Influence of Flow Parameters and Spark Characteristics on the Early Flame Development in a SI-Engine

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ABSTRACT

To find out to what extent the cyclic variability of mean velocity, turbulence and spark characteristics can explain the variations in the early flame development, simultaneous measurements of flow velocity close to the spark plug with LDV and flame imaging with two orthogonal Schlieren systems were performed together with spark voltage and current registration.

The results show a significant correlation between the flow field and the rate of early combustion, with faster flame propagation for higher levels of both mean velocity and turbulence. For the very early flame propagation the mean velocity seems to be of major importance, but as the flame expands, turbulence turns more important.

The breakdown voltage, which gives an indication on the breakdown energy, shows no significant correlation to any combustion parameter. The supplied charge to the spark plug during the interval 10 µs to 1 ms shows significant correlation to the early flame development. The correlation between the spark discharge and heatrelease tends to reach higher levels with large spark plug gaps.

INTRODUCTION

Lean air-fuel ratios or large amounts of Exhaust Gas Recycled (EGR) has the potential of lowering the emissions of Nitric Oxides (NO_X) from a spark ignition engine. There is, however, a limit for the use of diluted mixtures. Close to the limit, the combustion event experience a large cycle to cycle variation and this variation in combination with slower flame propagation gives cycles where the combustion is not completed before the exhaust valve opens. This will result in high levels of unburned hydrocarbons [1].

Several different causes to cyclic variations in the combustion event can be found but the major ones seems to be fluctuations in local parameters close to the spark plug where the early, easily disturbed, flame propagation takes place. These causes are:

1. Variation of fuel, air and residual gas concentrations in the vicinity of the spark plug
2. Variation of flow field.
3. Variation of spark discharge.

The local concentration of fuel or residual gas close to the spark plug can successfully be measured with Laser Induced Fluorescence (LIF). High correlation between local concentration of fuel and rate of heatrelease in the early phase of the combustion have been found [2]. Significant correlations between the flow field and combustion have also been found [3]. As the flame propagation in a SI-engine is very turbulent in the main part of the combustion, a variation in the turbulence intensity from cycle to cycle can give rise to very large variation in burn-rate. The variation in turbulence intensity can also influence the early combustion where the flame kernel expands lamminarlike to a fully developed turbulent flame. The cyclic variation of the mean velocity can also influence the early combustion. The mean velocity of the flow moves the small flame kernel and different contact areas to the cool wall are possible [4].

The spark discharge can influence early combustion if the supplied energy to the small flame kernel changes significantly from cycle to cycle. There is also a possible effect in change of time at which the discharge supplies energy to the cylinder air/fuel-mixture. The efficiency of the energy transfer from spark to the gas have been reported to change between 95% and 5% depending on the discharge phase, with better efficiency for the short breakdown phase [5].

Previous attempts to correlate the flow field and early combustion have all been based on heat release analysis from pressure measurements to obtain information about the combustion rate [3][6][7]. Unfortunately the lowest levels of detectable heat release with sufficient accuracy from this method, corresponds to a flame size of approximately 50 mm in diameter in our research engine. This size is to large for detection of effects occurring in the very early part of the combustion (0-10 mm flame size). To detect the very early part of combustion, flame imaging was chosen as a complement to pressure analysis.

The main objectives for our experiments were to investigate if;

1. Variations in breakdown voltage, and consequently supplied breakdown energy, influences early combustion.
2. Variations in the later part of the spark discharge influence the early combustion.
3. The relations between fluid flow and early combustion obtained by previous experiments can be extended to be valid even when flame imaging is used, and thus smaller flames are detectable.

THE ENGINE

The measurements were performed in a single cylinder engine based on a six-cylinder Volvo TD 102 diesel. Its main geometric properties are shown in table 1. Optical access was provided by four windows in a spacer between the cylinder head and engine block.

Table 1: Geometric properties of the engine.

