Real-Sized Pressure Swirl GDI Injector Investigation with HSFV and FPIV

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Abstract. This paper demonstrates the application of optical diagnostics to the study of internal flows in real-sized GDI injector nozzles. The application of non-intrusive optical techniques provides an opportunity for in-depth study of internal flows in GDI injectors, allowing comprehensive measurement and investigation of injection phenomenon. It also allows the study of spray structures and other physical processes generating atomised fuel. In this study, a series of pressure swirl injectors with varying internal geometry were manufactured from fused silica to allow an investigation of variable driving pressure, variable swirl ratio and pintle angles of 30°, 45° and 60°. Data is presented for the structure of the aircore formed within the nozzle of the injector, together with FPIV data of the axial and tangential components of the internal flow field. The data is compared with semi-empirical relationships found in literature and good agreement was obtained.

1. Introduction
The study of Gasoline Direct Injection (GDI) systems used in internal combustion engines is well documented [7 & 12]. The implementation of more stringent legislation for vehicles emissions requires closer control of the combustion processes and GDI is recognised as the next evolutionary step in automotive technology. The application of GDI offers the potential for improvements in emissions, fuel economy and performance in both homogeneous and stratified combustion over the conventional port injection. Major OEMs are committed to GDI as a technology that can provide the controllability required for future engines and also offers the ability to be integrated into hybrid electric vehicles which is touted as the next revolutionary step [5].

There have been several optical studies of internal fuel flow processes using both real-sized and large-scale model nozzles aimed at achieving a more consistent spray under different engine operating conditions. These studies are aided by the advancement and the application of laser-based optical diagnostic as a major component in experimental investigations of fluid flow phenomena. Soteriou et al [11] and Chaves et al [2] provide examples of the application of optical diagnostic for in-nozzle analysis. Soteriou et al [11] investigated the liquid breakup from 4 different flow geometries, from simple geometry circular orifices to multi-hole nozzles. A simple photographic method was used to record the flow structure to infer mechanisms for cavitation and atomization processes in DI Diesel sprays. Chaves et al [2] applied flow visualization technique in their investigation of the flow region of their glass nozzles. A high efficiency pulsing LED was used to provide the internal flow
illumination. These studies showed the development of cavitation and “supercavitation” in their fuel nozzles.

This paper presents new experimental data from current studies directed to the application of optical diagnostics to the development of real-sized optical orifices and the measurement of the fundamental process of in-nozzle fluid flow. This research is a continuation from previous published works [8] from non-swirl injectors. A range of optical diagnostics is described and discussed in relation to their applications with the real sized optical rig and orifices. High-speed flow visualisation (HSFV) and fluorescent particle image velocimetry (FPIV) were used to collect and analyse the internal and external flow field of these orifices. These data are compared with semi-empirical relationships found in literature and good agreement was obtained.

2. Experimental Setup

2.1. Optical Rig

An injector optical test rig [8] was used to allow the incorporation of optically accessible components to facilitate investigation of the internal flow structures in a laboratory based environment. These optical components were constructed from fused silicate glass and manufactured as real-sized injector components. The flexibility of the optical rig also allowed swirl generators with pintle valves to be incorporated. The schematics of the nozzle geometry with a swirl generator were shown in figure 1. All the nozzles used have a length to diameter (L/D) ratio of 4 and pintle valve chamfer angle from 60° to 120° have been evaluated. This setup allowed non-intrusive optical diagnostic techniques to be employed in the internal flow investigations.

A fuel delivery system was setup and incorporated onto the optical injector rig. This fuel delivery system allowed any liquid fuel (white spirit, gasoline and diesel) to be supplied to the optical rig. The principle fuel used for the results presented here was white spirit; a petroleum derivative with a density, viscosity and refractive index similar to that of gasoline fuel, which is less volatile and flammable than gasoline and offers a safer alternative for laboratory studies. The fuel delivery system enabled any liquid fuel to be pressurized from 1MPa to 15MPa using a controlled supply of nitrogen gas. The liquid fuel was stored in an accumulator and pressurized by nitrogen gas to the required
pressure before each controlled injection. A control valve was attached to the head of the optical rig to allow manual actuation for each injection process.

2.2. Laser Diagnostic Techniques
Two optical diagnostic techniques were used in this study to analyse the flow field. High-speed flow visualization (HSFV) provided detailed analysis of both the internal flow and the external spray structure for high pressure direct injectors. Fluorescent Particle Image velocimetry (FPIV) was employed to provide quantitative data for characterizing in-nozzle fluid flow.

