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Additional note: Please note Professor Benjamin was working at Gaydon Technology Limited at the time of publication.

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The development of the GTL 'barrel swirl' combustion system with application to four-valve spark ignition engines

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SYNOPSIS The development of the GTL 'barrel swirl' combustion system is described. The system is demonstrated to give improved combustion performance for operation with high levels of charge dilution.

1 INTRODUCTION

Over the last few years attention has focussed in the automotive industry on the design of new combustion systems providing low levels of emissions in order to comply with evermore stringent emission regulations. Industrial competitiveness, commitment to governments coupled with changing fuel quality have, at the same time, meant that improvements in fuel economy must also be attained.

One approach to these problems has been to adopt a combustion strategy which will permit operation with high levels of charge dilution (using either air or recirculated exhaust gas).

Operating with high levels of air dilution (lean burn) can give reductions in emissions of CO and NO_x whilst at the same time providing improvements in fuel economy(1). Dilution with recirculated exhaust gas (EGR) can also provide similar benefits (2). This latter strategy is normally applied to vehicles fitted with closed loop three-way catalysts which need to operate at the stoichiometric mixture strength.

Operating with high charge dilution places increasing demands on the combustion system. Burn durations are increased and the inherent cyclic variability at these conditions can cause abnormal combustion - either misfire or partial burn events.

This paper describes the development of a combustion system capable of operating with high levels of charge dilution. The combustion system is characterised by the generation and development of a novel type of flow field. The development of the concept is described and the effects on engine performance are evaluated.

2 EVALUATION OF CHAMBER CONCEPTS

Various chamber and port concepts have been proposed over the years aimed at providing systems capable of being adopted for operation with high charge dilution. In order to investigate the potential of these various designs a study was initiated on a single cylinder research engine to evaluate several of these concepts.

Figure 1 illustrates four of the numerous design concepts which were evaluated. Figure 2 (taken from reference (1)) provides a comparative plot of the part load performance of these chambers. The plots show brake specific fuel consumption (BSFC) against emissions of NO_x and (HC+NO_x) as a function of air fuel ratio for a constant speed and load condition (2000 r/min, 2 bar b.m.e.p.).

Both the four valve and compact chambers were able to operate at lean air fuel ratios and hence achieve low levels of NO_x. The high swirl and disc chambers however showed poor lean burn capability and inferior economy. For reasons of engine control it is necessary to tune a nominal number of air fuel ratios back from the leanest point so that stable operation is not compromised. In the case of the four valve chamber it can be seen that operating at 21 to 22 AFR would ensure that best economy and emissions could be achieved. This would not be the case for the disc and high swirl chambers.

These chambers were all evaluated at 12:1 compression ratio. However it must be stated that for successful operation throughout the operating range the performance at wide open throttle must also be acceptable.

It has been found to be good practice to use the highest compression ratio possible for best part load economy that will allow detonation free operation above 2000 r/min at wide open throttle (WOT). This ensures that at higher engine speeds a margin of safety is given to avoid the damaging effects of high speed detonation. Hence, for comparative purposes, the compression ratios of these various chambers should be chosen to comply with this practice for a given fuel octane quality. In figure 3 comparisons are shown for the four chambers adjusted both for min. BSFC and for BSFC at the stoichiometric air fuel ratio at compression ratios consistent with the above criteria assuming operation with 95 RON/85 MON fuel. The BSFC's at stoichiometric air fuel ratio are relevant to applications where three-way catalysts are to be employed. Figure 3 shows that the relatively good detonation characteristics of the four valve chamber ensures that its part load economy is confirmed as superior to the other chambers

The compact chamber is due to its inferior detonation characteristics at full load - it requires operation at a relatively low compression ratio due to its high octane requirement at the 12:1 compression ratio. Figure 3 shows that the differences between chambers in BSFC at the stoichiometric air fuel ratio are less than those for min. BSFC. However it has been demonstrated (2) that chambers able to operate with high levels of air dilution (lean burn) can also achieve economy improvements when EGR is applied at the stoichiometric air fuel ratio.

The good performance of the four valve chamber both at full load and part load suggests that certain inherent properties of the design are beneficial. The reduced ignition requirement as shown in figure 2 suggests that the four valve is a fast burning chamber. It has been postulated that with fast burn operation the effect of cycle to cycle variations are mitigated due to the fact that the probability of a misfire or partial burn cycle is thereby reduced. Also short burn paths should aid in reducing the probability of end gas detonation and therefore tendency to knock at WOT.

The open design of the four valve chamber with its central plug location is clearly at an advantage for providing reduced burn paths. However, geometry apart, it is believed that mixture motion within the chamber must be exerting a large influence on the burn characteristics of the chamber.

Figure 4 (taken from reference 1) shows results obtained using hot wire anemometry probes to measure the flow field at the spark plug under motoring conditions for the four valve, high swirl and disc chambers. Mean gas velocities are shown between 50° BTDC to 30° ATDC as obtained from triple wire probes. This crank angle window would normally include the main burn period.

