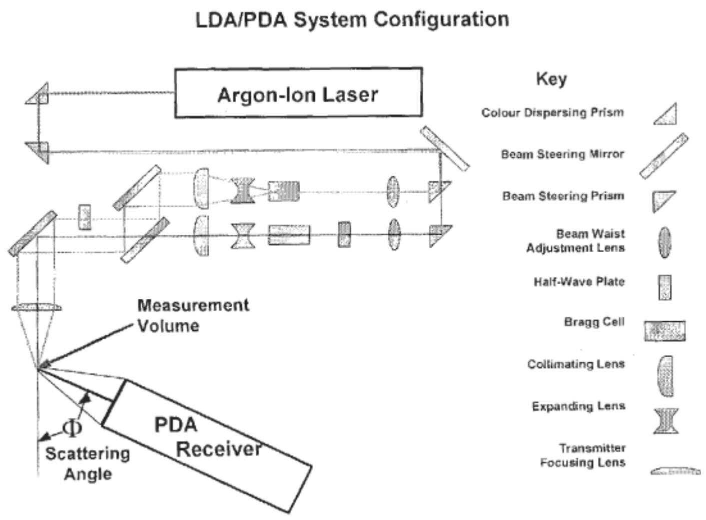

Fig. 1. Schematic of PDA Optical geometry.

and 50 mm respectively. With the transmitter focusing lens (9) of 300 mm focal length these separations produced fringe spacings of 3.44 and 2.94 microns in the two component measurement volume with cross-sectional diameters of 48 and 41 microns respectively. So, although the spatial resolution for the axial velocity component (514 nm) was compromised by having to choose a larger fringe spacing to meet the higher axial velocities, the smaller measurement volume for the radial velocity component (488) restores the spatial resolution since only droplets passing through both measurement volumes will be recorded. The power in each beam forming the axial and radial measurement volumes was 200 and 120 mW respectively. The Dantec 57×10 'classic' PDA receiver with its large scattered light collection aperture was positioned at a scattering angle Φ of 70 degrees for the best spatial resolution at the measurement volume and insensitivity of the dropsize/phase relationship to refractive index changes. The Dantec enhanced 58N50 PDA signal processor was used which, with full bandwidth, allowed axial and radial velocity measurement ranges of -35 to 120 m/s and -30 to 105 m/s respectively and a dropsize range of up to 65 microns.

2.2 Laser Sheet Mie Imaging Technique

This imaging technique was used to provide a planar view of the structure and temporal development of the spray, yielding cone angle and spray penetration data, and to aid understanding of the detailed PDA data. The basic imaging arrangement is shown schematically in Fig. 2. Two methods of imaging were found necessary to faithfully represent the true nature of the spray. Firstly, the vertical light sheet was aligned with the vertical symmetry axis of the spray and secondly, aligned to illuminate a diffuse scattering plate placed behind the injector to back-light the spray. It was found that the former alone could lead to false conclusions about the atomization of the fuel (Wigley et al., 1998).

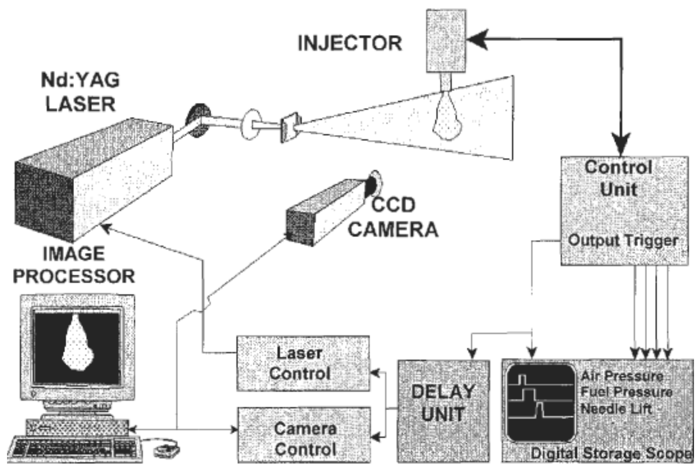

Fig. 2. A schematic of the imaging system.

