1. INTRODUCTION

The use of Direct Injection (DI) for SI engines is an increasing trend with a number of major OEM’s committed to convert their vehicle fleet to DI. Gasoline Direct Injection (GDI) technology can provide the controllability required for future engines and also offers the ability to be integrated into hybrid electric vehicles, touted as the next revolutionary step. The implementation of more stringent legislations for vehicle emissions also 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 for both homogeneous and stratified combustion.

The advancements and developments of laser-based optical diagnostics has become a major component in experimental investigations of fluid flow phenomena. The application of optical diagnostic techniques for in-nozzle flow studies was demonstrated by Soteriou et al [2] and Gavaises et al [7]. The authors used both real-sized and large scale model nozzles to investigate internal flow structures in a study aimed at achieving a more consistent spray under different engine operating conditions. Soteriou et al [2] investigated the liquid breakup from four different flow geometries, ranging from simple geometry circular orifices to multi-hole nozzles. A straightforward photographic method was used to record the flow structure to infer mechanisms for cavitation and atomisation processes in DI sprays. Gavaises et al [7] in a recent study of pressure swirl atomisers for DI gasoline engines using

![Image of nozzles](image-url)

**Figure 1** Schematics of the nozzles used in the experiments.
high speed imaging, provided an important link between the fuel film thickness generated in the nozzle of a swirl injector and the resultant spray structure.

The aim of the research presented in this paper is to provide an understanding of the GDI injector spray behaviour using a combined experimental and theoretical modelling approach to provide a unique insight into flow processes. The experimental data from current studies uses optical diagnostic techniques to aid the development of real-sized optical orifices and the measurement of the fundamental process of in-nozzle fluid flow. These data are validated with Direct Numerical Simulation (DNS) modelling based on an initial study presented by Heather et al [5].

2. EXPERIMENTAL SETUP

2.1 Optical Rig

An optical rig was constructed which allowed the incorporation of optically accessible components to facilitate investigation of the internal flow structures in a laboratory based environment. The rig consisted of an aluminium body that supported the high pressure fuel delivery system and control valve, acted as a fuel reservoir and incorporated optical nozzles machined from fused silica. The fuel delivery system allowed pressurised liquid fuel up to 15 MPa to be supplied to the optical rig using a controlled supply of nitrogen gas. The liquid fuel is stored in an accumulator that was pressurised by a nitrogen gas supply 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. This allowed a relatively slow pressure rise in the reservoir and the investigation of the steady state period of the injection. The principle fuel used for the tests presented in this paper was white spirit; a petroleum derivative with a density, viscosity and refractive index similar to gasoline fuel.

The optical nozzles (figure 1) were constructed from fused silica and manufactured as real-sized injector components. The optical nozzles were polished internally and externally to achieve surface finishes of an optical quality required to minimise distortion of the fluid flow and optical light paths. A mount assembly was incorporated on the optical rig that allowed easy access to optical components for rapid changes between different geometrical arrangements. The flexibility of the optical rig also allowed swirl generators with pintle valves to be used. 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.

2.2 Optical Diagnostic

Two optical diagnostic techniques were used in this study to analyse the flow field. A high speed flow visualisation system provided detailed images of the internal flow field and external spray structures. This system consisted of a Copper vapour laser synchronised to a high-speed camera capable of providing video recording up to 27,000 frames per second. The laser source, 30 ns light pulses with 2 mJ per pulse, 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.

The Fluorescent Particle Image Velocimetry (FPIV) system shown in figure 2 was used to quantify in-nozzle fluid velocity. The system consisted of a doubled pulsed Nd:YAG laser and a 1008 x 1008 pixel resolution CCD camera. Fluorescent seeding particles, introduced into the flow as flow tracers, were polyamide spheres with an encapsulated rhodamine laser dye with particle diameter ranging from 5 to 7 micron. When the particles were excited by the laser light at 532 nm, they emitted at 620 nm.

![Figure 2 Optical diagnostic setup in the laboratory.](image-url)
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.