The disc chamber exhibits a low velocity throughout the period and this is reflected in the advanced ignition requirement needed for this head (see figure 2). Both the four valve and high swirl chambers exhibit high velocities at 30° to 40° BTDC but thereafter the characteristics of the flows are quite dissimilar. The high swirl chamber maintains a high velocity throughout the burn period whereas the four valve exhibits a marked reduction in speed to a relatively low level at TDC and beyond.

It is possible that the high mean velocities associated with the high swirl chamber at or near the point of ignition are proving detrimental to flame growth at the weak mixture ratios and may account for the relatively poor lean burn potential of this chamber. The weak flow field in the disc chamber suggests that inadequate flame speeds are occurring and hence poor stability is obtained. The four valve flow field however suggests that swirl energy is clearly available in the chamber but that somehow this is dissipated at or about the time of ignition. It is therefore postulated that this 'restructuring' of the swirl field may in some way be providing the optimum flow field

stable operation at weak mixture ratios.

3 BARREL SWIRL CONCEPT

Results from the four valve chamber suggest that for stable operation with high charge

dilution the following conditions were apparently needed:

- (a) generation of a swirl motion during the induction process
- (b) breaking down the swirl energy into turbulence during the compression phase

It would appear that the turbulent energy is then used to provide enhanced flame propagation leading to reduced cyclic variability and hence stable combustion at high levels of charge dilution.

Figure 5 shows a schematic of the type of motion believed to be operating in the four valve chamber. The process is believed to occur in three distinct phases:

Phase 1

A swirling motion is generated during induction around an axis perpendicular to the cylinder centre line. The intensity of the induced swirl is governed by the design of the ports and chamber but principally it is generated by permitting the incoming gas to detach from the port floor and thence flow over the top of the valve. This type of swirl motion is referred to as 'barrel' swirl.

Phase 2

During compression the barrel swirl vortex is subject to enhancement (spin-up) through conservation of angular momentum. This will be offset to a degree by degradation of the vortex due to shearing effects.

Phase 3

As the piston nears the top of its stroke the barrel swirl vortex begins to distort as it is forced into a shape incompatible with its structure. At this point the shear is very high and the whole structure breaks down.

The flow concept described above has been investigated using a variety of techniques. Steady state flow rigs have been designed to quantify the flow and barrel swirl from cylinder heads. Dynamic studies have been performed using flow visualisation and hot wire anemometry techniques to obtain both qualitative and quantitative information regarding the flow behaviour in motored engines. This work is also supported by the development of complex computer modelling techniques which will enable the whole flow field to be predicted from induction up to the point of ignition. Finally correlation with combustion and overall engine performance has been made on firing engines.

The following sections describe these aspects and in particular the application of

the concept to a four valve engine.

3.1 Steady state flow studies

To evaluate the flow and swirl characteristics of four valve heads a steady state flow rig has been designed with the capability of measuring the barrel swirl component.

Air is blown through the inlet ports at a fixed pressure drop for incremental valve lift openings. Air flow is measured with a viscous flow meter and the barrel swirl is measured using a suitably adapted torque meter mounted downstream of the cylinder head. Knowing the cam profile and engine geometry the air flow and swirl are then integrated over the whole cam period to provide a measure of the total flow restriction (mach index) and barrel swirl ratio for the head. The mach index provides a measure of inlet velocity at 6000 rev/min and hence flow restrictiveness.

Figure 6 shows an example of the flow and swirl characteristics of a four valve and a two valve head of the same bore and stroke. The non-dimensional (N-D) swirl provides a measure of the induced vortex. It is proportional to $G/\dot{m} B V_o$ where:

G = Angular momentum flux (in appropriate plane)

\dot{m} = Air mass flow rate through the port

B = Cylinder bore

V_o = Velocity head across the port

It can be seen that for the four valve at lifts above 7mm the flow past the valves has become 'directional' and is registering a significant barrel swirl component as shown by the increase in the value of ND swirl. This coincides with a levelling off of the flow due to the effectively reduced 'forward' flow area available at the valve. Also shown on the figure is a plot of flow and swirl corresponding to the more conventional 'axial' swirl type of chamber. Here 'axial' swirl refers to swirl around a vertical axis parallel to the cylinder centre line. It can be seen that the characteristics of the swirls as shown by the ND swirl curves are quite different between the two valve and four valve heads.

Also of note is the fact that a barrel swirling four valve can produce the same level of swirl (but in a different plane) as the more traditional axial swirl two valve chamber but with more flow and hence more power. The swirl ratios of the two heads are given on figure 6.

Figure 7 shows a correlation between steady state barrel swirl and ignition advance over many engines (for a typical part load condition); the ignition advance provides an indication of the burn speed. The scatter is large but a trend of reduced ignition advance with increasing the barrel swirl is discernable. This is more evident when studying the effect of increasing barrel swirl on particular engines. The lines drawn on figure 7 demonstrate this by grouping common engines differing only in respect of their port design and hence swirl level. The overall scatter is due to the variation in engine geometry, chamber shape and port profiles over the many

engines investigated and also the influence of dynamic affects which are very important. This is especially true with port induced swirl concepts where flow separation can be heavily influenced by transient phenomena. To understand this aspect studies have been performed to assess the in-cylinder flow field under engine motoring conditions.