The aim of the single-shot imaging was to record high resolution, instantaneous, cycle resolved images of the spray structure. The light source for the single-shot imaging was a Continuum SureliteII Nd:YAG laser, frequency doubled to 532 nm and providing a pulse duration of 10 ns. The laser was operated at approximately 35 mJ per pulse and with a light sheet height of 150 mm. A trigger from the injector control unit provided a trigger referenced to the opening pulse of the fuel supply solenoid. This trigger was passed to a delay unit which controlled both the laser firing and the image capture. The maximum pulse repetition rate for this laser is 10 Hz and was synchronised with the injection frequency, so only one image could be recorded per injection. The single-shot images were recorded in two ways, digitally and on film. The film images were recorded using a medium format camera and 200 ASA colour film. The digital imaging used a Kodak Megaplus 4.2 CCD camera which provided 2000 by 2000 pixel images at a resolution of 8 bits. The CCD camera was connected to a Matrox IM1280 frame grabber and image processor installed in an IBM 486 computer.

3. Fuel Spray Rig

In this atmospheric rig, the GDI injectors were mounted to spray vertically down through a circular opening into a large steel plenum. The plenum was connected to an exhaust blower to establish a low velocity co-flow of air below the injector to draw all the spray into the plenum. The experiments used unleaded gasoline as there is sufficient evidence to suggest that there are no inert test fluids that can simulate accurately the atomisation characteristics of gasoline (Pitcher and Winklhofer, 1998). The high fuel pressure required by the GDI injector was supplied by a pneumatic/hydraulic ram system. The injector was operated at 50 Bar fuel pressure with fuel solenoid opening times of 0.4, 0.84 and 4.23 ms corresponding to fuel delivery rates of 6.5, 11.0 and 53.0 mg per injection. Data were also obtained for fuel pressures of 40 and 60 Bar for the high fuel load case.

The GDI injector was driven by a control unit that provided the electronic timing gate for the injector solenoid and produced external trigger pulses for synchronising the data acquisition system for the optical diagnostics and logging of the injector operating conditions. Its cycle time, or injection frequency, was derived from a function generator and set at 10 Hz to synchronise with the pulse rate of the laser used for the imaging and to remove all droplets from a spray before another commenced. The GDI injector was supported from a gantry incorporating three precision traverses, two horizontal and one vertical to position the spray with respect to the static LDA/PDA measurement volume and laser light sheet.

4. PDA Measurements

The axial measurement locations chosen were from Z = 5 to 50 mm in 5 mm increments. Radial scans were made from the nozzle axis in steps equal to 10% of the axial Z value down to Z = 25 mm then generally kept at 2.5 mm from Z = 25 to 50 mm.

Data acquisition and processing followed the same practice as adopted in LDA for 'rotating machinery.' A fixed, large number of validated velocity/size samples were collected at each measurement point and then averaged over small time windows to produce time varying mean quantities for the droplet velocity components and size. The data acquisition time, i.e. number of injections, required for each measurement point therefore varied according to the local droplet arrival rate. This is a function of the fuel delivery and atomization process and varies throughout both space and time. In general, when the droplet density and validated data rate are high the acquisition time should still be longer than the longest flow time-scales and, when the droplet density and validated date rate are sparse, the acquisition time should be long enough to ensure that the droplet field has been sampled with a sufficiently high statistical significance. It must also be noted that a high droplet arrival rate does not necessarily lead to a short data acquisition time since the validation can be very much reduced due to a high probability for obscuration of the incident and scattered light.

Data were collected over many injections until 20,000 validated data samples had been acquired for each measurement position. The radial extent of the measurement scan, into the sparse droplet density region of the spray periphery, was limited to the point where the data arrival rate dropped below 20 drops acquired per injection, i.e. a maximum of acquisition time of 1,000 injections was set. Each sample consisted of the droplet's axial and radial velocity components, the diameter and the arrival time relative to a trigger derived from the electronic signal to open the injector solenoid. The data were time averaged over sequential time bins of 40 microsecond to provide time resolved mean profiles of velocity and size for each position. The diameter calculated was the arithmetic mean value. Mean data were not calculated for those time bins containing fewer than 10 droplet samples. When the measurement grid and time averaging data processing had been completed the whole data array was programmed to provide a vector and scalar field plot showing the spatial development of the droplet field as a function of time. Although the number of injections at each measurement point and the sample number in each time bin are known no attempt has been made here to 'weight' the velocity vector or dropsize with a grey scale or colour representation of the droplet number per injection. Droplet density distributions can be inferred for each PDA data plot from the corresponding CCD image.

