# Quantitative Analysis of Combustion in High-speed Direct Injection Diesel Engines

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## ABSTRACT

This paper reports the results of work performed on a Ricardo Hydra direct-injection diesel engine. High speed photographs, at framing rates of 10,000 frames/s, were taken on the engine through a piston with a quartz piston bowl, at an engine speed of 1000 rev/min. After the initiation of combustion, the process was self-illuminating and information on the combustion process was obtained by analysing the radiation emitted by the carbon particles. The two-colour method has been used to evaluate the temperature of the combustion gases, and a cross-correlation technique to obtain velocity information, over the full field of view This paper concentrates on techniques for obtaining quantitative data from photographs of the combustion process.

This paper will emphasise the effect of swirl ratio on combustion. It will be shown that too much swirl increases the ignition delay period, and results in an increase in the amount of fuel burned in the pre-mixed mode. This results in an increase in the $NO_X$ emissions, but decrease in the soot. It will also be shown that an increase in the swirl setting results in larger tangential velocities in the combustion chamber - as might be expected.

## INTRODUCTION

The high speed direct injection diesel engine offers the highest overall efficiency of all reciprocating engines in its size range. It also presents challenges to achieve this efficiency within the emissions regulations, in particular smoke, particulates and $NO_X$. The key to understanding the interaction between efficiency and emissions lies in better knowledge of the combustion processes. This paper presents a study of the processes inside the cylinder during the important combustion periods. The techniques have been based on high speed photography through a transparent piston bowl. Before ignition commenced the combustion chamber was illuminated by a Copper-vapour laser, but after combustion the processes were self-illuminating. The visible light from the radiating carbon particles in the combustion chamber was used to evaluate the "flame temperature" by spectroscopic means, and also the flows inside the chamber by cross-correlation methods. Both of these techniques have the shortcoming of giving an "average" value through the depth of the chamber, but nevertheless they provide, in a relatively easy manner, information that has not been previously available.

## EQUIPMENT

The equipment has been described in detail in a number of previous papers[1,2], and a comprehensive report is in publication. A summary of the main elements will be presented here.

### Hydra Single Cylinder Research Engine

The Hydra single cylinder research engine is one which was developed specifically for this project. The geometry of the engine combustion chamber is based on an early version of the Ford York direct injection diesel engine, but the conventional fuel injection system has been replaced by a Lucas high pressure electronic unit injector CAV EUI50, capable of achieving a maximum injection pressure of 120 MPa. The engine can be run in two forms: as a conventional engine, or with a photographic adaptation that allows the combustion chamber to be viewed through the base of the piston bowl. The specification of the engine is summarised in table 1. The engine and piston arrangements, together with tests to obtain macroscopic results, have been described in detail in refs 1, 2, 3. A view of the combustion chamber is given in fig 1. The first feature to note is that the combustion bowl is not on the centre-line of the cylinder, and the fuel injector is on neither centre-line. Hence, the combustion chamber is extremely asymmetrical, and this has a significant effect on the resulting flow inside the engine. It will be seen that the photographs from the Hydra exhibit little symmetry in any aspect of the combustion: each fuel jet is different; the initiation sites of combustion vary between jets, and the flow structure is complex.

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Ricardo Hydra single-cylinder engine
Bowditch system: photography through piston bowl

| | |
|---|---|
| Bore: | 93.67 mm |
| Piston bowl diameter | 46.4 mm |
| Stroke: | 90.54 mm |
| Compression ratio: | 16.75 |
| Rated speed (normal) | 4000 rev/min |
| (photographic) | 3600 rev/min |

Variable swirl mechanism

Table 1: Engine specification

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The engine has been operated in the photographic mode at engine speeds of up to 3000 rev/min, which is the fastest reported for an engine with photography through the piston. These tests have focused on the fuel injection and combustion phases of the engine processes at a single engine speed of 1000 rev/min. The combustion has been photographed using a high-speed camera capable of recording images over number of consecutive combustion cycles. This latter requirement is an essential one to ensure that the combustion cycles are repeatable, and representative of "steady" conditions.

### Two-Colour Measurement of Temperature

The measurement of temperature and "soot" by the two-colour method was originally proposed by Hottel and Broughton [4], who used it to estimate the temperatures of furnaces. The first application of the approach to engines was by Uyehara *et al* [5], and this was followed by Matsuoka and Kamimoto [6]. The objective in this project was to obtain a measurement of the temperature of the combustion products over the whole field of view through the base of the piston. The easiest way to achieve this would be by analysis of combustion films, but the difficulty is ensuring the colour balance of the film, both during exposure (when the window will be getting dirty) and during processing (when development might change the colours). Both of these potential problems can be overcome by performing a "live" measurement of the temperature at one point in the cylinder, while taking high speed combustion photographs over the whole field of view. The photographs can then be analysed later, and calibrated using the data from the single point. The calibration system is itself calibrated using a tungsten ribbon lamp.