3.2 Hot wire anemometry studies

To quantify the dynamic flow field hot wire anemometry techniques have been used. For the four valve application wires are placed at the spark plug electrode gap and orientated in various directions so that more than one component of the flow can be measured.

Figure 8 shows hot wire anemometry traces obtained from a number of four valve engines. Ensemble averaged measurements are shown over a 100 cycles with the wires orientated in the 'barrel' position to measure the major barrel swirl component as illustrated in figure 5. Velocities are shown for the induction and compression part of the cycle.

The velocities recorded during induction are critically dependent on the proximity of the probe to the inlet flow past the valve because around this region large velocity gradients are observed.

During the part of the cycle when the valves are closed the recorded velocities should be less sensitive to probe positional variations and reflect (albeit at only one point) the 'true' variation of the swirl field during the cycle.

Figure 8 clearly shows that during the compression phase velocities generally increase reaching a maximum value before TDC. It is believed that this corresponds to the point of maximum swirl intensity as the induced swirl 'spins-up' due to conservation of angular momentum.

The general reduction in velocities observed as the piston approaches TDC are believed to be indicative of the degeneration of the swirl vortex as it is compressed into the high aspect ratio chamber.

The phasing and magnitude of the peak velocities observed during compression and the rate at which the swirl field is degenerated as TDC is approached have been found to be dependent on both the intensity of the induced swirl level and the geometry of the pentroof combustion chamber. For an optimised system both swirl level and chamber shape need to be 'tuned' if best results are to be achieved.

Whilst lending support to the barrel swirl concept hot wire data by its nature can only provide information at a few points within the combustion chamber. A technique under development is the production of computer simulation models capable of predicting the total flow and turbulence fields within the chamber. Whilst still under development recent work has demonstrated the considerable potential for such models and it is instructive to examine the conclusion from a simple yet

performed and is described in reference (3).

3.3 Computer simulation

The computation was performed for a simple engine geometry featuring a flat head and piston with a centrally located 180° shrouded valve. Figure 9 (taken from reference 3) shows the computational grid used for the simulation. Only half the grid is shown as the chamber is symmetrical.

The simulation bears a resemblance to the type of induced flow field that might be expected from a four valve barrel swirl head; the shrouded valve only permitting flow out of one side.

Figure 9 also shows the predicted flow fields at $\theta = 144^\circ$ induction and at $\theta = 270^\circ$ compression. The velocity fields are shown in a plane taken approximately through the centre of the valve. During induction a large vortex is generated similar in nature to that shown schematically in figure 5. This vortex is seen to be maintained during the compression stroke. The magnitude of the compressed vortex is governed by the 'spin-up' effect and also the rate at which it loses energy due to the higher shearing stresses generated as the piston approaches top dead centre.

The simulation also demonstrated that turbulent kinetic energy production during the compression part of the cycle was dominated by stress production resulting from the high shear field associated with the compressing barrel swirl vortex. Total turbulent energy production exceeds the dissipation rate until about $\theta = 330^\circ$. At that point the vortex breaks down and the turbulent kinetic energy is thereafter dissipated.

This simulation, although an idealised representation of a four valve chamber, does show that the flow field characteristics deduced from the steady state flow studies and the hot wire anemometry work are qualitatively paralleled. Computer software developments should in the near future permit simulations of more representative four valve chambers and help to confirm and/or refine the understanding of this particular type of flow field.

4 APPLICATION

The previous sections have described the evolution of the barrel swirl concept as a means of improving the performance of combustion chambers designed to operate with high levels of charge dilution.

This section gives an example of the application of this concept to a four valve chamber.

The objective of the study was to improve the combustion performance of the engine when operating with higher levels of charge dilution. Steady state flow analysis of the standard design showed that the head had a relatively low swirl level. A new head was designed and manufactured featuring both revised ports and chamber with the intention of generating higher swirl levels during induction

vortex during the latter part of the compression stroke.

Figure 10 shows the hot wire anemometry velocity data obtained from the heads with the probe orientated in the 'barrel' position at the electrode gap position. The higher swirl levels of the modified active head manifest themselves in higher in-cylinder peak velocities during the compression stroke. As TDC is approached the swirl is degenerated.

Figure 11 shows the burn durations as a function of ignition timing at stoichiometric air fuel ratio. It is clear that the more active swirl chamber is producing reduced burn durations.

Figure 12 shows the BSFC and coefficient of variation of IMEP observed for both heads. The active chamber is more stable at the higher air dilutions (leaner air fuel ratios) than the standard head and an improvement in BSFC is also observed.

Figure 13 illustrates the effects of EGR applied at a stoichiometric AFR. The standard head would not readily accept any EGR without becoming quite unstable whereas the modified head shows that even with 10% EGR combustion is quite stable. This manifests itself in an improved economy and lower NOx levels and confirms the potential benefits of this type of chamber concept for operation with high charge dilution either with air or recirculated exhaust gas.

5 CONCLUSIONS

Operating spark ignition engines with high levels of charge dilution offers benefits in terms of improved economy and reduced emissions.

It has been demonstrated that the barrel swirl concept applied to four valve engines can be exploited to achieve stable combustion at high levels of charge dilution with improvements in engine performance.