Displaced volume	1600 cm^3
Bore	120.65 mm
Stroke	140 mm
Connecting rod	260 mm
Swirl ratio	2.8:1
Compression ratio	10:1

The ignition system was of the Transistorised Coil Ignition (TCI) type. The spark plug was a standard NGK BCRE527Y. The engine was run in a skip-fire mode with three fired and three motored cycles. All measurements were performed in the first cycle with combustion. The fuel was natural gas containing 91%(vol.) methane. The engine was running at λ=1.5 (ϕ=0.67) and the engine speed was 700 RPM. Ignition timing was set at either 25 or 20 CAD BTDC and the engine was operated unthrottled.

FLUID FLOW

The LDV System

The velocity measurements were performed with a 2-component DANTEC fibre-flow system equipped with BSA enhanced signal processors. The probe volume had a diameter of 50 µm and a length of 700 µm and was located 1 mm from the centre of the spark plug gap. The used seeding was a polystyrene-latex dispersion. The mean polystyrene particle size was 0.31 µm.

Cycle-resolved Analysis of the Gas Velocity

For each component, the velocity was low-pass (LP) filtered with the moving window technique to extract a low frequency part (mean velocity) and a high frequency part (turbulence) of the flow. To get a smoother low-pass filtering a Hanning window was also introduced [3]. The window width used was 6 CAD, corresponding to a cut-off frequency of 700 Hz at 700 rpm.

SPARK CHARACTERISTICS

Data Acquisition Equipment

To achieve sampling of voltage and current, with resolution both in time and amplitude during 5 decades of time (Figure 1), it is necessary to use two sampling devices. One very fast for the breakdown phase and a slower for the entire spark duration.

The breakdown and early spark was measured with a high voltage probe (40 kV f = DC-80 MHz) and a fast current probe (f = 985 Hz-120 MHz) and sampled at 1 GS/s by a digitising storage oscilloscope (DSO) during the first 1.5 µs and the entire spark current was measured by another current probe (f = 12 Hz-70 MHz) and sampled at 2.5 MS/s during 2 ms by another DSO together with the voltage and the trigger pulse to the ignition system, both in single shot mode. Due to noise suppression it was necessary to use a resistor spark plug which limited the accurate voltage measurement to breakdown voltage.

Data Processing

First Micro Second. From the first micro second of data (Figure 2) the breakdown voltage (V_{bd}) is extracted and the negative slope of current is estimated by

$$i(t) = I_0 e^{-t/\tau_{bd}}$$

where I_0 is the top value and τ_{bd} is the time constant.

The Entire Spark. The entire current data is sampled (Figure 3) and LP-filtered (f_u= 20 kHz) to suppress disturbance from restrike (Figure 4) [8]. Spark duration was estimated by measuring the time for current to fall below a threshold value (i_{th}) (Figure 4) [7]. The charge Q was calculated according to

$$Q = \int_0^{\tau} i(t)dt$$

The charge (Q) is well correlated (Correlation coefficient: R=0.8-0.9) to spark duration (τ) and thus both showed similar correlations to the early combustion.

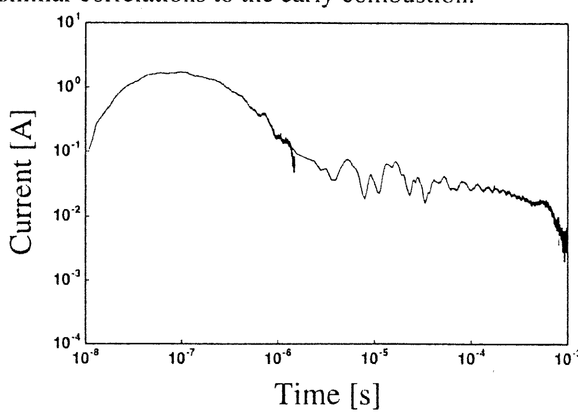

Figure 1. Spark current sampled over 5 decades of time by 2 DSO starting at 10 ns with overlap at 1.0 µs.

