

Multi-Plane Airflow Measurements in the Cylinder of a Tumble Based Engine

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ABSTRACT

The tumble flow in modern spark ignition engines is assuming an evermore important role for fuel guiding, air/fuel mixing and the generation of turbulence kinetic energy to enhance the combustion process. This paper describes results obtained with laser Doppler anemometry in multiple vertical planes in the cylinder of a motored, tumble flow engine and looks at the post processed data in terms of tumble ratios and mean and turbulence kinetic energies.

The tumble results indicate very different flow fields in parallel planes lying in the main tumble direction, showing the complex nature of the flows in the cylinder. A simple method of integrating the tumble ratios from the different planes is suggested, leading to a tumble ratio more in line with those expected from an integrated method of measuring tumble, albeit these results are crank angle dependent. The tumble in a perpendicular plane shows unexpected asymmetries and values for the tumble.

The kinetic energy data shows evidence of a decaying mean kinetic energy contributing to the turbulence kinetic energy and is most obvious in plots of the percentage of total kinetic energy contained in the turbulence component of the energy. The mean kinetic energy also suggests that the asymmetries observed in the tumble in the cross tumble plane are likely to be due to the positions of the counter rotating vortices, rather than the magnitude of the velocities in these vortices.

One of the major conclusions from this piece of work is that a simple integrated tumble ratio is unlikely to yield much information on the expected engine performance given the complex nature of the in-cylinder flows.

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INTRODUCTION

The evermore stringent legislation for both noxious and greenhouse gas emissions has led to increasing optimisation of the combustion strategy in internal combustion engines. One of the important elements determining this strategy is the in-cylinder airflow which for most modern gasoline engines is of the tumble type. The tumble flow impacts on the combustion in many disparate areas of the engine cycle. Firstly and perhaps most obviously a strong tumble flow during the inlet stroke helps to promote fast and complete mixing of the fuel and air for standard homogeneous combustion strategies with either port fuel injection or early direct injection. In the early days of four valve, pent roof geometry heads this was considered the main attribute of having a tumble flow.

The second reason to consider the tumble flow arises when considering stratified charge strategies. These arose in the late 1990s where stratification of the air/fuel charge was being used for lean burn systems, with late injection, where the fuel was guided to the spark plug by a combination of wall effects from

piston crown shaping and air effects from the tumble flow. These systems have fallen out of favour to some extent due to the requirement of a lean NOx trap when running in this mode. However, the strategy is still used but now to generate a late, hot combustion process on cold start of engines to facilitate faster heating of the catalytic converter to gain a quick light off, [1]. Here some fuel is injected early in the induction stroke giving a lean homogeneous mixture with extra fuel added late in the compression stroke as a stratified mixture. Late ignition is then used combined with the insulating effect of the burn, to generate hot exhaust gases when the exhaust valve opens to aid heating of the catalytic converter. The NOx is not considered to be an issue before catalyst light off. The tumble flow in the cylinder is required to help guide the late injected fuel towards the spark plug and to aid in the persistence of the tumble late into the compression stroke a tumble flap was used in the inlet port where the bottom half of the port could be closed during this mode of operation and so forcing all the air to the top of the port. This increases the amount of tumble in the cylinder, allowing the flow to continue during the

compression stroke and the partial closing of the port causes no problems as this is a part load condition. After catalyst light off the engine reverts back to normal homogeneous operation.

The next two points are concerned with the combustion process more directly. The first concerns the improvement to combustion stability that can be gained from an enhanced tumble flow, [2, 3]. The authors found that a good tumble flow greatly reduced the cycle by cycle variation, measured by the covariance of IMEP, particularly for low loads. The second point arises from an increased combustion rate seen with the higher tumble flow and this effect is also described in [4]. For this to occur the tumble must persist long enough so that on the subsequent breakdown of the bulk flow the turbulence kinetic energy so formed will be available to aid the combustion process. This faster burn leads to a greater combustion efficiency due to be able to make more use of the expansion stroke and also to less fuel enrichment being required at high loads due to the earlier end of combustion leading to lower exhaust gas temperatures.