ACKNOWLEDGEMENTS

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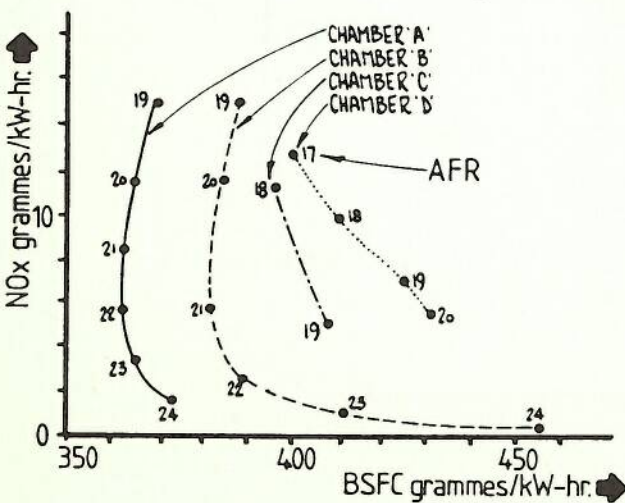
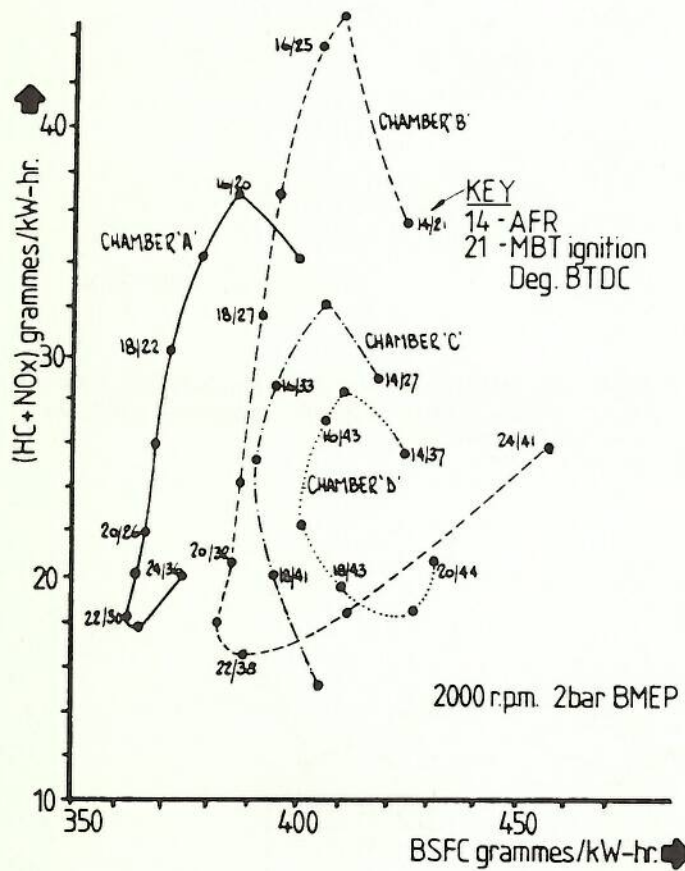


Fig 2 Relationship between emissions and b.s.f.c. as a function of air-fuel ratio on four chambers

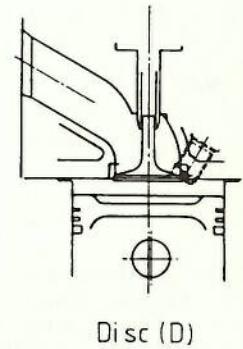
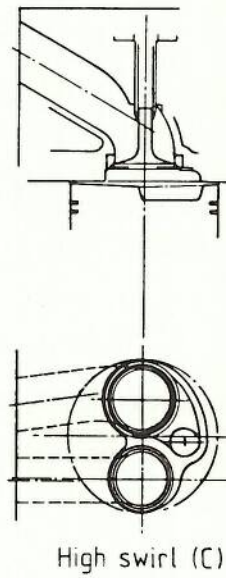
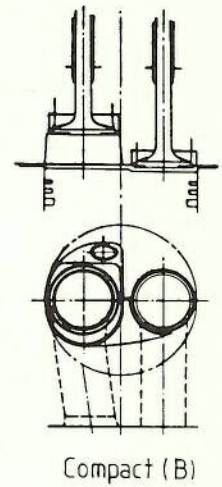
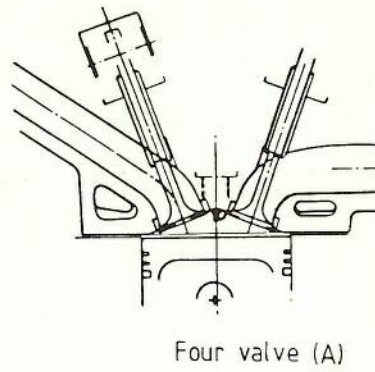