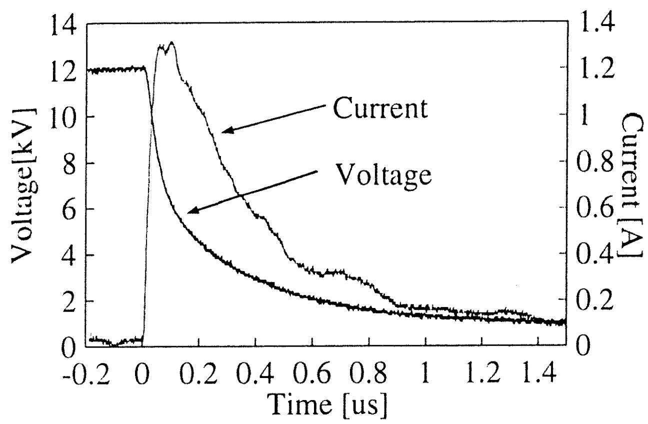

Figure 2. Breakdown voltage and current during breakdown.

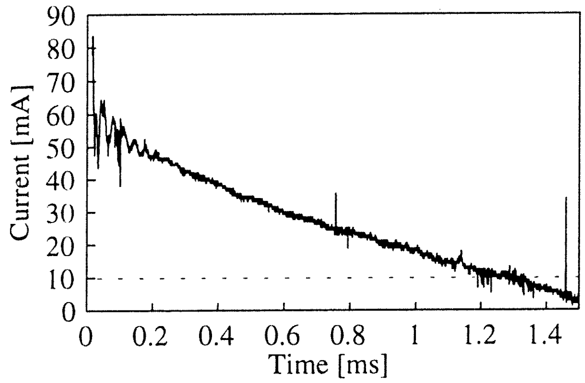

Figure 3. The entire spark current sampled at 2.5 MS/s. Noise make it difficult to detect threshold crossing.

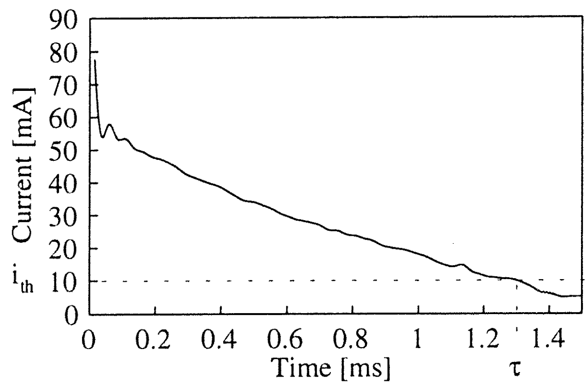

Figure 4. Filtered spark current (f_u= 20 kHz) with spark duration measured as time (τ) current is above the threshold value. (i_{th}).

FLAME SIZE DETECTION

The purpose of flame photographing was to extract more information about the early heat release. With this method very small amount of heat released can be detected several CAD before the pressure measurement becomes useful.

Equipment

The cameras used for flame photographing were two gateable, image intensified CCD-cameras from Princeton Instruments. The photo method chosen, due to low light emission from the flame itself, was the Schlieren method. As the cameras are of the slow scan type, only one frame per cycle and camera can be obtained. This leads to the optimising problem of either getting one image per cycle from each camera in two perpendicular directions, which gives information about the flame geometry, or to get two time resolved images from one direction, which gives information about flame development. Both methods have been used and the results are shown further on in this paper.

Image Processing and Evaluation

The raw images were processed in a computer aided digital image process, based upon morphologic filtering technique [9] and a custom designed identifying program, giving the projected flame area for each cycle at the time of imaging. The areas from the two perpendicular directions were then used to estimate the flame volume at the time of exposure by use of the equation below.

$$V = \frac{V_1 + V_2}{2} = \frac{2}{3\sqrt{\pi}}\left[A_1^{3/2} + A_2^{3/2}\right]$$

V = flame volume
A = projected flame area in each field of view, indexed as 1 and 2

The volume was then scaled with the equations below to give an equivalent energy release and heat release ratio [10].

$$X_b = \frac{mass\ burned}{chamber\ mass} = \left[1 - k(1/Y_b - 1)\right]^{-1}$$

$$Y_b = \frac{volume\ burned}{chamber\ volume} = \frac{V_b}{V}$$

$$k = \frac{density\ unburned\ mixture}{density\ buned\ mixture} = \frac{\delta_u}{\delta_b} \approx 4$$

The factor k =4 was adopted from ref. [1].