![Figure 2. High-speed flow visualisation and FPIV setup in the laboratory.](image)

High-speed flow visualization provided detailed images of the internal flow field and external spray structure. This technique consisted of a copper vapour laser, capable of providing 30 ns light pulses with 2 mJ per pulse, was synchronized to a high-speed digital camera at 9 kHz. The laser source was used to provide back illumination through a fibre-optic delivery system to a diffusion screen placed close to the back of the optical injector.

Fluorescent particle image velocimetry was used to quantify in-nozzle fluid velocity. The system consisted of a doubled pulsed Nd:YAG laser and a CCD camera with a 1008 x 1008 pixel resolution. Fluorescent seeding particles with particle diameter ranging from 5 to 7 micron were introduced into the flow as tracers. The encapsulated rhodamine laser dye in the fluorescent particles, when excited by the laser light at 532 nm emitted at 620 nm. Imaging these particles through a 620 nm filter allowed the rejection of interference from unwanted scattering caused by the injector and liquid surfaces. The fluorescence emitted by these particles was then recorded on the twin-frame CCD camera with a 1 μsec separation between frames. The FPIV doubled-pulsed images were then processed using cross-correlation analysis with 32 x 32 and 64 x 64 pixel interrogation regions and a 50% overlap. The size of the analysis region is dependent on the nozzle geometry investigated.

3. Results and Discussions

3.1. High Speed Flow Visualisation
Figure 3 shows a sequence of images taken from the 9000 frames/second the high-speed flow visualisation record of the flow in the 1mm swirl injector with a 30° swirler with a 45° chamfered inlet orifice and a driving pressure at 60 bar. After opening of the control valve, as the nozzle driving pressure increases, the swirl flow generates a vortex in the nozzle as shown in image (b). This vortex grows in strength and draws a swirling aircore into the nozzle. The length of the aircore increases until
it attaches to the pintle (See images (d)-(h)). This flow forces the exiting fuel flow into a thin annular region close to the nozzle wall.

This basic internal flow structure was the same for all the swirl nozzles investigated. The visualised flow generated formed an almost perfect aircore from the pintle to the nozzle exit and a thin liquid film at the nozzle periphery. A similar uniform aircore structure was also seen in the experimental study conducted by Allen and Hargrave [1]. The authors used a commercial GDI injector with a tangential swirl on a smooth 45° nozzle to generate these swirl flow structures.

![Figure 3. High-speed flow visualisation 45° chamfer 30° swirler with 60 bar pressure.](image)

From the video sequences for a range of nozzle geometries and driving pressures, data was extracted for the shape of the aircore. Two different types of aircore were observed in this study, tapered and uniform aircore. The tapered aircore structure was seen in all the 45° chamfered inlet orifice studies regardless of the change in swirl generators. The 30° and 60° chamfered inlet orifices exhibit a more uniform aircore structure in the nozzle. Figure 4 presents the variation in annulus thickness and aircore diameter along the length of the injector for the 30° swirler at a driving pressure of 30 bar. The data for all the configurations shows the annulus thickness decreases along the nozzle. This finding is supported by the experimental work of Cooper et al [4] and numerical modelling work of Shaikh et al [10]. There is clear indication of the formation of a wave-like structure in the annular flow for all the nozzle geometries, which is also noted by the experimental work of Cooper et al [4]. These wave
structures are a result of the radial velocity component imparted by the contraction from the reservoir into the nozzle. The flow enters the nozzle with a significant inward radial velocity causing the liquid surface to rise; decreasing the aircore increasing film thickness. As flow progresses along the nozzle the relatively small radial momentum is redirected by the large tangential and radial components. In this way, the annulus thickness reduces along the nozzle all the way to the exit.

In order to quantify the liquid film thickness, the data obtained was compared to an empirical relationship provided by Dorfner et al [6] for the calculation of annulus thickness for pressure swirl atomisers. According to Dorfner et al [6], the film annulus thickness, \( h_o \), at the nozzle exit is given by:

\[
h_o = \left[ 3.66 \frac{m_l d_o \mu_l}{\rho_l \Delta P_l} \right]^{0.25}
\]

where \( m_l \) is the liquid mass flow rate, \( d_o \) is the nozzle exit diameter, \( \mu_l \) and \( \rho_l \) are the liquid viscosity and density. The pressure difference across the nozzle is given as \( \Delta P_l \).

Figure 5. Experimental and calculated annulus thickness comparison with a 45° chamfered inlet orifice.

Figure 5 presents annulus thickness data for all three swirlers, with a 45° chamfered inlet orifice and driving pressure from 20 to 60 bar. Comparison of the current data with the relationship provided by Dorfner et al [6] shows that the constant of 3.66 significantly under-predicts the experimental results. By increasing the constant value in equation 1 from 3.66 to 6, the calculated annulus thickness values fit better to the experimental data for the 30° swirler configuration. However, the equation still under predicts the annulus thickness for the 45° and 60° swirlers. Clearly the thickness is a function of the swirler geometry, but this is not accounted for in the Dorfner et al [6] relationship.