Fig 1 Combustion chamber designs

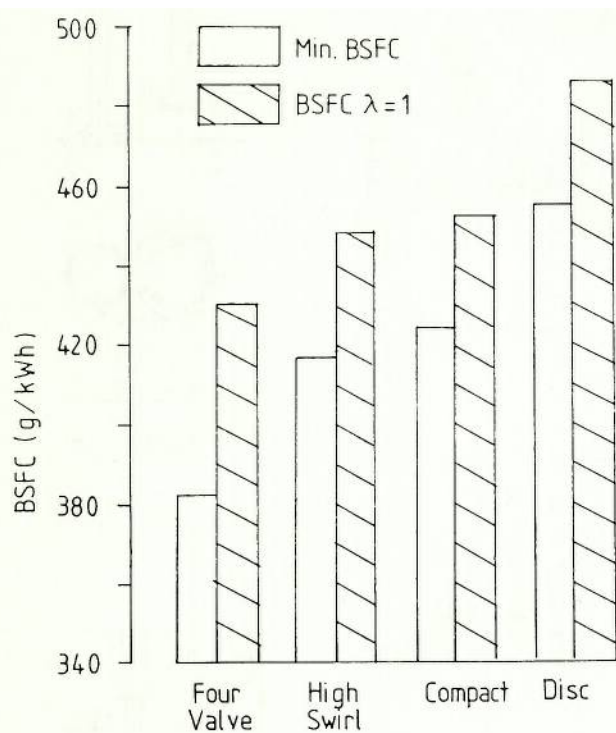


Fig 3 Comparisons of b.s.f.c. (2000 r/min, 2 bar b.m.e.p.) on four chambers at compression ratios consistent with detonation free operation above 2000 r/min on 95 RON/85 MON fuel

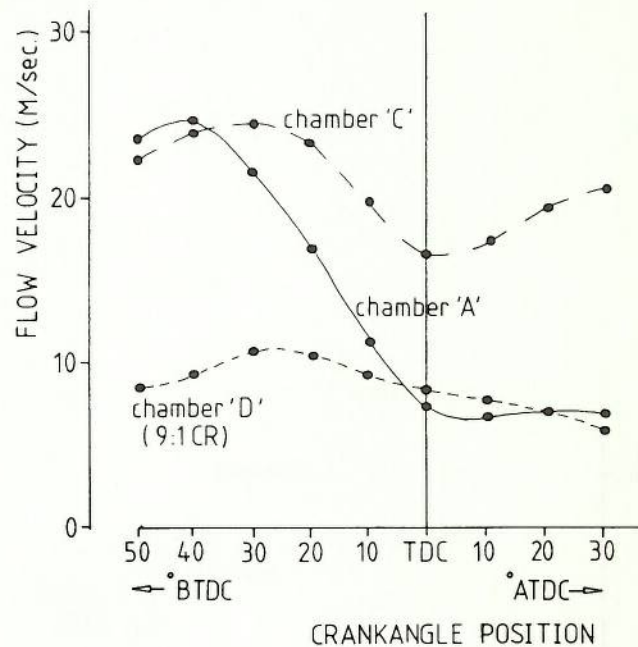


Fig 4 The mean flow field at the spark plug under motoring conditions on three chambers. Operating condition is 2000 r/min, 2 bar b.m.e.p.