Good correlation can be shown from this method to the 0.5 % heat released CAD position, obtained from the pressure transducer and heatrelease analysis (R= 0.90-0.95, 2:nd order polynomial fit). This has been a method of validating the image processing. Perfect alignment between these two factors could never be expected, due to variation in flame speed between flame imaging and heatrelease detection.

Two major problems have been recognised during the image processing, foul windows and Schlieren signal from heat transfer regions. The first phenomenon can be seen in the upper left image in figure 5 as a weak Schlieren signal, the second phenomenon can be seen on all four images as a "boiling" on the upper and lower surfaces. Both giving problem to separate flame from the surroundings.

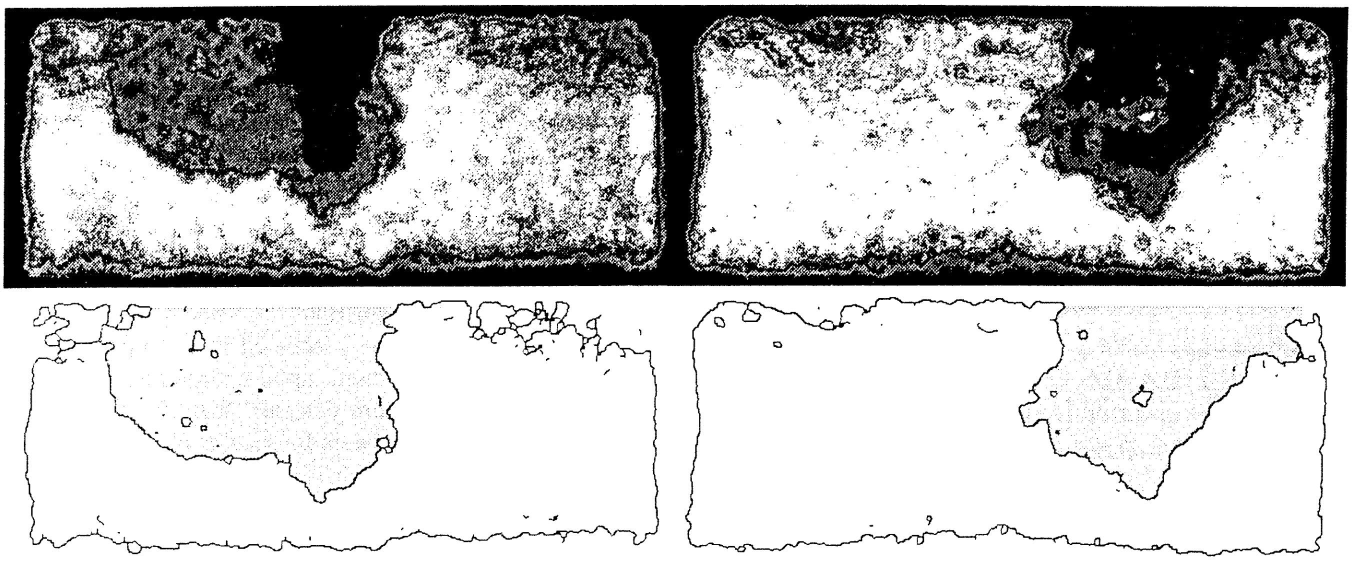

Figure 5. Flame photo from two perpendicular directions before processing (upper couple), and after processing (lower couple). Photo taken at 5 CAD after ignition, Ignition at 25 CAD BTDC.

PRESSURE AND HEAT RELEASE

The Pressure Measurement System
The pressure in the cylinder was measured with a AVL QC42x piezo-electric transducer connected to a Kistler 5001 charge amplifier. The charge amplifier voltage output was connected to a Data Translation DT2823 100 kHz 16-bit A/D-card which was triggered from a crank shaft encoder at a rate of five registrations per crank angle degree (CAD) [3].

