Study of Barrel Swirl in a Four-Valve Optical IC Engine Using Particle Image Velocimetry

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ABSTRACT

Particle Image Velocimetry (PIV) has been used here to characterise barrel swirl ("tumble") throughout the compression stroke in a production geometry, four-stroke, four-valve pentroof optical IC engine. Images were recorded over a range of crank angles from 180 degrees before TDC to 22 degrees before TDC at a motored engine speed of 1000 RPM, wide open throttle. PIV results are presented from a single plane perpendicular to the cylinder axis and crank, bisecting the centrelines of an inlet and exhaust valve.

Large scale barrel swirl is shown to persist throughout most of the compression stroke. However, early in the stroke this is confused by significant small scale structure which progressively decays until a repeatable, ordered tumble motion is revealed after Inlet Valve Closure. This predominantly large scale structure is subsequently seen to exist up to the ignition point at 22 degrees before TDC, well after the expected swirl breakdown. This suggests that the flow at ignition has not broken down into a quiescent flow characterised by homogeneous small scale turbulence, but instead consists of turbulent fluctuations superimposed on a relatively ordered bulk flow.

INTRODUCTION

It has been shown that fluid flow within an IC engine has a fundamental effect on engine performance [1, 2]. Modern multi-valve spark ignition engines with four valves per cylinder [3] exhibit favourable characteristics with regard to power output and exhaust emissions. This has been attributed in part to turbulence enhancement resulting from the breakdown of barrel or "tumbling" motion which is generated during the induction stroke [4]. As the piston approaches TDC the large scale tumble is believed to break down into relatively homogeneous microturbulence due to severe vortex distortion and shear. The enhanced turbulent flow field promotes rapid burn rate, improved flame propagation and better cyclic variability even under the high charge dilution conditions required for emissions control.

Although liquid analogue and steady flow studies have been used to characterise induction flows, they cannot be used to study the process of turbulence generation during compression [5]. Until recently therefore, barrel swirl evolution in motored and fired engines has been studied using Hot Wire Anemometry (HWA) [3] and Laser Doppler Anemometry (LDA) [6,7,8] and these have provided much useful velocity and turbulence data at selected points within the flow field. However, whole field measurements are also required if a full characterisation of the rapidly evolving flow field is to be made. This has led to the development of full-field techniques such as Particle Tracking Velocimetry (PTV) [9,10] and Particle Image Velocimetry (PIV) [11]. IC engine related PIV studies to-date have included the measurement of: motored [12] and fired [13] flows in high axial swirl engines; intake flow past an inlet valve [14] ; and cylinder wall ported engine flows under motored and fired conditions [15]. Recently the authors have reported initial measurements of barrel swirl in a motored engine [16, 17].

By using high energy pulsed laser illumination, PIV permits the use of microscopic seeding particles which are able to follow the rapid velocity fluctuations inherent in in-cylinder IC engine flows [18]. PIV can therefore provide images of turbulent flow structures on spatial scales down to the order of one millimetre, together with quantitative measurements of larger scale structures. The technique is therefore ideally suited to the study of tumble breakdown in IC engines. The high resolution imaging which PIV entails does however necessitate correction of optical aberrations and careful optimisation of the imaging system, flow seeding and illumination.

Here the authors present PIV measurements of barrel swirl throughout the compression stroke in a production-geometry motored optical IC engine. PIV images have been recorded at crank angles throughout compression in a plane parallel to the cylinder axis. This has been made possible by the development of a special corrective optical system which provides almost diffraction-limited imaging of particles within the thick glass cylinder. Experimental methods permitting the routine acquisition of PIV images from the engine are briefly described. A representative set of PIV data are then presented and qualitatively compared with PTV and LDA results from similar engine geometries. The implications for future PIV engine studies and future refinements to the PIV technique are briefly discussed.

EXPERIMENTAL

Optical engine

Measurements were made on a single cylinder four stroke motored optical engine, designed and built by Advanced Power Train, Rover Group, Gaydon. The four-valve four-stroke pentroof chamber engine was equipped with a glass piston crown and cylinder (Fig. 1). This permitted optical access from the piston crown at BDC to the spark electrode in the apex of the combustion chamber for a single camera position. The engine configuration is summarised in Table 1.