3. RESULTS AND ANALYSIS

The sequence of images shown in figure 3 presents the high-speed flow visualisation for a 1mm nozzle with a 30° swirler and a 30° chamfered inlet orifice at a driving pressure of 30 bar. When the control valve is activated and the pressure in the nozzle begins to build up, the swirl flow generates a vortex (image (b)) in the nozzle. As the vortex grows in strength, it draws a swirling aircore into the nozzle and attaches to the pintle as shown by images (c)-(f). The swirling aircore forces the exiting fuel flow into a thin annular region close to the nozzle wall. The same internal flow structure was also seen on figure 4 using a 60° chamfered inlet orifice and also for all the swirl nozzles investigated.

![Figure 3](image3.png)
![Figure 4](image4.png)

Figure 3 High-speed flow visualisation for a 30° chamfer orifice with 30 bar fuel pressure flow images.

Figure 4 High-speed flow visualisation for a 60° chamfer orifice with 30 bar fuel pressure flow images.

From the video sequences, data was extracted for the shape of the aircore for the range of nozzle geometries and driving pressures tested. Figure 5 presents the variation in annulus thickness and aircore diameter along the length of the nozzle.

![Figure 5](image5.png)

Figure 5 Variation in aircore and diameter and annulus thickness for the 30° chamfered inlet orifice.
the injector for the 30° chamfered inlet orifice with 30 bar driving pressure under steady state conditions. Two different type of aircore were observed in the graphs: tapered and uniform aircore. The tapered aircore structure was seen in all the 45° and 60° swirler, with the 30° swirler exhibiting a more uniform aircore structure in the nozzle.

Figure 6 Fluorescent particle image and velocity field for experimental.

The high-speed flow visualization provided insight knowledge of the in-nozzle flow processes, highlighting the change in aircore diameter and structure over the length of the nozzle. These changes indicates the variation in axial velocity of the liquid through the orifice. However, the presence of the aircore generates unwanted Mie scattering which prevents the use of normal PIV technique. Figure 6 highlights the necessity of using FPIV to remove this unwanted scattering. The image on the left clearly indicated the fluorescent particles flow direction through the orifice. With a known laser pulse separation of 1 micro-sec, the liquid velocity was analysed and measured using a commercial software. The right image show a typical example of a derived velocity field for a 30° swirler with a 45° chamfered inlet orifice. Further examples are also seen in figure 7 for 30° chamfered inlet orifice with 30° and 60° swirler generators.

Figure 8 presents the radial and axial components for the 30° chamfered inlet orifice with three different swirlers at 30 bar driving pressure. The graphs show that the radial and axial velocities increase gradually in the convergent section (0-2mm) of the orifice. In the radial velocity graph, different swirlers appear to have varying effects on the flow from the convergent section of the nozzle into the straight section (2-6 mm). However the axial velocity component shows that the velocity remains constant in the straight section of the nozzle as the flow exits the nozzle.

4. DISCUSSIONS

In this paper, we present a comparison between the current experimental results and the modelling work by Heather et al [5]. The numerical work employed the open source Computational Fluid Dynamics (CFD) C++ libraries,
Open FOAM [4]. The codes used a pseudo- Direct Numerical Simulation (DNS) to model the injector internal-and near-nozzle flow of a pressure-swirl injector. The three-dimensional, transient segregated two-phase flow was computed with the Volume of Fluid (VOF) technique to capture the evolution of the gas-liquid interface. Both gaseous and liquid phases were treated as incompressible; cavitation, thermal and turbulence effects were neglected. The nozzle had an exit diameter of 0.9 mm with a 30° chamfered inlet orifice and a final parallel section length of 1.15 mm. The fuel pressure set at the pump is 50 bar but the study operating pressure at the swirl generator equates to 35 bar at the entry under full pintle lift, steady state conditions.