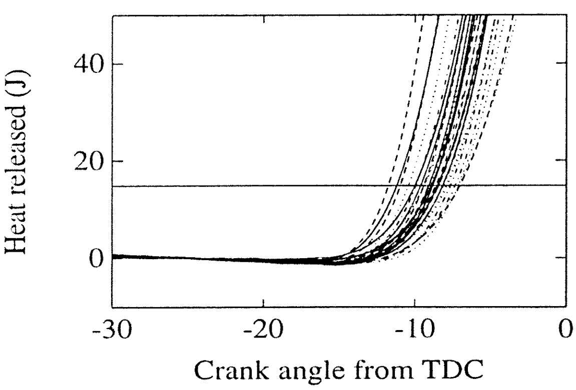

Figure 6. Accumulated heat released in the early phase.

One-zone Heatrelease Model
To extract information on the early flame development, a cycle-resolved heatrelease (HR) calculation was performed. The parameters in the model are tuned in against the last motored cycle in the skip-fire sequence until the heat release analysis showed only small levels of apparent released heat. The rate of combustion in the early phase was measured by detecting the crank angle position at which a small, but measurable, fraction of the heat was released. In this case 0.5% of the heat released was found to be a suitable level [3]. Figure 6 shows the heat released in the early phase of the combustion. The ignition system was in this case triggered at 20 CAD BTDC and the 0.5 % heat released is reached at approximately 10 CAD after ignition. The horizontal line indicates 0.5% HR.

STATISTICAL EVALUATION

As the aim for the experiments was to obtain information concerning the relationships between different parameters and the success of the early flame development, some kind of statistical model is needed. The choice was a multiple regression analysis in which different possible variables can be used to explain the cyclic variation in the early flame development. The regression was performed with both the full set of explaining parameters and with only one parameter at a time to get an indication of the relative importance of each. The multiple correlation coefficient was used as an indicator of the importance for each parameter [11]. Each parameter was used with a second order polynom to fit the data [3].

RESULTS

Correlation Between Breakdown Voltage and Early Combustion
Neither V_{bd}, I_0 nor τ_{bd} gives any significant correlation ($R < 0.25$) to other parameters (e.g. gas mean velocity , turbulence, flame size or HR). This indicates that the breakdown phase of the spark discharge is insensitive to flow field variations. The variations found in the break-down phase are also of minor importance to cycle to cycle variations in early combustion.

Correlation Between Spark Charge, Mean Velocity, Turbulence and Early Combustion
There are significant correlations when the flow field parameters (mean velocity and turbulence) and the later part of the spark discharge (spark charge Q) are used to explain the cyclic variability of the early combustion. Figure 7 shows the crank angle position of 0.5% heat released as a function of the turbulence for some 150 individual cycles.

Also shown is a second order polynom fitted to the data in a least squares sense.

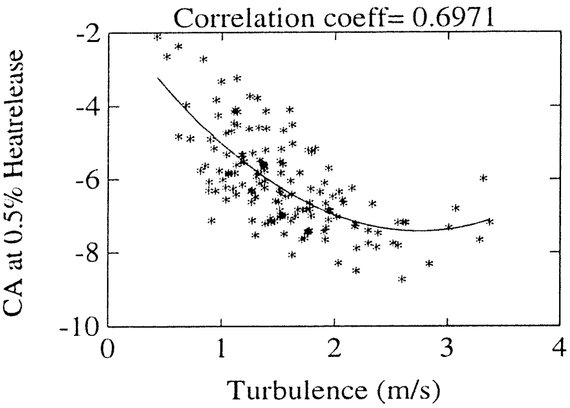

Figure 7. CAD for 0.5% heat released as a function of turbulence for 150 individual cycles.

Figure 7 was obtained with the turbulence information at ignition. It is not always this crank angle position which gives the highest correlation, as can be seen in figure 8. To get an estimation of the maximum correlation, the flow field parameters were evaluated in the interval -10 to +2 CAD from ignition. The highest correlation obtained within this interval was used.