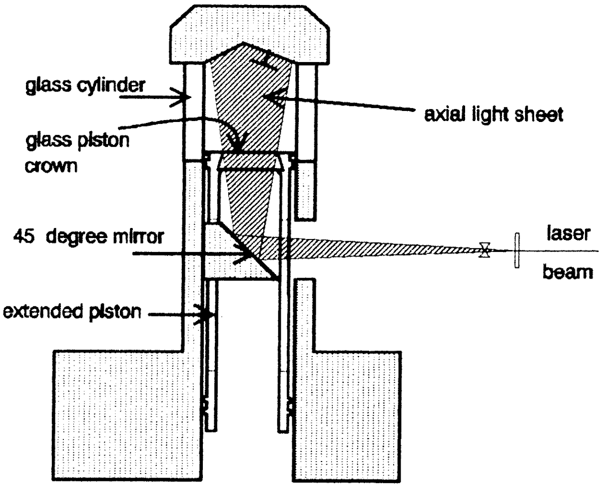

Fig. 1 Schematic of optical engine and illumination

Table 1 Engine configuration

BORE mm	84.45
STROKE mm	89
SWEPT VOLUME cc	500
COMPRESSION RATIO	10.5:1
VALVE LIFT mm	10.16
INLET VALVE PEAK LIFT	70^{o} Before BDC
EXHAUST PEAK LIFT	70^{o} After BDC
CAM PERIOD	240^{o}
ENGINE SPEED RPM	1000

Measurement Conditions

The position of the vertical measurement plane is indicated in Fig. 2. This plane passes through the centreline of an inlet and exhaust valve and is perpendicular to the engine crank.

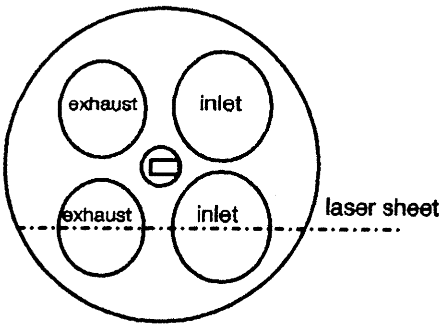

Fig. 2 Location of vertical measurement plane, viewing the underside of the cylinder head

Images were recorded at a pulse separation of $25\mu s$ at a crank speed of 1000 RPM, wide open throttle. The required pulse separation was estimated from previous successful lower speed results for a BDC position. For efficient use of engine running time the same pulse separation was used for the complete range of crank angles in Table 2 below.

Table 2 Measurement Crank Angles

Crank Angle Degrees after TDC Inlet	Significance
180	BDC
222	Inlet Valve Closure
260	Intermediate point
300	Expected Swirl Breakdown
338	Ignition point

PIV Imaging Equipment

The light source was a frequency doubled, dual oscillator, dual amplifier Spectron Nd:YAG system. Individual pulses were of 8ns duration with pulse energies of 100-120 mJ at a wavelength of 532nm.

A purpose built electronic unit was used to time the pulsed laser illumination to a resolution and repeatability of 0.1 degree crank angle. Fixed delays in the timing system were accounted for by strobing the engine flywheel with a small proportion of the laser beam. The timing datum for the system could then be evaluated directly and timing jitter assessed.

A medium format Mamiya 645 camera with a Mamiya Sekor f4 80mm macro lens was used at an aperture of f#= 5.6 and a magnification of 0.4, producing particle images of 10 to 20 μm in diameter, over fields of view up to 60mm wide and 95mm high. The depth of field was approximately 0.8mm. Kodak Technical Pan 2415 film was developed with D-19 to give a speed of around 100 ASA at a resolution of up to 300 line pairs per mm.

EXPERIMENTAL TECHNIQUES

Light Sheet Formation.

A collimated sheet approximately 600μm thick was formed using a 200mm focal length positive cylindrical lens and a -30mm focal length biconcave spherical lens. Precise overlap of the two laser sheets was determined by measuring their intensity profiles using a pinhole and photodetector assembly. In this way intensity profiles were measured at three points along the sheet centreline and adjustments were performed until the beam centres coincided to +/- 50μm.

The vertical sheets were introduced through the piston crown via a dielectric mirror, minimising stray reflections within the field of interest. Datum plates located on machined engine faces were used to position the sheets to an accuracy +/- 0.25 mm over the measurement region.

Flow Seeding.