5. Results and Discussion

The data presented are used to identify the phenomena occurring in a transient high pressure, single fluid, swirl injected gasoline spray and will use both single-hot Mie imaging and phase Doppler anemometry to highlight the nature in which these techniques complement each other for characterising the spatial and temporal behaviour of sprays.

Six frames of PDA vector and scalar field plots, showing the mean droplet velocity and size, as a function of time are presented in Figs. 3(a) and 3(b) together with the corresponding single shot planar Mie image. A scale vector length of 40 m/s and scale droplet diameter of 20 microns is included. Each vector is centred on the measurement position and the arrow head size also scales with the velocity. These field plots are compared directly with the planar single shot images recorded at the same instant. The time indicated is the time relative to the trigger coincident with the fuel solenoid opening signal. Both measurement techniques show that the fuel emerges from the nozzle at a time of 0.42 ms after the trigger, i.e. the time required for the injector needle to open and the fuel in the nozzle to start to move under the fuel line pressure.

The time of 0.72 ms shows that a spray cone has just started to form at Z = 5 mm from the nozzle as the swirl momentum builds up and that during these initial 0.3 ms of injection the fuel leaves the injector as a 'solid' axial jet which has penetrated down to Z = 25 mm, i.e. an average spray tip velocity of 83 m/s. The fuel in the axial jet is generally poorly atomized and large fluid filaments are transported downstream before breaking up to form a much larger size class of droplets than produced by the 'prompt' atomization of the fuel (Wigley et al. ,1998). These large drops in the axial jet penetrate rapidly downstream, reaching Z = 50 mm after a further 0.4 ms, and move radially outwards, as readily seen, in the second frame, at the time of 1.22 ms. Experiments conducted with a very low injection time and fuel loading, 0.4 ms and 6.5 mg per injection respectively, show that only the axial jet is formed and is virtually identical to this spray at 1.22 ms from Z = 35 mm and below.

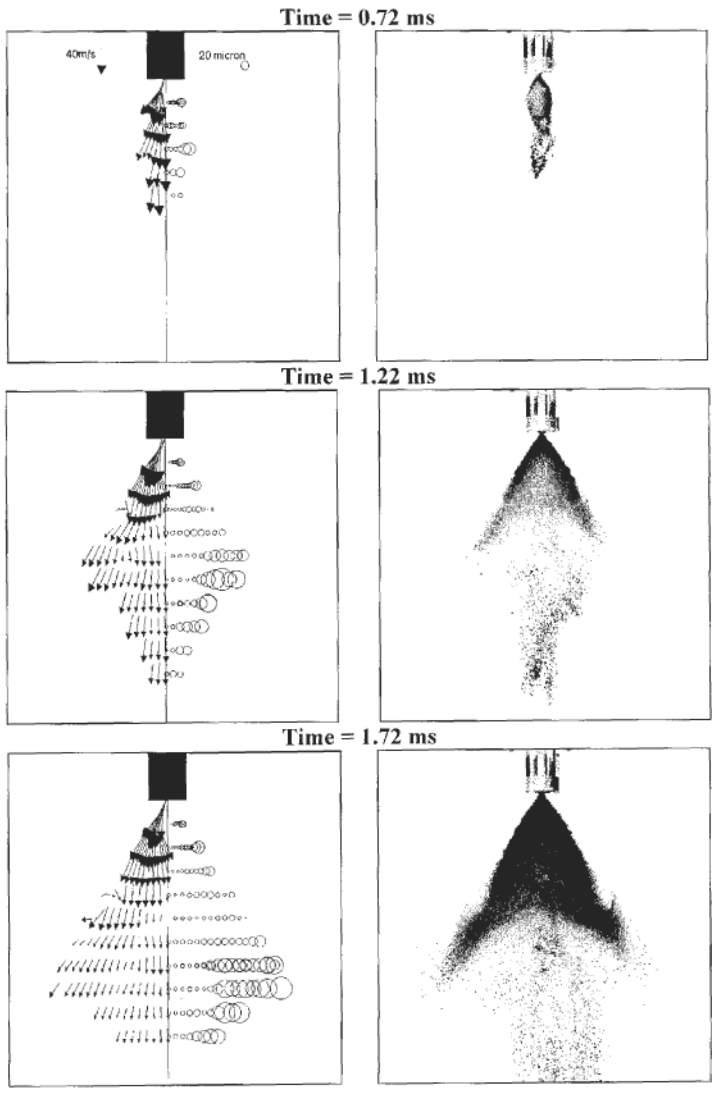

Fig. 3(a). PDA vector and scalar fields and single-shot images at 50 Bar fuel pressure and 53 mg/injection.