The evolution of the calculated flow development is shown in figure 9. Red is used to signify fuel-filled region and blue the ambient gas-filled region. The intermediate colours represent the transitional region that implies the presence of the interface between the fuel and air. Figure 9(b) shows the formation of an aircore. As the flow develops, the aircore grows into the nozzle and attaches itself to the injector pintle. This flow phenomenon is identical to the experimental flow development shown in figure 3. Similar flow phenomena is also seen in Allen et al [8], using the same swirl generator but with a longer nozzle.

Figure 10 shows the graph for liquid annulus thickness and aircore diameter for the numerical 30° chamfered inlet orifice. As both experimental and numerical nozzle are of different length, the graphs is normalized to observe and trends in the two flows. The liquid annulus thickness and aircore diameter clearly display similar trends to the 30° swirler shown in red. All the plots shows the annulus thickness decreases along the nozzle as the flow moves towards the nozzle exit. This finding is also supported by the experimental work of Cooper et al [9] and numerical modeling 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. These wave structures are a result of the radial velocity component imparted by the contraction from the reservoir to the nozzle. The flow enters the nozzle with a significant inward radial velocity causing the liquid surface to rise; decreasing the aircore and increasing the film thickness. As the 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.

![Figure 9](image1.png)

**Figure 9** Flow images of the numerical nozzle with 35 bar equivalent nozzle pressure.

![Figure 10](image2.png)

**Figure 10** Aircore diameter and annulus thickness for the 30° chamfered inlet orifice.

The left image in figure 11 shows the in-nozzle flow velocity vectors for the straight section, rotating in a clockwise direction due to the swirl generator. The radial and axial velocity components are plotted on a graph shown on the right of figure 11. The graph shows the flow from left to right, with the zero point being the nozzle exit. The radial velocity shows the velocity decreases from 35 m/s to 25 m/s as the flow exits the nozzle but the axial velocity increases from -10 m/s to about -50 m/s. The variation in the flow velocity is similar to the 60° swirler shown in figure 6.
Figure 11 Axial and radial component for numerical 30° nozzle with 30 bar nozzle pressure.

Figure 12 Comparison of experimental and numerical radial and axial velocity for straight section of the nozzle.

Figure 12 shows the comparison study for both experimental and numerical velocities for the straight section of the nozzle. The radial velocity components shows that the CFD model is similar to the 45° and 60° swirlers. For the axial velocity component, the CFD model under predicts and the velocity is only half of the experimental velocity components. However, all the nozzles shows axial velocity component remains constant in the straight section of the nozzle as the flow exits the nozzle. This finding is in agreement with the data presented by Gavaises et al [07] for a pressure swirl atomiser (nominal size 1 mm) and may be attributed to the fact that the radial (swirl) to axial velocity ratio is independent of the driving pressure. The ratio is only a function of the geometry of the swirler and thereby the imposed tangential velocity at the inlet to the nozzle.

5. CONCLUSIONS

Experimental and computed results are presented in this paper for real-sized GDI injectors with different swirl generators. The analysis of the experimental results with the computed data shows reasonable agreement, able to identify the significant in-nozzle flow development characteristics. Although the swirl generator and nozzle length used are different in this comparison, both experiment and numerical results showed that the internal velocity flow are similar for a given driving pressure condition. However, more research to determine the optimal calculation strategy is required to refine and reap the full benefits of this CFD approach.

The combination of high-speed flow imaging and FPIV data provides a unique understanding of the fluid process inside the nozzle. The modelling tool provides further validation of the in-nozzle flow process and gives an insight into the factors that affect the initial spray development on leaving the nozzle.

6. NOMENCLATURE

DI Direct Injection
DNS Direct Numerical Simulation
VOF Volume of Fluid
GDI Gasoline Direct Injection
CFD Computational Fluid Dynamics
CCD Charge Coupled Device
PIV Particle Image Velocimetry
FPIV Fluorescent Particle Image Velocimetry

7. REFERENCES

1. Iwamoto, Y., Noma, K., Nakayama, O., Yamauchi, T., Ando, H., Development of Gasoline Direct Injection Engine, SAE 970541, 1997