A Laskin atomiser and separator was used to generate a fine mist of 0.5 to 2.0 μm olive oil droplets. The seed was introduced into the engine's intake plenum to achieve uniform mixing. The seed density was controlled by the air supply pressure to the atomiser using a precision low pressure regulator. Seed density within the engine was monitored using a photodetector mounted in the camera viewfinder whose voltage output was calibrated against particle image density at BDC. Re-optimisation of seed density for crank angles close to TDC was achieved by reducing the density measured at BDC by a factor appropriate to the compression at the measurement crank angle.

Photographic Techniques.

The camera was oriented perpendicular to the light sheet by ensuring that the front of the lens was parallel to an engine datum face. The geometry for viewing the vertical sheet was therefore as in Fig. 3 below.

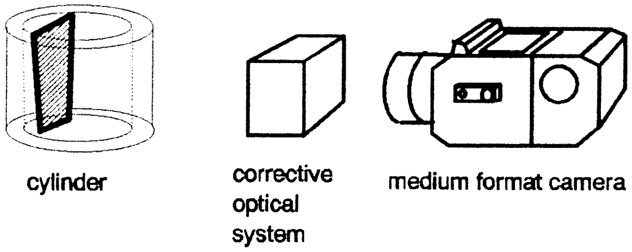

Fig. 3 Viewing of vertical sheet

Accurate camera focusing was achieved using a technique described by Hocker and Kompenhans [19]. A microscope imaged a small region of the camera image plane onto a CCD array, allowing a highly magnified view of the region to be displayed on a monitor (Fig. 4). The quality and density of live particle images in that region could then be assessed and optimised.

The camera lens was operated at fixed focus to eliminate the need for repeated calibration of magnification. Focusing was performed by translating the camera and microscope assembly on coarse and fine translation stages. Once focusing was complete, the microscope could be removed and the loaded film cassette clipped in place.

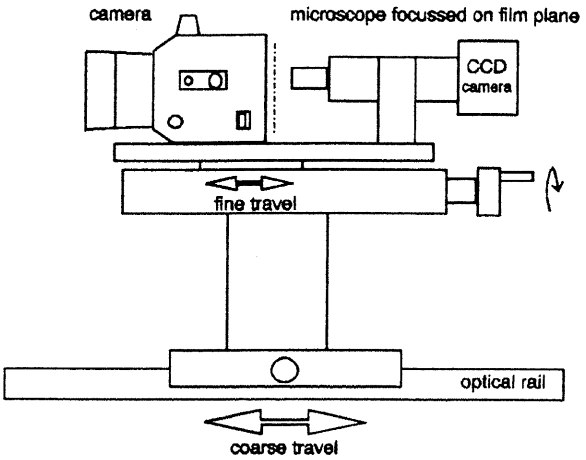

Fig. 4 CCD microscope focusing assembly

The curved walls of the glass engine cylinder produced highly astigmatised particle images when vertical sheets were viewed. A special corrective optical system was therefore developed which allowed high quality particle images to be formed. The performance and design of this system will be discussed more thoroughly in reference [20]. The CCD microscope arrangement was employed to optimise the complete imaging system for the plane of interest prior to PIV measurements. Video prints of a USAF resolution chart before and after optical correction are shown in Fig. 5 and 6 below.

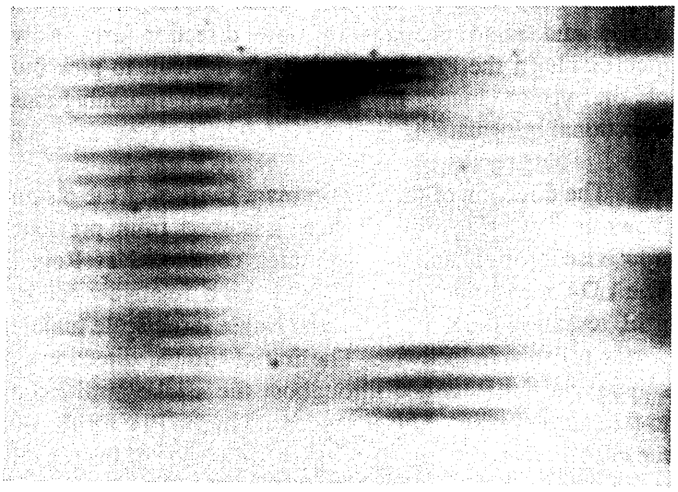

Fig. 5 USAF resolution chart within cylinder at plane of best focus, without correction.