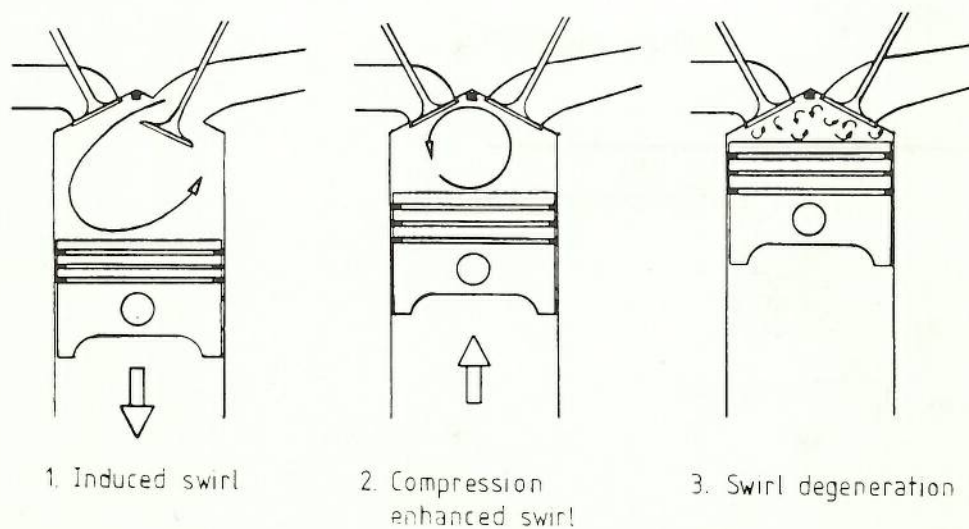


Fig 5 Schematic of 'barrel' swirl behaviour in a four-valve chamber

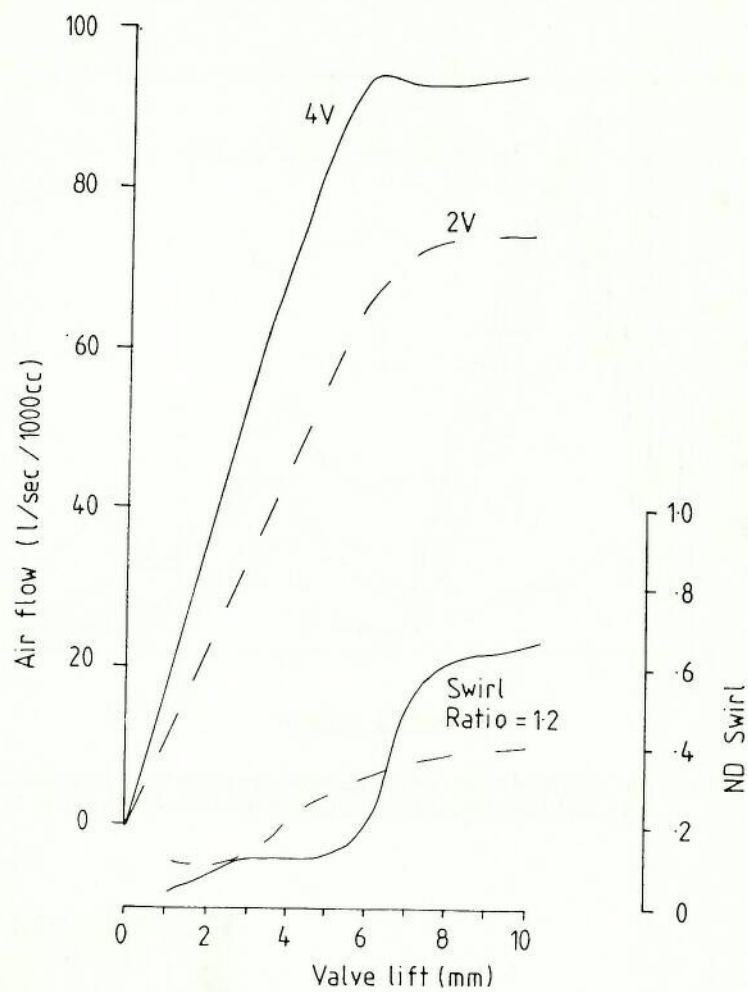


Fig 6 Flow and swirl characteristics of a four-valve and two-valve head

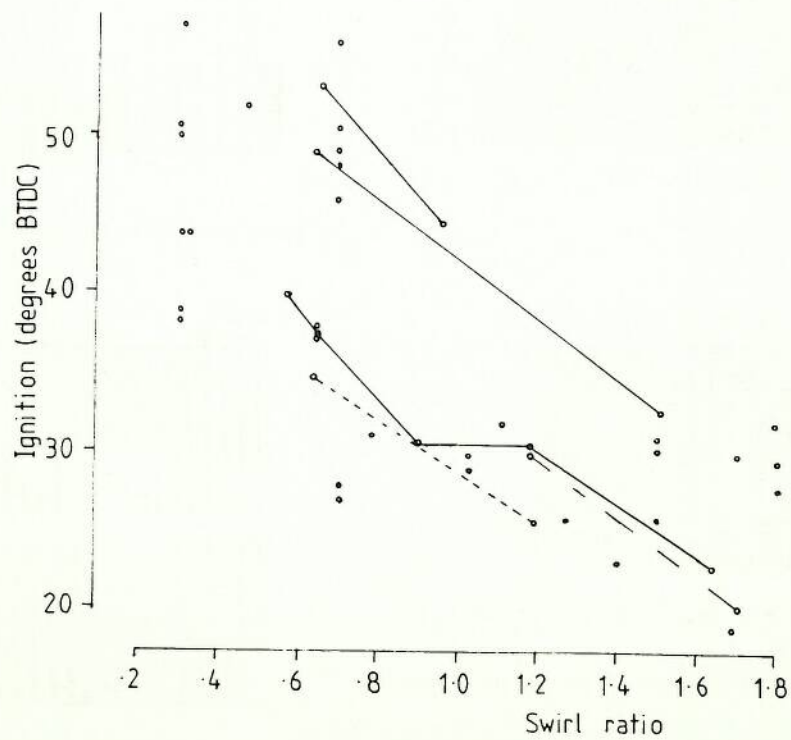


Fig 7 Relationship between steady state barrel swirl ratio and MBT ignition advance (2000 r/min, 2 bar b.m.e.p. 18:1 air-fuel ratio)