### Cross-Correlation Technique for the Evaluation of Gas Velocities after Combustion

The cross-correlation technique adopted in this project was reported by Shioji *et al* [7]. The basis of the technique is to identify features of the combustion photographs in one frame and to locate those features in the next frame. The distance moved by the features between the frames is directly related to the velocity of the gas in that region of the combustion chamber: the velocity can be evaluated by dividing the distance moved by the time between consecutive frames of the film. Features of the combustion photographs can be identified by "capturing" the image in a computer by means of a CCD camera, in a similar manner to that described above.

## RESULTS

High speed photographs of combustion in the Hydra engine were taken at three conditions of inlet swirl ratio (SR = 2.80, 3.16, 4.00). A camera speed of around 10,000 frames/s is quite adequate for an engine speed of 1000 rev/min, and gives a resolution of about ¾° crankangle between frames. The range of inlet swirl ratio covers the extremes of the swirl mechanism.

## Temperature and Carbon Measurements

Figures 2a and b show two-dimensional temperature distributions measured using the two-colour method at swirl ratios of 3.16 and 4.00 respectively. They were obtained at an engine speed of 1000 rev/min, and a load of approximately 4 bar bmep, with all operating conditions beside the swirl ratio maintained, as far as possible, constant. The temperature range was divided into 12 bands, with a minimum temperature of 1600 K and a maximum of 2300 K. This covers the temperature range of interest in diesel engine combustion.

The photographs are two-dimensional images through the *depth* of the piston bowl, and the temperature will be a line "average" through the combustion zone. This means that any stratification through the depth of the bowl will not be resolved on the film, and the maximum temperatures will be underestimated. The injection timing was maintained at 9° btdc, and there was a period of ignition delay before either a luminous zone became apparent, or the p-$\alpha$ diagram showed heat release was occurring. The fuel jets do not start to burn simultaneously, and ignition occurs preferentially in two of the jets. The ignition starts on the downwind side of the jet centre-line and is enhanced by the deflection of the fuel jet off the combustion bowl wall. The points of combustion initiation at all three swirl ratios are shown in fig 3. After combustion has started the charge is consumed by the process. There is significant temperature stratification in the combustion chamber and the zone near the inlet valve appears to remain coolest throughout combustion. As the combustion period develops the burning zone spreads throughout the chamber, and high temperatures are reached in some regions: it is here that the $NO_x$ is formed. Comparison of figs 2a and b, which differ only in the swirl ratio, shows that the premixed combustion period is more significant and the diffusion combustion is more rapid at the higher swirl ratio.

Figures 4a and b were obtained from the same combustion photographs as figs 2a and b, but in this case they have been processed to show the variation of KL throughout the combustion bowl. KL is a parameter that indicates the amount of "carbon" in the combustion chamber, and hence high values of KL will indicate where the largest concentration of soot is occurring. It can easily be seen from fig 4a (SR=3.16) that the initial combustion along the fuel jets (at about 3° atdc) results in the formation of more soot than at the higher swirl ratio. This situation persists throughout the combustion process with higher KL values occurring at the lower swirl ratio, and would lead to the conclusion that the carbon emissions from this engine will be higher at low swirl. This is borne out by the results of Gomes and Yates [8], where it is shown that the Bosch smoke number reduces from 2 to 1.5 as the swirl ratio is increased from 3.16 to 4.

## Gas Velocities in the Combustion Chamber

Figures 2a, 2b, 4a,and 4b are computer processed images of the original combustion photographs, and indicate the way in which basic photographic information can be taken into the computer. The cross-correlation method for evaluating the gas velocities after combustion is based on image processing of pictures of this form, except that, in this case, the information is stored as a series of 512 by 512 pixel files of monochrome images with 256 grey levels (see Winterbone *et al* [9]). Since that paper[9], the technique has been refined, as described by Sun[10], to reduce the unprocessed border to 2.5mm (from the original 6mm); this improvement in the method is quite apparent when comparing the velocity diagrams shown in this paper with those in ref 9.

Figures 5a and b show samples of the velocities evaluated at 110 points in the combustion bowl at swirl ratios of 2.8 and 4.0 at about 12° atdc. For both cases velocities have been calculated over the period from a few degrees after tdc, when sufficient of the combustion chamber is enflamed to enable an image to be defined, to 25 degrees down the expansion stroke (these diagrams are an abstract). The following features are readily apparent:

i the velocities at SR = 4.0 are larger than at SR = 2.8;

ii the velocities are essentially those of a forced vortex, as would be expected from a swirl flow;

iii the swirl flow is maintained over the whole period examined;

iv the velocities decrease as the piston moves down from tdc;

v the maximum magnitude of the velocities is around 10 to 18 m/s (between 3 and $6V_p$).