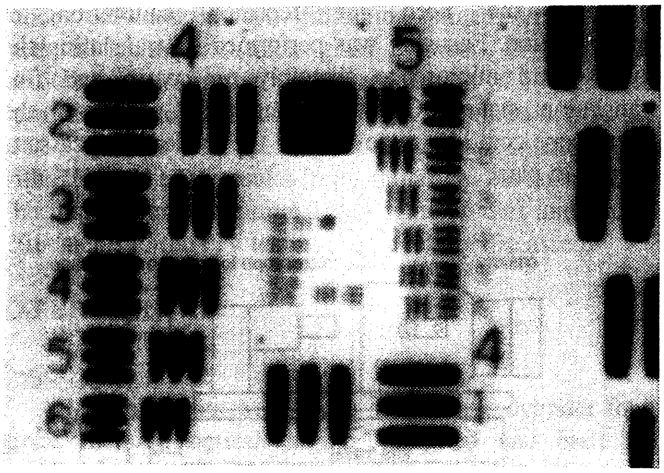

Fig. 6 Image of resolution chart with correction.

RESULTS AND DISCUSSION

Images were interrogated within 1.1mm square regions with 50% overlap, using a commercial digital autocorrelation system developed by AEA Harwell. The raw vector maps were edited to remove inconsistent vectors, which constituted approximately 15% of the total. Data dropout occurred in regions where the velocity was smaller than the lower extreme of the dynamic range ($\sim 2.9\ ms^{-1}$), where velocity gradients and out-of-plane velocities were excessive and where flare caused background image noise.

Owing to the predominance of small scale structure in the images prior to Inlet Valve Closure and the limits of space in this publication, complete velocity maps are presented here only for crank angles after Inlet Valve Closure. In the vector maps of Fig. 7a to 7d, assumed flow directions are superimposed. Small scale structures in the vector maps which correspond to identifiable features in the original PIV images have also been highlighted. Such eddies and rapid changes in flow direction are easily identifiable in the PIV images but are difficult to pick out of the vector maps in the absence of unambiguous directional information.

The direction of the predominant swirl over the piston crown at IVC (Fig 7a) has been assumed from previous flow visualisation and LDA studies conducted at Rover. The LDA measurements were made on a relatively coarse grid, revealing the direction of the single large scale tumble vortex to be anticlockwise. The initial tumble direction is subsequently maintained throughout the stroke until close to the ignition point. This is evidenced in the PIV results by the ever increasing flow angle on the inlet side of the piston crown as the instantaneous piston speed increases from BDC (Figs 7a,b,c). Strictly, the direction of flow vectors within smaller scale flow structures is subject to the usual 180^{0} ambiguity inherent in autocorrelation PIV interrogation.

As the piston proceeds upwards the small scale structure evident in the flow map at IVC decays to leave a progressively more ordered and repeatable large scale barrel swirl which penetrates the combustion chamber apex at 260 degrees after TDC (Fig 7b). At 300^{0} CA after TDC a single ordered vortex is seen (Fig 7c). The flow from the inlet valve side of the piston crown is now almost vertical, while to the exhaust side the mean flow is horizontal but exhibits small scale structure due to competition between the downward flow moving towards the piston and the rapid upward motion of air moving at the instantaneous piston speed.

It is interesting to note that the typical maximum flow velocity of approximately $10ms^{-1}$ means that even the fastest moving particles can complete at most one vortex revolution during the compression stroke. Hence the phenomenon of tumble "spin up" (ie. increase in angular velocity) and breakdown must be considered a highly transient event.

At the ignition point of 22 degrees before TDC a strongly ordered flow is still apparent (Fig 7d). Data dropout at this crank angle was due to flare from the valves and an oil smear deposited at the top of the piston stroke by the piston rings. The major flow features revealed at this crank angle are the formation of two vortices and an approximately 90^{0} shift in flow direction on the bore centreline compared to the 300^{0} CA case. Visual analysis of the original transparencies revealed these features to be quite repeatable. This indicates that the process of tumble breakdown into small scale turbulence is not yet complete. The predominant length scales are therefore of the order of the clearance volume dimensions at this crank angle. This is not to say that single point measurements should not indicate high turbulence at this condition. The large scale structures, though repeatable, may move rapidly past a point velocity transducer, which determines turbulence from measurements taken over a larger crank angle window than the $25\mu s$ or 0.3^{0} CA window of the "instantaneous" PIV image.