The final point deals with a problem encountered with tumble flow when inlet valve profiles are utilised as a method of partial load control by closing the inlet valve early but leaving the throttle wider open to reduce pumping losses, [5]. In this piece of work a strategy of early inlet valve closing combined with a low valve lift was used to control the engine load with a fully variable valve train. A back to back comparison was made at the same engine load between standard valve profiles and heavy throttling, and the modified valve profiles. The results showed a much slower 0% to 10% burn rate with the modified profile, giving a much earlier time of ignition being required to give best torque. Two reasons have been given for this slower combustion rate, [6]. The first was that the early spark timing required, and the subsequent lower in-cylinder pressures and temperatures resulted in a slower laminar flame speed and the second was that the early inlet valve closing led to an earlier decay of the tumble flow and hence dissipation of the generated turbulence kinetic energy which was then no longer available to aid the combustion process. This second argument was confirmed by laser Doppler anemometry measurements where the RMS, root mean squared, component of the velocity was significantly lower during the combustion period for the modified valve strategy. This problem was also noted in [7], where valve shrouding of the inlet valve was used to enhance the tumble flow at low valve lifts.

The above points help to highlight the importance of tumble flow in a modern spark ignited engine and this paper describes some detailed measurements, with laser Doppler anemometry, which have been performed in the cylinder of a four valve, pent roof, single cylinder engine. The subsequent post processing of the measured results helps to provide tools to enable an analysis of the flow through the induction and compression strokes. Previous studies have used steady flow rig measurements to perform this analysis and a comparison and

correlation between steady state and motored engines flows for this engine can be found in [8]. The effect on the tumble of variable valve timing in a motored engine is described in [9].

EXPERIMENTAL SETUP

The experimental setup can be split into three basic components: the optical engine, the laser Doppler anemometry system and the measurement matrix.

The Optical Engine

The Lotus optical engine has been designed specifically for the use of optical diagnostics, [10] and is shown in [Figure 1](#). The cylinder bore is 88 mm and the stroke is 82.1 mm. The compression ratio is 10:1, producing a theoretical peak adiabatic compression pressure of 25.1 bar. Optical access is provided through a full length fused silica liner and a sapphire window in the piston crown. A carbon fibre piston ring runs in the optical liner to maintain correct compression pressures. An extended bifurcated piston allows a 45° mirror to be located between the upper and lower piston crown allowing illumination or viewing into the cylinder from below. A maximum engine speed of 5000 rpm has been achieved through the use of light weight materials for the piston components and the use of primary and secondary balance shafts in the crankcase. The bifurcated piston is manufactured from aluminium while the piston crown is made from titanium, chosen due to the similarity in thermal expansivity between titanium and the sapphire of the piston window.

Engine timing data were provided by two optical encoders: One with 1.0° resolution mounted on the end of the crankshaft and one with 0.2° resolution mounted on a 2:1 drive representing the camshaft. The overhead poppet valves are actuated by means of a fully variable electro-hydraulic valve system, 'Lotus Active Valve Train', which allows complete control of the individual valve profiles. The engine specifications used for this work are given in [Table 1](#), and the valve timings and profiles are shown in [Table 2](#) and [Figure 2](#) respectively. The valve timing data is given relative to TDC valve overlap.

Table 1. Engine Specification

Bore	88.0 mm
Stroke	82.1 mm
Capacity	500 cc
Maximum Speed	5000 rpm
Compression Ratio	10:1
Peak Otto Cycle Compression	25.1 bar
Peak Compression (2000 rpm)	22.1 bar

Table 2. Valve Timing Data

IVO	675°
IVC	264°
Max. Inlet Lift	9.35 mm
EVO	462°
EVC	45°
Max. Exhaust Lift	9.35 mm

scattered light was collected in the direct backscatter direction, aiding traversing for all measurement sets. The main parameters for the system are given in Table 3.