The basic view of the flow being a forced vortex is in good agreement with the LDA measurements of Arcoumanis *et al* [11]. The general characteristics of the flow in the inner 20mm radius are both basically forced vortices. The level of the mean tangential velocity at 6° atdc is about $2.3V_p$ at high swirl, and $1.3V_p$ at low swirl. These values should be compared with about $3.5V_p$ and $3V_p$ at high and low swirl respectively at 40° btdc, as obtained by Arcoumanis. While there are obvious differences in the values, they are sufficiently close to give confidence in their veracity. These results are also in good qualitative agreement with the measurements by Arcoumanis *et al* [12] in the bowl of a low compression ratio model "diesel" engine, when the swirl velocity achieved a maximum value of between 4 and $5V_p$ in the combustion chamber bowl (which should be compared with the maximum swirl velocity of around $4.6V_p$ at the high swirl setting). An additional feature noted in ref 11 is that the vortex motion restricts the penetration of squish into the bowl and this distorts the flow patterns, which could explain the complex fluid motion found in figs 5a and b.

Figures 5a and b can be further processed to obtain additional macroscopic information. For example, fig 6 shows the variation of average tangential, radial and mean velocities at the high swirl respectively. Dissipation is high at this setting and by 25° atdc the velocities are almost the same as in the low swirl case (not shown). Since both cases have experienced the same variation in geometric factors it is likely that the reduction is due to the higher frictional dissipation suffered in the high swirl case.

## OVERALL CONCLUSIONS

The two techniques applied in this study of high-speed direct injection diesel engines have enabled quantitative data to be obtained during the important combustion period. The results give information on the distribution of temperature and velocity in the combustion chamber during the burning process, and this information correlates well with the gross parameter measurements.

The effects of asymmetry in the combustion chamber are clearly visible, and it can be stated that an engine with a symmetrical chamber would have a significantly better emissions performance than this engine. Such an engine would have better utilisation of the air available by sharing it more equitably between all the fuel jets, giving a more even distribution of temperature in the chamber which should reduce both $NO_x$ and particulates.

It has also been shown that it is important to match the level of swirl to the injection system, and it is possible to provide both too much and too little swirl. This parameter also interacts with the extremely important wall impingement effects which, while they improve fuel-air mixing, appear to play a major role in the production of soot. The trend towards even higher injection pressures may reduce the need to have high swirl and wall impingement, and this should improve the combined $NO_x$ and particulates levels.

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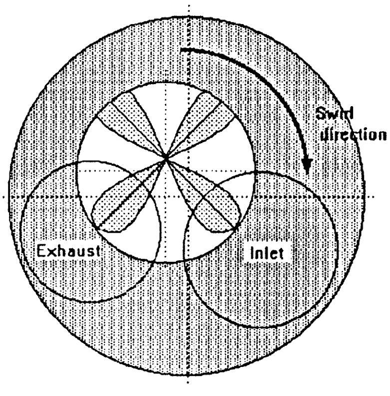


Figure 1. : Layout of bowl in piston, showing viewing window,and asymmetrical arrangement of combustion chamber

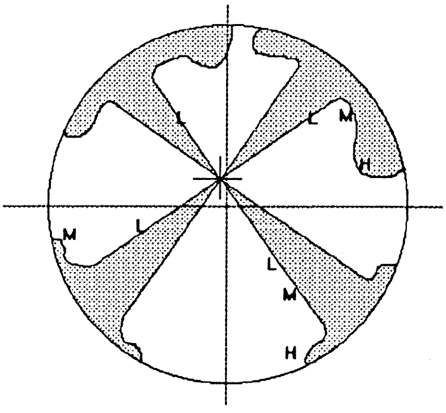


Figure 3: Points of initiation of combustion
L = low swirl ratio; M = medium swirl ratio;
H = high swirl ratio