A detailed quantitative analysis of the flow fields has not yet been performed. However, trends in the apparent turbulence content and maximum flow velocities are found to closely match those resulting from LDA and Hotwire measurements in this type of engine geometry [7,8]. Specifically, the maximum flow velocities in the PIV data both in the cylinder head and close to the piston crown are found to be relatively constant at between 2 and 3.5 times the mean piston speed of $\sim 3ms^{-1}$, for crank angles from BDC up to the ignition point. This suggests that the tendency for the tumble to accelerate due to conservation of angular momentum is largely balanced by kinetic energy dissipation due to shear induced turbulence. Further, the continued presence of large scale structure at ignition reinforces LDA and Hotwire findings that the local peak in

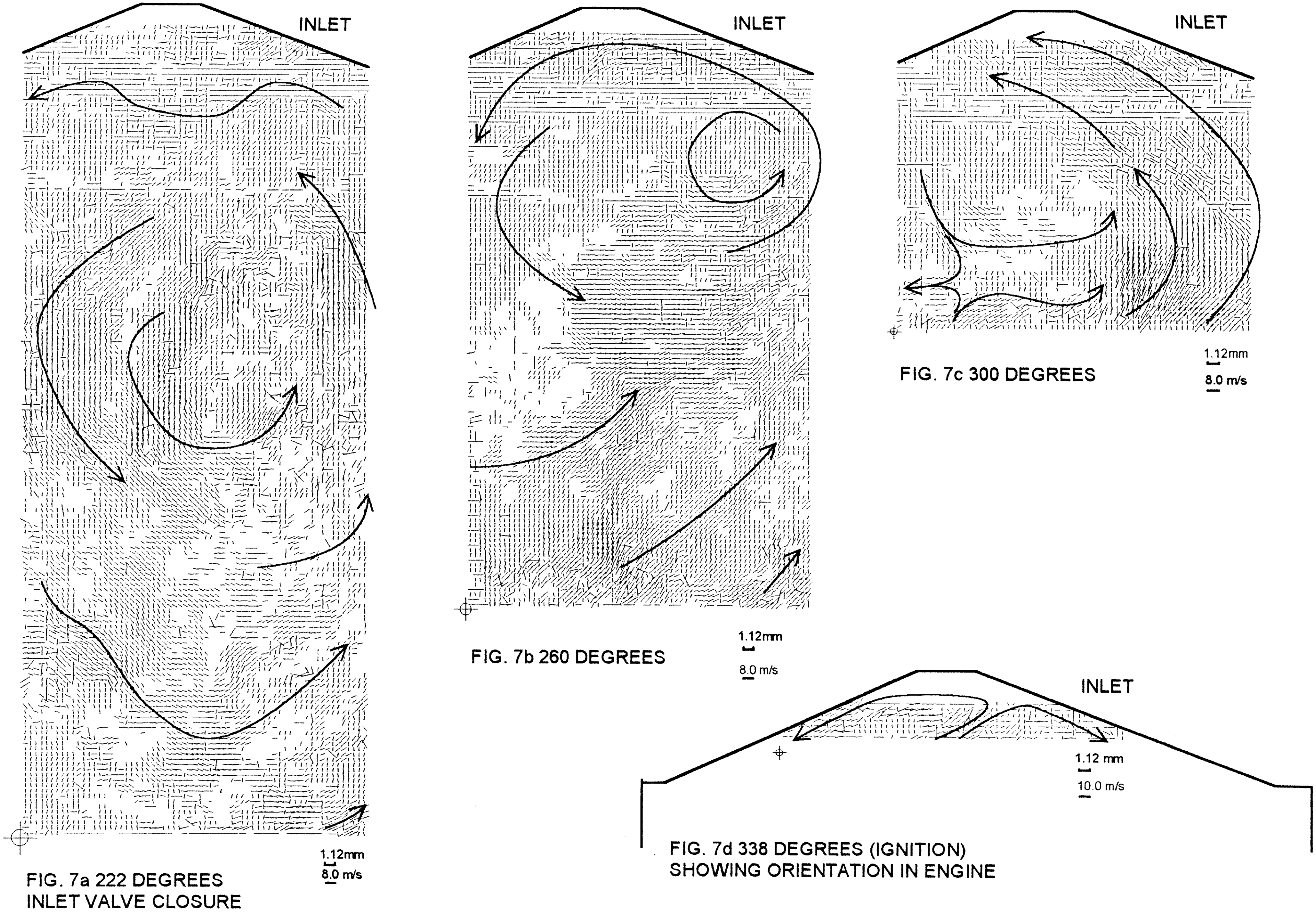

FIG. 7a 222 DEGREES
INLET VALVE CLOSURE

FIG. 7b 260 DEGREES

FIG. 7c 300 DEGREES

FIG. 7d 338 DEGREES (IGNITION)
SHOWING ORIENTATION IN ENGINE

Fig 7 Barrel plane PIV vector maps at various crank angle positions at 1000 RPM turbulence intensity due to tumble breakdown occurs some time after the ignition point in engine geometries which have been designed specifically to support barrel swirl.

Recent PIV measurements by the authors indicate that the major features of the compression velocity field are similar for a parallel plane through the spark position, with velocities close to the spark of approximately 11 ms^{-1} at the ignition point at an engine speed of 1000 RPM. Flow patterns obtained at 22^{0} before TDC closely resemble those determined by Kiyota et al. using particle tracking in a high tumble engine [10] and suggest that better control of flame kernel growth may be achieved by modification of the high speed, directional flow in the spark region at the ignition point, or optimisation of the spark position and orientation.

Developments in the PIV Technique

The direction of bulk flows within the engine can in many cases be inferred from flow visualisation or fluid dynamic considerations. However, this is not true for small scale structures. For example, in the vector maps close to ignition, the flow directions are subject to a 180^{0} directional ambiguity. Several methods have been proposed for resolving such directional ambiguity, including image labelling and image shifting schemes. Particle image labelling by colour [15], polarisation [21] or holographic recording [22] give potential for cross-correlation thereby resolving ambiguity while at the same time improving velocity dynamic range, spatial resolution and signal to noise ratio.