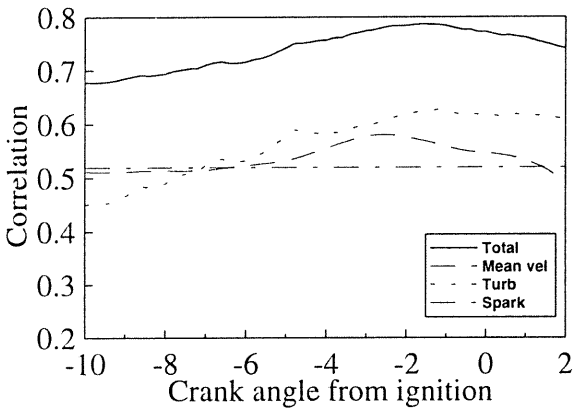

Figure 8. The correlation obtained when mean velocity, turbulence and spark charge are used to explain the variation in the early rate of heat release 0-0.5% HR.

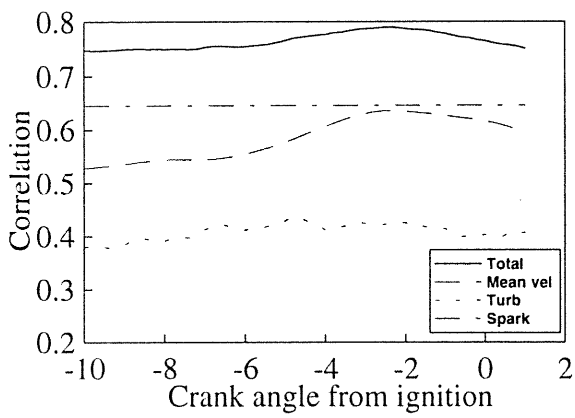

Figure 9. The correlation obtained when mean velocity, turbulence and spark charge are used to explain the variation in the early rate of heat release indicated by different sizes of the flame at 4 CAD after ignition.

When the flame size, a few degrees after ignition, was used as a value of early flame development instead of CAD at 0.5% heat released, interesting results are found. For these small flames the mean velocity and spark charge are more important than the turbulence (figure 9), in contradiction to the results with heatrelease analysis (figure 8). The same engine run was used in both cases.

To detect possible trends with different flame sizes, a series of engine runs were performed with different timing of the flame imaging system. Delays of 2, 4 and 5 CAD between spark timing and flame size detection was chosen. The flow field, spark characteristics, flame size and cylinder pressure were all recorded simultaneously for 100 to 200 individual engine cycles per experimental run. Figure 10 shows the correlation obtained between mean velocity, turbulence, spark charge and rate of combustion in the early phase. For crank angle positions earlier that 10 CAD after ignition, flame imaging was used to detect the rate of combustion and after this point heat release analysis was employed. The correlation between turbulence and combustion is rather low in the very early phase and increases in importance when the flame grows up to a size equivalent with 0.5 % heat released. The cyclic fluctuations of mean velocity and spark discharge tends to be most important to the very early flame development and the correlation are reduced for larger flames. This is most likely an effect of the changing contact areas between the flame kernel and walls and hence different kernel temperatures. The very small kernel in the early phase is expected to be most sensitive to changes in temperature. The correlation between spark charge and early combustion can be explained in the same fashion. Enhanced spark charge will heat up the small kernel to a higher extent.

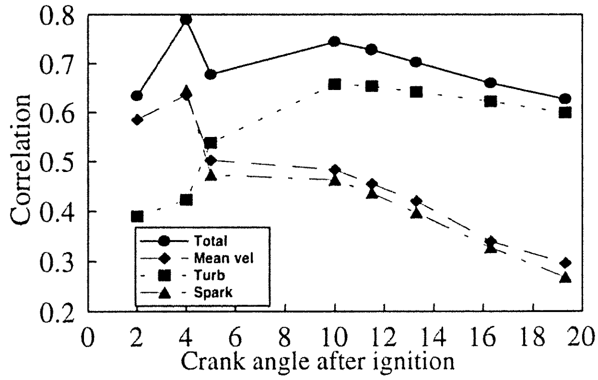

Figure 10. The correlation obtained when mean velocity, turbulence and spark charge are used to explain the variation in the early rate of heat release. Results before 6 CAD from ignition, was obtained with flame imaging.