Fig 5a: Velocities in combustion chamber at 11.5° atdc with swirl ratio of 4.0

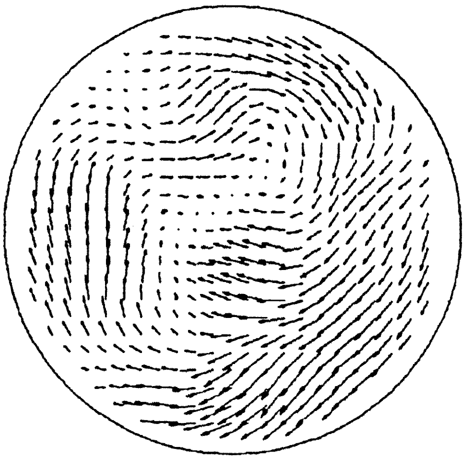


Fig 5b: Velocities in combustion chamber at 11.5° atdc with swirl ratio of 2.8

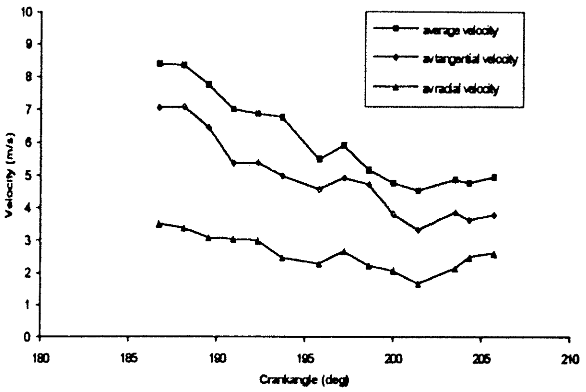
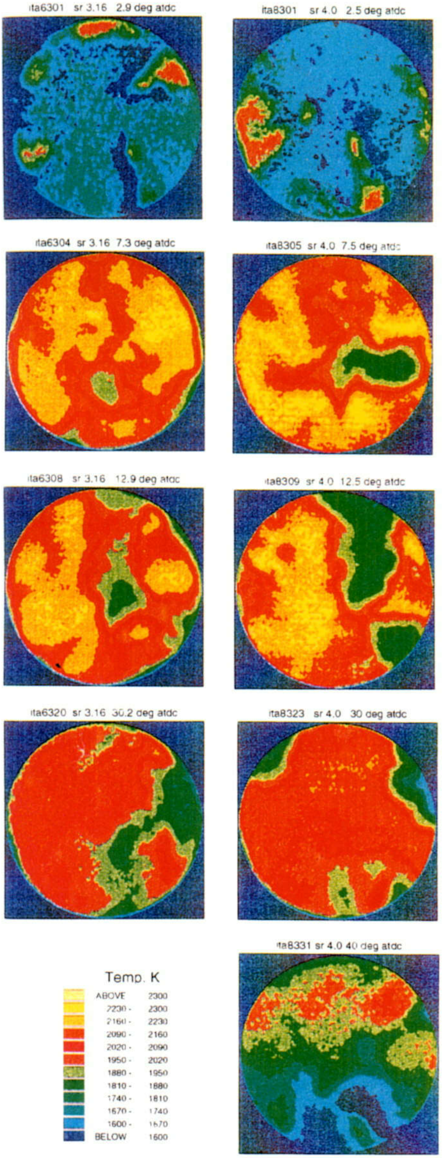
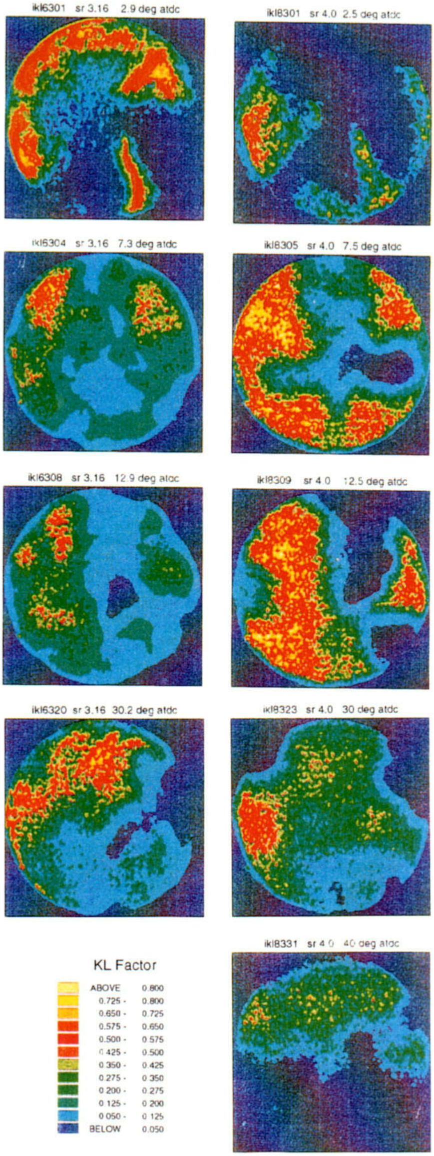


Fig 6: Variation of average tangential, radial and mean velocities at a swirl ratio of 4.0



**(a) swirl ratio of 3.16** **(b) swirl ratio of 4.00**

**Figure 2 Temperature distribution in combustion chamber**



**(a) swirl ratio of 3.16** **(b) swirl ratio of 4.00**

**Figure 4 Distribution of carbon in combustion chamber**