The use of slightly larger seeding particles will improve the scattering efficiency such that the illumination energy can be significantly reduced. This will reduce data dropout due to flare and stray reflections. Preliminary experiments show that the use of adaptive thresholding techniques to reject remaining film noise from interrogation regions will further improve data yield and permit velocity measurements within one millimetre of the combustion chamber walls. Improved optical access into the cylinder head would permit PIV measurements up to TDC and reveal the nature of the flow field during the period of flame kernel growth. It will then be possible to correlate the instantaneous flow fields close to ignition with cycle resolved measurements of heat release and flame propagation.

The almost constant velocity range measured throughout the compression stroke allowed the same pulse separation to be used for each measurement crank angle. This allows extremely rapid acquisition of engine flow maps during the compression stroke and reveals the potential for recording multiple PIV images within a single engine cycle using rapidly pulsed metal vapour lasers and high speed cameras.

CONCLUSIONS

The evolution of barrel swirl in a realistic geometry pentroof four-valve motored engine, from BDC through to the ignition point, has been studied using PIV. The measurements correlate well with LDA, Hotwire and Particle Tracking measurements performed by other workers in similar engine geometries. Ordered motion with typical velocities of over three times the mean piston speed is preserved through the ignition phase. The ability to measure this flow close to spark will permit detailed study of the effects of local flow on flame kernel growth.

Cross correlation is seen as the definitive means for improving PIV performance, resolving directional ambiguity, expanding dynamic range, improving signal to noise ratio and increasing spatial resolution. The use of rapid pulse train lasers with fixed pulse separation will enable cycle resolved measurements of tumble evolution.

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NOMENCLATURE

^{0} CA	Degrees Crank Angle
TDC	Top Dead Centre
BDC	Bottom Dead Centre
IVC	Inlet Valve Closure
PIV	Particle Image Velocimetry
LDA	Laser Doppler Anemometry

REFERENCES

[1]. Arcoumanis, C. and Whitelaw, J.H., "Fluid Mechanics of Internal Combustion Engines -a Review". Proc. Instn. Mech. Engrs., 1987, 201, C1.

[2]. Heywood, J.B., "Fluid Motion Within the Cylinder of Internal Combustion Engines - The 1986 Freeman Scholar Lecture", Trans. ASME, Journal of Fluids

Engineering, 1987, 109, p 3.

[3] Benjamin, S.F., "The Development of the GTL 'Barrel Swirl' Combustion System with Application to Four-Valve Spark Ignition Engines", IMechE., C54/88, 1988, p 203.