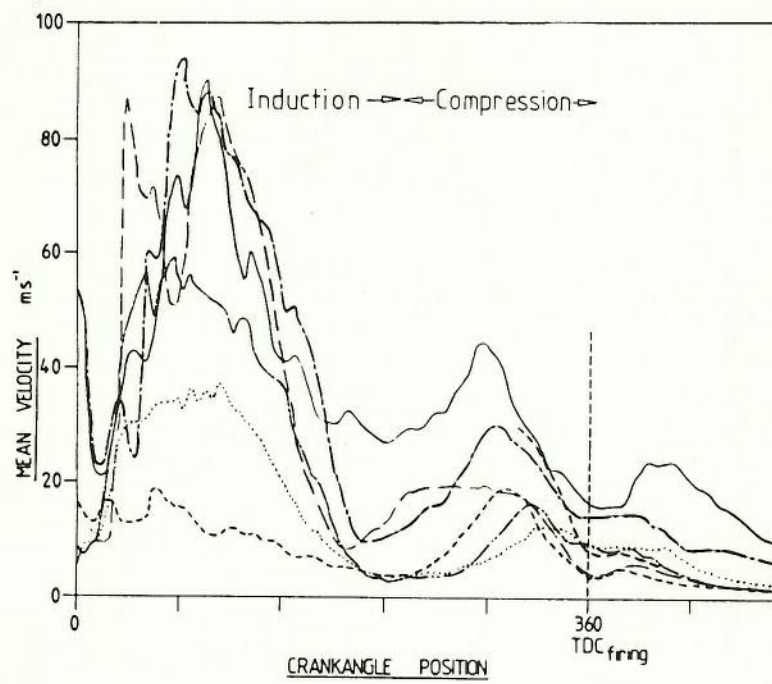


Fig 8 Hot wire anemometry measurements obtained from a number of four-valve chambers under motoring conditions (2000 r/min)

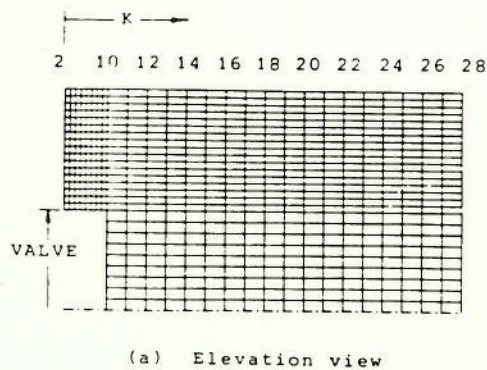
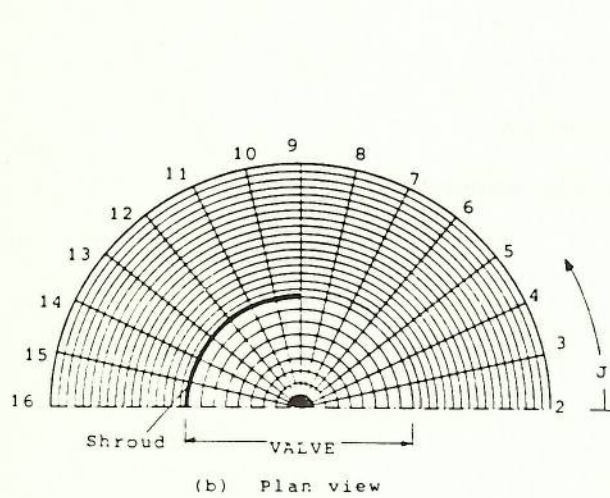
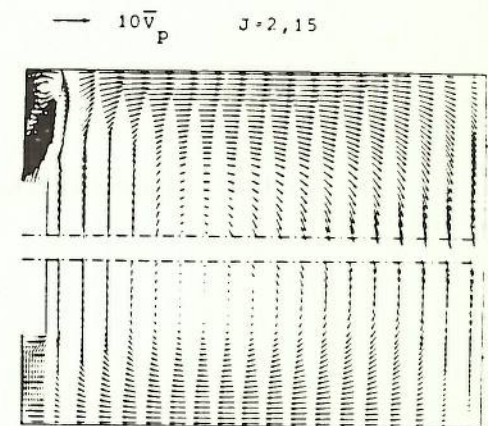
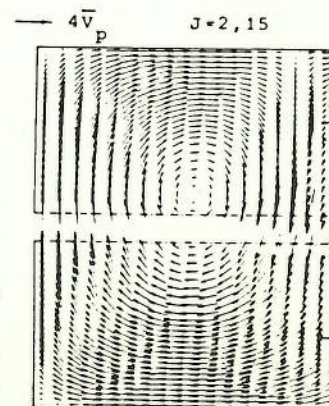


Illustration of computational grid and indexing system.



Flow predictions for $\theta=144^\circ$ induction.



Flow field predictions at $\theta=270^\circ$ compression

Fig 9 Computer simulation of the in-cylinder flow field obtained from reference (3)

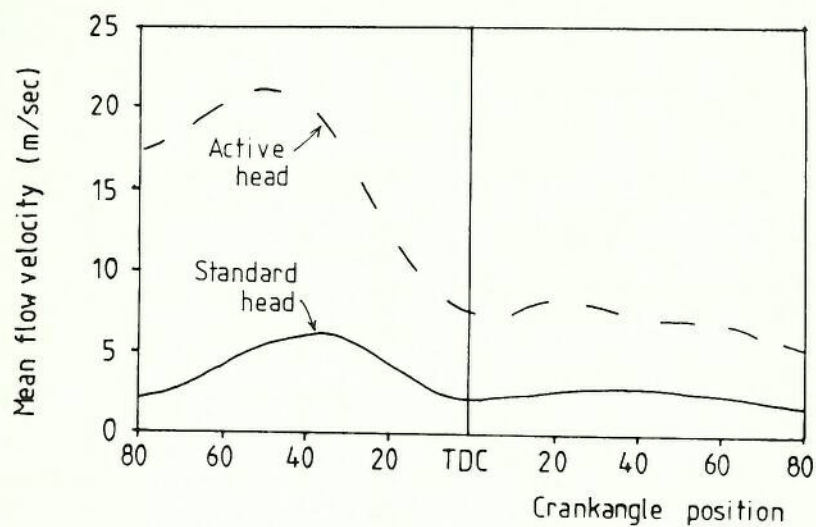


Fig 10 Hot wire anemometry measurements for the standard and active four-valve heads