3.2. Fluorescent Particle Image Velocimetry

The high-speed flow images provide insight knowledge of the in-nozzle flow processes, highlighting the change in aircore diameter and structure through the length of the nozzle. These changes also indicate the variation in axial velocity of the fluid through the orifice. However, the presence of the aircore generates unwanted Mie scattering which prevents the use of the normal PIV technique. Figure 6 highlights the necessity of using FPIV to remove this unwanted scattering. The first image on the left clearly indicates the fluorescent particles flow direction through the orifice. With a known
laser pulse separation of 1 μsec, the fluid velocity was analysed and measured using commercial software. The right image shows a typical example of a derived velocity field of a 30° swirler with a 45° chamfered inlet orifice.

![Image](image_url)

**Figure 6.** Fluorescent PIV image and vector field for the 45° nozzle.

![Image](image_url)

**Figure 7.** Axial and radial velocity components for the 45° nozzle.

Figure 7 presents radial and axial velocity components for driving pressure ranging from 20 bar to 60 bar for 45° chamfered inlet orifice with a 30° swirler. The graphs show the radial and axial velocities increase gradually in the convergent section of the orifice. In the radial velocity graph, the lower driving pressure range remains constant in the nozzle section. However, the higher driving pressures (30 bar to 60 bar) appear to decrease slightly as the flow reaches the orifice exit. In the case of the axial velocity component, the velocity remains constant with increasing driving pressure in the nozzle section. At 60 bar driving pressure, the average axial velocity is about 110 m/s in the nozzle section.
Figure 8. Exit velocities for a 30° chamfered inlet orifice.

Dorfner *et al* [6] and Chryssakis [3] provided a relationship to determine the total exit velocity. This is given by:

\[
U = K_v \left( \frac{2 \Delta P_t}{\rho_l} \right)^{0.5}
\]

where \( \dot{m}_l \) is the liquid mass flow rate, \( d_o \) is the nozzle exit diameter, \( \mu_l \) and \( \rho_l \) are the liquid viscosity and density. The pressure difference across the nozzle is given as \( \Delta P_t \). \( K_v \) is the nozzle coefficient, which was defined by Lefebvre [9] as:

\[
K_v = 0.00367 K^{0.29} \left( \frac{\Delta P_t \rho_l}{\mu_l} \right)^{0.2}
\]

where \( K \) is the atomiser constant, \( K = \frac{A_p}{d_o D_s} \).

\( A_p \) is the tangential inlet port, \( d_o \) is the orifice diameter and \( D_s \) is the swirl chamber diameter. For the injectors used in the current study, the \( A_p \) values are known (6 x 1 mm by 1mm ports) and \( d_o \) is known (1 mm). However, it is not clear how to define \( D_s \). It should also be noted that the velocity coefficient \( K \) given by Lefebvre [9] is not dimensionally balanced [6] and is completely dependent on the actual nozzle geometry. Thus, following the methodology of Lefebvre [9], it was not possible to satisfactorily define the atomiser constant, \( K \), for the current injector geometries.

Therefore, the data presented in figure 8 presents a best fit of equation 2 to the experimental data, by varying the value of \( K \) in equation 3. Figure 8 shows the experimental and calculated exit velocities for 30° chamfered inlet orifices with \( K \) values ranging from 1.67 to 2.14. These \( K \) values allow the calculated exit velocities matched those of the experimental results. All the figures show gradual increment in exit velocities with increasing driving pressure.
4. Conclusions
This paper has presented results from an investigation of the internal flow structure of real-sized GDI injectors using optical diagnostic techniques. Results were presented for varying nozzle pintle valve geometries and swirl generators. Two different types of aircore were observed from flow visualisation study; tapered aircore showed by 45° chamfered inlet orifice and uniformed aircore structures were observed in 30° and 60° chamfered inlet orifices. The annulus thickness results compared with Dorfner et al [06] empirical equation shows good agreement. The film thickness was found to be dependent of driving pressure and nozzle geometry.

The FPIV study highlighted the swirl velocity increases with increasing injection pressure, with the axial component producing a higher velocity flow to the radial component. The exit velocities data was compared with a semi-empirical relationship provided by Dorfner et al [06] and the empirical constants modified to fit the current experimental results. By combining the high-speed flow visualisation and FPIV data provide a unique understanding of the fluid flow process inside the nozzles and gave an insight on their effect on the spray structure once the flow exits the nozzle.

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