Table 3. Laser Doppler Anemometer Parameters

Parameter	Value
Wavelength	514.5 nm
Beam separation	60 mm
Beam diameter	3 mm
Focal length	310 mm
Crossing angle	11.06°
Fringe spacing	2.66 μm
Measurement Volume:	
Length δz	702 μm
Height δy	67.69 μm
Width δx	68.0 μm
Number of fringes	25
Frequency Shift	40.0 MHz

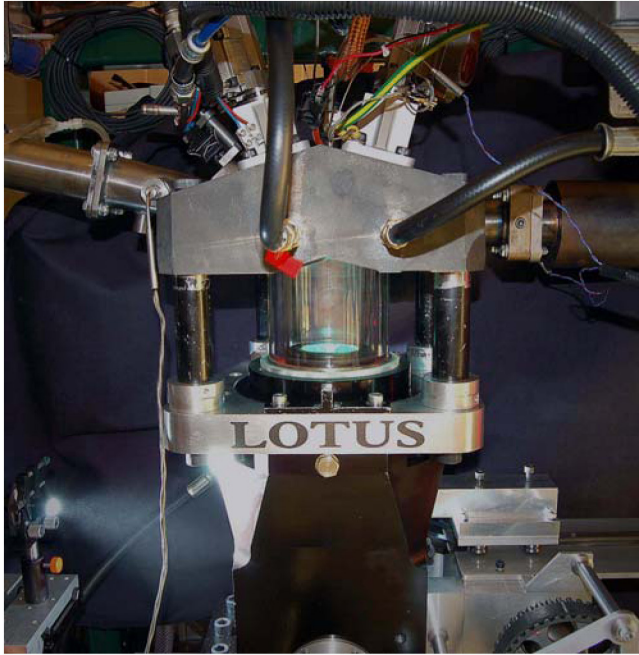


Figure 1. Single Cylinder Optical Research Engine (SCORE)

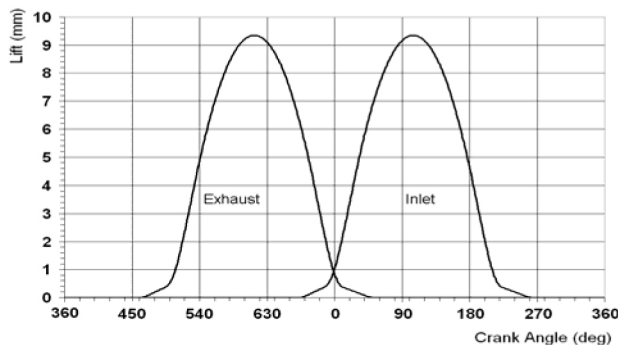


Figure 2. Valve timing profiles

The LDA System

The laser Doppler anemometry system employed in this work was a Bragg cell based fibre optics system. This optical system was implemented to ease traversing of the measurement volume in the cylinder of the engine and was operated in single component mode, utilizing an Argon ion laser as the light source, operating in single line mode at 514.5 nm. The

Measurement Matrix

All measurements were performed with the engine motored at 2000rpm and at wide open throttle conditions. These conditions were chosen as they represent conditions similar to those used in the more conventional steady state flow measurements. The engine was pre-heated to 60° C, which was a compromise between normal engine running temperatures and not allowing the fused silica liner to become too hot before measurements were started.

The motored engine measurements were made in four vertical planes, the main tumble diameter, the cross tumble diameter and two chords across the centre of the inlet and the exhaust valves, Figure 3. Seven locations were used in this vertical plane from 10mm below the flame face to 70mm below the flame face in 10mm steps. The measurements were performed as horizontal scans at each vertical location, with a step size of 5mm, beginning 4mm in from the cylinder wall. All three components of velocity were measured independently. Data were collected throughout the inlet and compression stroke, with the data collection window being adjusted with vertical location to reflect the position of the piston. The number of samples collected was also adjusted to match the size of the total window with the number of samples set to equate to 100 samples per degree. The data were then ensemble averaged into 4 degree crank-angle windows to produce mean and RMS values of velocity.