[4] Arcoumanis, C., Hu, Z., Vafidis, C. and Whitelaw, J.H., "Tumbling Motion: A Mechanism for Turbulence Enhancement in Spark-Ignition Engines", SAE Paper 900060, 1990.

[5] Khaligi, B., "Intake-Generated Swirl and Tumble Motions in a 4-Valve Engine with Various Intake Configurations- Flow Visualisation and Particle Tracking Velocimetry", SAE Congress and Exp., Detroit, paper 900059, 1990.

[6] Witze, P.O., "A Critical Comparison of Hot-Wire Anemometry and Laser Doppler Velocimetry for I.C. Engine Applications". Trans. SAE, paper 800132, 1980, 89, p711.

[7] Hu, Z., Vafidis, C., Whitelaw, J.H., Chapman, J. and Head, R.A., "Correlation Between In-Cylinder Flow, Performance and Emissions Characteristics of a Rover Pentroof Four-Valve Engine" IMechE., C448/026, 1992, p 157.

[8] Hadded, O. and Denbratt, I., "Turbulence Characteristics of Tumbling Air Motion in Four-Valve S.I. Engines and their Correlation with Combustion Parameters" SAE paper 910478, 1991.

[9] Ronnback, M., Le, W.X. and Linna, J-R.,"Study of Induction Tumble by Particle Tracking Velocimetry in a 4-Valve Engine", Trans. SAE 912376, 1991.

[10] Kiyota, Y., Akishino, K. and Ando, H., "Concept of Lean Combustion by Barrel Stratification", SAE paper 920678, 1992.

[11] Pickering, C.J.D. and Halliwell, N.A., "Particle Image Velocimetry: A New Field Measurement Technique", Inst. Phys. Conf. Ser. No. 77: Session 4, 1985.

[12] Reuss, D.L., Adrian, R.J., Landreth, C.C., French, D.T. and Fansler, T.D., "Instantaneous Planar Measurements of Velocity and Large-Scale Vorticity and Strain Rate in an Engine using Particle Image Velocimetry". SAE paper 890616, 1989.

[13] Reuss, D.L., Bardsley, M., Felton, P.G., Landreth, C.C. and Adrian, R.J., "Velocity, Vorticity, and Strain Rate Ahead of a Flame Measured in an Engine Using Particle Image Velocimetry" SAE paper 900053, 1990.

[14] Lee, J. and Farrell, P.V., "Intake Valve Flow Measurements of an IC Engine Using Particle Image Velocimetry" SAE paper 930480, 1993.

[15] Nino, E., Gajdeczko, B.F. and Felton, P.G., "Two-Colour Particle Image Velocimetry in an Engine with Combustion", SAE paper 930872, 1993.

[16] Reeves, M., Garner, C.P., Dent, J.C. and Halliwell, N.A., "In-Cylinder Particle Image Velocimetry Measurements in a Four-Stroke, Four Valve Optical IC Engine", C485/011 IMechE Conf., 'Optical Methods and Data Processing in Heat and Fluid Flow', 14-15 April 1994, City University, London.

[17] Reeves, M., Garner, C.P., Dent, J.C. and Halliwell, N.A., "Particle Image Velocimetry Measurements of Barrel Swirl in a Production Geometry Optical IC Engine", SAE Congress and Exp., Detroit, paper 940281, 1994.

[18] Haghgooie, M., Kent, J.C., and Tabaczynski, R.J., "Verification of LDA and Seed Generator Performance", Experiments in Fluids, Vol 4, p27-32, 1986.

[19] Hocker, R. and Kompenhans, J., "Application of Particle Image Velocimetry to Transonic Flows", Proc. of 5th Int. Symp. on App. of Las. Tech. to Fluid Mech., Lisbon, Portugal, 1990.

[20] Reeves, M., PhD Thesis, Loughborough University of Technology, UK, (in preparation) 1994.

[21] Lawson, N.J., Reeves, M., Coupland, J.M. and Halliwell, N.A.,"Particle Image Velocimetry: Image Labelling Using Encoding of the Point Spread Function by Application of a Polarisation Sensitive Pupil Mask", to be published in Journal of Applied Optics 1994.

[22] Coupland, J.M., Pickering, C.D. and Halliwell, N.A., "Particle Image Velocimetry: Theory of Directional Ambiguity Removal using Holographic Image Separation", Applied Optics, 1987, Vol 26 No. 9.