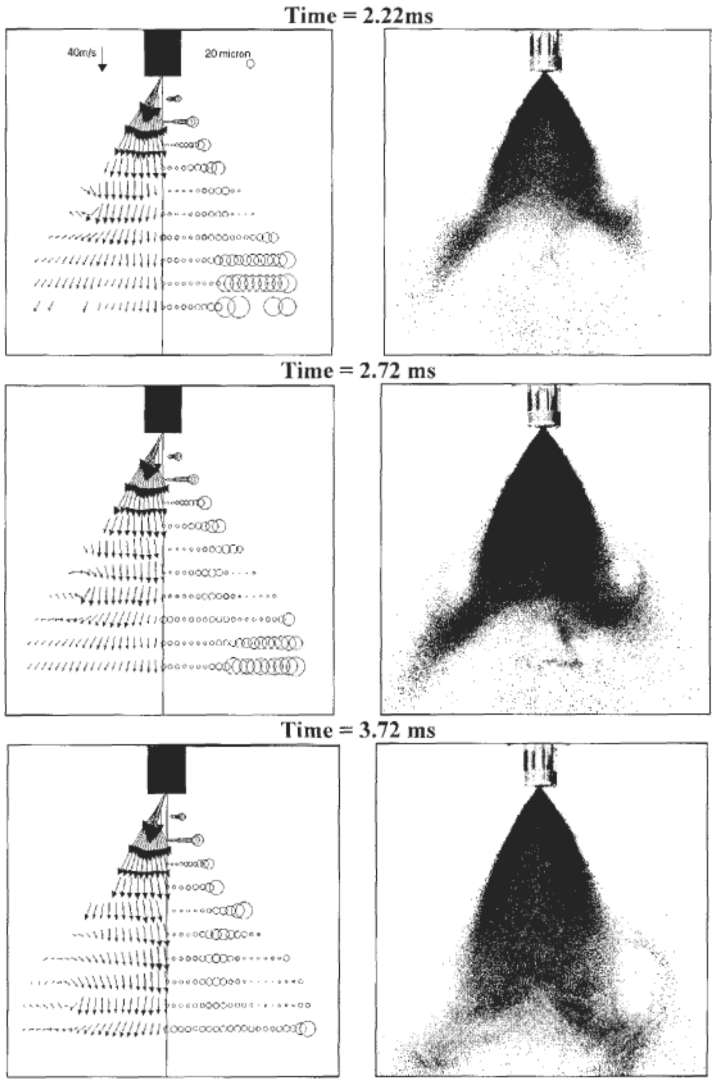

Fig. 3(b). PDA vector and scalar fields and single-shot images at 50 Bar fuel pressure and 53 mg/injection.

The spray cone has also seen significant penetration, from $Z = 5$ to 30 mm, and has two main features of interest that dominate the spray structure and development. Just as the axial jet was poorly atomized so is the spray cone during its early development as seen by the large drop sizes being generated, by fuel filament break-up, in the periphery of the spray at $Z = 25$ and 30 mm. The second main feature concerns the generation of a vortex on the spray periphery at $Z = 15$ mm which, as both the PDA and single shot imaging show, is associated only with the smallest of dropsizes and serves to limit the radial spread of the spray cone forcing it to take on the characteristic tulip shape. There is no unique spray cone angle, it can only be specified as a function of distance downstream from the nozzle.

The distribution of the fuel mass within the droplets contained in the spray is very difficult to derive accurately from the PDA data. It is best shown in the single shot images since the recorded scattered light intensities are proportional to the droplet diameter and number density present, e.g., at 1.22 ms there are high mass flows in the spray cone down to $Z = 10$ mm and in the droplets of the spray cone and axial jet below $Z = 30$ mm. The images also show that the number count of large droplets is far lower than for the small, barely resolved, drop size classes.

As the spray develops it covers a much greater area and so the number density of large droplets decreases dramatically. This is a difficult measurement situation for single point particle counting techniques, such as PDA, since the probability of detecting them and producing statistically significant mean data obviously improves as the measurement time is increased. Even with measurement times of 100 seconds, i.e. 1,000 injections, per position in the periphery of the spray the probability of detecting large droplets was low. This does not necessarily affect the arithmetic mean droplet diameter, as presented here, but can cause significant problems when calculating the Sauter mean diameter. A much more detailed presentation of the PDA spray data would involve plotting the mean data as a function of different dropsize classes.