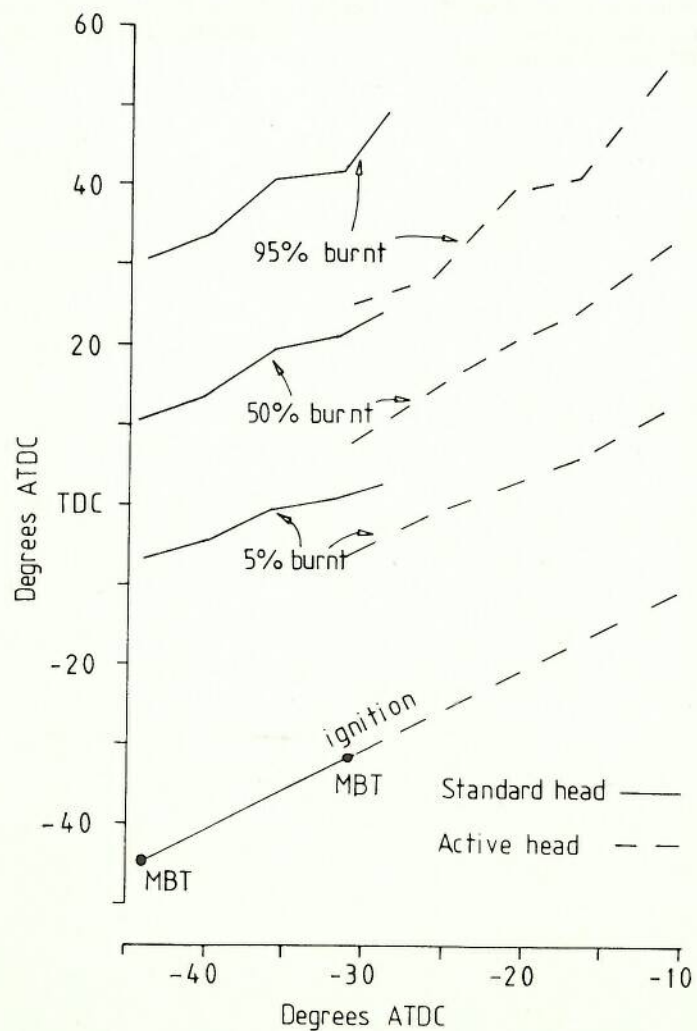


Fig 11 Burn durations for the standard and active heads as a function of ignition advance at stoichiometric air-fuel ratio (2000 r/min, 2 bar b.m.e.p.)

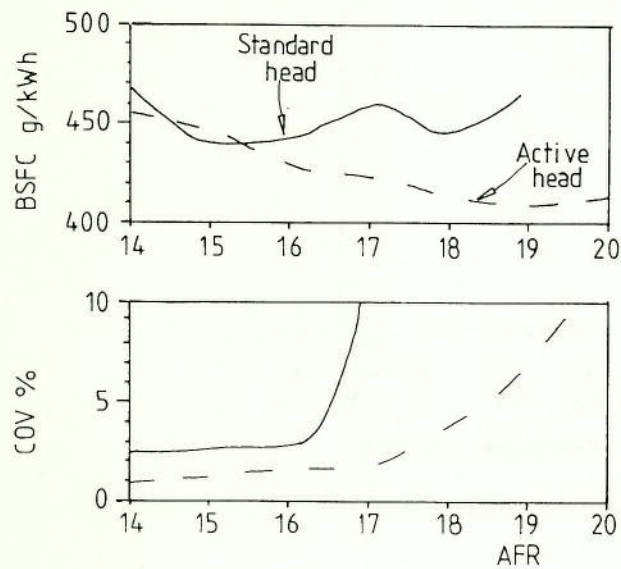


Fig 12 Variation of b.s.f.c. and coefficient of the variation of i.m.e.p. as a function of air-fuel ratio for the standard and active heads (2000 r/min, 2 bar b.m.e.p.)

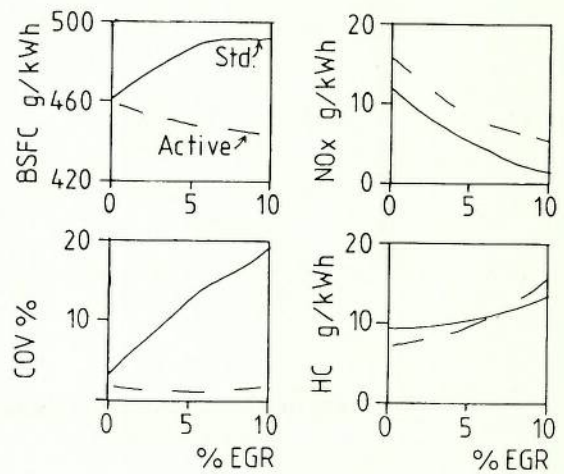


Fig 13 Effect of EGR at stoichiometric air-fuel ratio on the standard and active heads