The results above are all obtained with the mean combustion rate from ignition to a given HR-fraction (pressure analysis) or to a given crank angle event (flame imaging). It would also be interesting to detect the instantaneous rate of combustion for a given flame size. To achieve this the arrangement with two ICCD cameras in one Schlieren system was used. Although only one field of view could be obtained, the flame size at two different crank angle positions could be detected. Figure 11 shows the correlations obtained when mean velocity, turbulence and spark charge were used to explain the rate of combustion in the intervals 3-4, 4-5 and 5-6 CAD. The correlations are somewhat lower with this experimental set-up. This can be due to the decreased accuracy when two flame images are subtracted and the lack of information in the other field of view. The results in figure 11 indicates that the turbulence have the largest effect on the flame propagation in this part of the combustion. The mean velocity and spark charge tends to lose significance for larger flames, once again suggesting that the effect of those parameters are to be found in the very early part of the combustion.

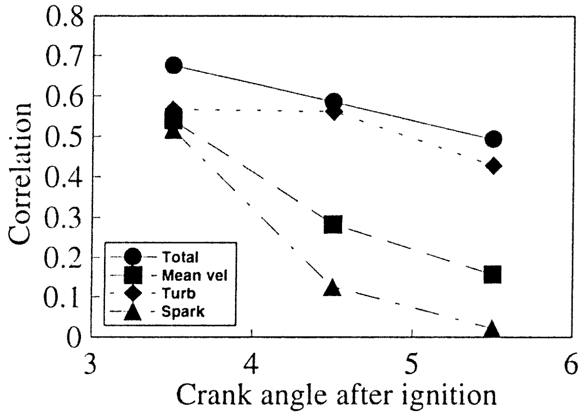

Figure 11. The correlation obtained when mean velocity, turbulence and spark charge are used to explain the variation in the rate of heat release, within the interval 3 to 6 CAD after ignition.

To detect possible trends in the correlation between the spark characteristics and early combustion with different spark plug electrode gaps, a series of runs were performed with 0.7, 0.9 and 1.1 mm gap. The spark plug used in these runs was a modified Champion RC582YC with a sharpened side electrode for a repetitive spark location. The correlations obtained, when the flame size at 6 CAD after ignition is used, are showed in figure 12.

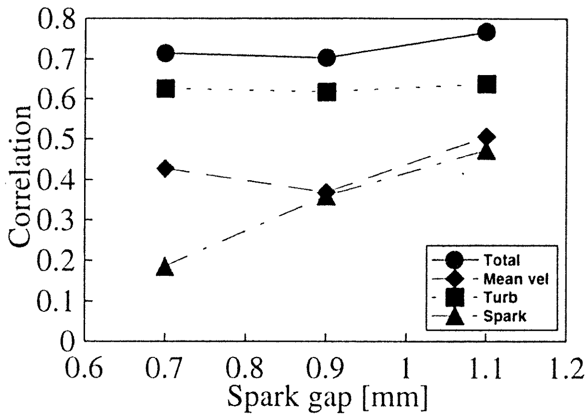

Figure 12. Effect of different spark plug gaps on the correlation between the flow field, spark charge and very early combustion, 0-6 CAD from ignition.

The mean velocity and turbulence correlations are only influenced to a small extent by the spark gap. The spark charge does, however, experience a large change, with increasing correlation for larger gaps.

CONCLUSIONS

1. The variations in breakdown voltage and hence breakdown energy from cycle to cycle shows no correlation to neither the flow field nor the early combustion.
2. The later part of the spark influence the early combustion. The correlations obtained between the charge, supplied to the spark plug within the interval 10 µs and 1 ms, and the early combustion is in the range 0.2-0.65.
3. The correlation between spark discharge and early combustion decreases for larger flames and smaller spark gaps.
4. The mean velocity close to the spark plug influence the very early flame development. The correlation between mean velocity and early flame development decreases as the flame grows.
5. The correlation between turbulence and early flame development peaks with a flame size equivalent with 0.5% heat released.

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