The velocity profile across the spray radius for frame times of 1.22 and 1.72 ms at $Z = 10$ mm clearly show that the largest velocity vector is on the 'inside edge' of the spray cone and between this position, a radius of 7 mm, and the nozzle axis there is significant entrainment of the droplets. It is also clear from the dropsize data that as the developing vortex moves downstream, from 16 mm at 1.22 ms to 22 mm at 1.72 ms, that only the smallest droplets are drawn into the vortex. The large droplets and the developing cone is simply deflected by the vortex and the flowlines are directed around the inner edge of the taurus.

Another interesting point to note from both the PDA vector plot and the image at 1.72 ms is that as the main cone flow passes the inner edge of the taurus it acquires some radial velocity from the rapidly rotating vortex which causes the cone to expand more rapidly downstream of the vortex. It is also apparent from the image at 1.72 ms that the spray is assymmetric with the cone penetrating faster on the left side of the spray.

The dropsize data for the frame time of 1.72 ms and 2.22 ms show the 'appearance' of large drops at 35-40 mm from the exit just downstream of the vortex. There are no droplets larger than 25 microns at the earlier measurement locations. The reason for their appearance is the breakup of liquid ligaments. Single shot imaging demonstrated that significant ligaments of fuel are still present as far down as 25 mm from the exit. These liquid ligaments are breaking up to generate the large drops measured at 35 mm.

As frame time increases the vortex grows and the vortex centre moves downstream and radially out from the axis. At 2.72 ms the centre is at 30 mm downstream and at 3.72 ms it is at 40 mm. In these later stages the whole flow pattern and penetration is dominated by the large scale taurus, containing only the smallest of droplets, while the main mass of fuel is convected around the vortex and towards the spray axis.

6. Conclusions

In order to continue the rapid development and refinement of injection systems for Gasoline Direct Injection, GDI, it is essential to provide powertrain design engineers with full field data to understand the structure of high pressure liquid fuel sprays. For the fundamental scientific understanding of the processes involved in fuel atomisation data are required under all environmental conditions while, from the engineering point of view, the injection systems have to be studied under typical engine operating conditions. The primary data required must be able to characterise the spatial and temporal distribution of the fuel state, i.e. liquid, droplets and vapour as well as the air state.

It has been shown that the single point measurements techniques of laser Doppler anemometry (LDA) and phase Doppler anemometry (PDA) and the planar imaging techniques of laser sheet visualisation provide complementary views of the structure and temporal development of the spray.

Experimental data has revealed that for the high pressure injection systems investigated in this study the spray development is dominated by a large scale toroidal vortex which is generated in the outer shear layer of the spray. This vortex recirculates the smaller droplets and also limits the radial development of the cone and deflects it to generate a spray which has no unique cone angle, it can only be specified as a function of distance downstream from the nozzle. The PDA data and CCD images revealed the appearance of large droplets on the leading edge of the spray cone 30 mm downstream of the nozzle exit. These were attributable to the existence of fuel ligaments which exist as far as 25 mm downstream and break-up in the periphery of the spray to generate the large droplets.

References

Berckmueller, M., Tait, N. P. and Greenhalgh, D. A., 'The Time History of the Mixture Formation Process in a Lean Burn Stratified Charge Engine,' SAE 961929, 1996.

Comer, M. A., Bowen, P. J., Sapsford, S. M. and Johns, R. J. R., 'The Transient Effects of Line Pressure for Pressure Swirl Gasoline Injectors,' ILASS- Europe '98, 1998.

Evers, L. W., 'Characterization of the Transient Spray from a High Pressure Swirl Injector,' SAE 940188, 1998.

Fujikawa, T., Hattori, Y., Akihama, K., Koike, M., Kobayashi, T. and Mitsushita, 'Quantitative 2D Fuel Distribution Measurements in a Direct Injection Gasoline Engine using Laser Induced Fluorescence Technique,' Comodia 98, 1998.

Harada, J., Tomita, T., Mizuno, H., Mashiko, Z. and Ito, Y., 'Development of Direct Injection Gasoline Engine,' SAE 970540, 1997.

Ikeda, Y., Hosokawa, S., Sekihara, F. and Hakajima, T., 'Cycle-resolved PDA Measurement of Size-Classified Structure of Air-Assist Injector,' SAE 970631, 1997.

Iwamoto, Y., Noma, K., Nakayama, O., Yamaguchi, T. and Ando, H., 'Development of Gasoline Direct Injection Engine,' SAE 970541, 1997.

Le Coz, J. F., 'Comparison of Different Drop Sizing Techniques on Direct Injection Gasoline Sprays,' 9th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, 1998.

Parrish, S.E. and Farell, P.V., 'Transient Spray Characterisation of a Direct Injection Spark Ignited Fuel Injector,' SAE 970629, 1997.

Pitcher, G. and Winklhofer, E., 'Droplet Size and Velocity Measurements in the Spray of a Direct Injection Gasoline Injector,' ILASS-Europe '98, Manchester, July 1998.

Tomoda, T., Saski, S., Sawada, D., Saito, A. and Sami, H., 'Development of Direct Injection Gasoline Engine- Study of Stratified Mixture Formation,' SAE 970539, 1997.

Wigley, G., Hargrave, G.K., and Heath, J., 'A High Power, High Resolution LDA/PDA System Applied to Dense Gasoline Direct Injection Sprays,' 9th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, 1998.

Author Profile

Graham K. Hargrave: He received his PhD in 1984 from the Department of Fuel and Energy, University of Leeds. His research work included studies of the structure and heat transfer from turbulent, premixed flames and the application of optical diagnostics for flow field characterisation in combustion systems. After his PhD he worked in Research and Development for British Gas plc, where he specialised in the development and application of optical diagnostic techniques. His current position is lecturer in Thermofluids in the Department of Mechanical Engineering at Loughborough University. His research interests include Particle Image velcimetry (PIV), Laser Induced Fluorescence (LIF) and High-Speed Imaging, with particular emphasis on their application to SI Engines, fuel injection systems, domestic and industrial burners, medical inhalers and the study of Flame propagation in explosions.

Graham Wigley: He is a Research Fellow in the Department of Aeronautical and Automotive Engineering at Loughborough University, UK. He received the degrees of BSc, MSc, and PhD in Applied Physics, Nuclear Engineering and Environmental Physics from the Universities of London, Manchester and Nottingham in 1968, 1970 and 1974 respectively. He joined the Department of Mechanical Engineering of Imperial College, London, in 1974 and was seconded to the Harwell Laboratory of the UK Atomic Energy Authority where, in 1978, he was appointed as Senior Scientific Officer to the Engineering Sciences Division. He moved to AVL in late 1981 and worked there until 1993 although there was a one year absence when, for 1985, he took the position of Special Systems Manager with Dantec Inc. in the USA. In September 1993, he founded Flow Measurement Consulting Service, FMCS, before joining Loughborough University in 1996. His work on Laser Diagnostics and Optical Instrumentation for Experimental Fluid Mechanics started in 1969 with flow studies related to nuclear reactor safety. Since 1974 his main studies have been concerned with energy production, combustion and two phase flow processes with the main emphasis though on the study of the fluid mechanics of internal combustion engines and their fuel injection systems.

Jeffrey Allen: He gained a BTech Honours degree in Automotive Engineering from Loughborough University in 1979. He joined Lotus Engineering, UK, 1983 and worked initially on the fuelling and combustion system for a Highly Pressure Charged F1 engine using Piezo-electric controlled Gasoline Direct Injection, GDI. In 1991 he joined the Powertrain Research Department to work on Variable Valve Actuation projects which resulted in the Lotus Active Valve Train and the Lotus Cam-Profile Switching tappet. He then spent 3 years managing a high volume production engine development programme before rejoining the Powertrain Research Department in 1996 as Manager. He is responsible for the implementation of GDI research, natural gas multi-point injection and two-stroke DI engine design and combustion development continued variable valve application and Hybrid optimisation application. Concurrently undertaking PhD at Loughborough University based on in-nozzle flow of GDI injectors.

Alastair Bacon: He has a BEng in Mechanical Engineering and a PhD in Automotive Diagnostics from the University of Nottingham. He is a chartered mechanical engineer and a member of the Institute of Mechanical Engineers, London. His career began in the civil aerospace division of Rolls-Royce but moved on to undertake diagnostic and control systems research and development for the Ford Motor Company. He subsequently worked as an expert engineering witness before joining Lotus Engineering in 1995. Dr. Bacon is presently a Principal Development Engineer within Lotus Engineering, UK, and a member the Powertrain Research team working on the development of direct injection technology for the next generation of automotive gasoline engines.