2D-LIF Investigation of Hot Spots in the Unburnt End Gas of I.C. Engines Using Formaldehyde as Tracer

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ABSTRACT

It is generally accepted that autoignition in S.I. engines starts in distinct areas of the end gas - the so-called "hot spots". The latter are caused by inhomogeneities in temperature and/or in charge distribution.

This paper reports on experiments in a modified one cylinder two-stroke engine with quartz windows. A two-dimensional laser-induced fluorescence (2D-LIF) technique is applied to the engine in order to monitor formaldehyde. The latter is formed early in the ignition process and consumed before the combustion is completed. Fluorescence signals are detected with an intensified CCD-camera.

2D-LIF frames taken in both knocking and non-knocking cycles show the formation and consumption of formaldehyde in the end gas. It is shown that autoignition starts in clearly bounded regions in the end gas which are identified by the absence of formaldehyde within these regions due to its consumption during the ignition process.

INTRODUCTION

The present discussion on increasing endogeneous pollutant emissions, such as CO_2 and NO_X, force to emphasize efforts in combustion research. A considerable amount of the overall emissions is caused by individual traffic, mostly powered by spark ignition engines. The latter are used due to their high power to weight ratio and their high standard of development.

The most efficient way of reducing both pollutant emissions and fuel consumption of S.I. engines is to increase the efficiency ratio. Basically, this is done by increasing the compression ratio, which yet again, is limited by knocking combustion due to higher temperatures at the end of the compression stroke. Knocking combustion itself decreases the efficiency ratio and causes severe damages to the surfaces of combustion chambers.

Generally, knock originates from autoignited exothermic centres (ETCs, so called "hot spots"); seldom from homogeneous reaction of the end gas. The formation of hot spots is supposed to arise from both temperature and compositional heterogeneity [1]. Higher temperature levels can be traced back to surface temperature hot spots, originated e.g. by particles, or imperfect mixing of residual gases of a previous cycle. The latter, especially, can be responsible for inhomogeneous distribution of species.

Ignition processes are discribed by mainly three stages, namely induction, ignition, and propagation which more or less follow each other. The latter, however, shows one of three possible modes, namely deflagration, thermal explosion, or developing detonation, described by Zel'dovich and coworkers [2].

Investigations of knocking combustion by means of optical devices, to date, have only been performed with Schlieren or "available light" technique. The Schlieren technique on the one hand, delivered, and still does, high speed or even ultra-high speed frames, on the other hand, it only depicts pressure gradients which can originate from either temperature (flame front) or pressure (shock wave). Laser induced fluorescence, however, is characterized by both high sensitivity and high selectivity in species. The chemical processes of early phase autoignition are fairly well understood, hence, this delivers valuable information about the occurance of intermediate species and their expected concentrations vs. time. With this information the detection of ETCs by two-dimensional laser induced fluorescence (2D-LIF) of appropriate species can be realized.

FORMALDEHYDE FORMATION AND DETECTION

In knocking cycles the occurence of cool flames has been observed just before the first pressure rise resulting from autoignition of ETCs is measurable. Generally, the weak blue light of these cool flames originates from the emission of excited formaldehyde. During the oxidation of the fuel various partially oxidized species like peroxides, ketones, and aldehydes are formed as intermediates which, at higher temperatures, are finally oxidized to carbon dioxide [3]. With respect to this experimental investigation, formaldehyde is the most interesting intermediate. It was first found in engines prior to knock by Rassweiler and Withrow [4]. In high temperature regimes formaldehyde is consumed very fast, whereas in low temperature regimes of cool flames the formation of formaldehyde is faster than its consumption. Hence all hydrocarbon content fuels form formaldehyde there is no need to seed this type of fuels.

As proposed in the literature [5, 6, 7, 8] and verified by

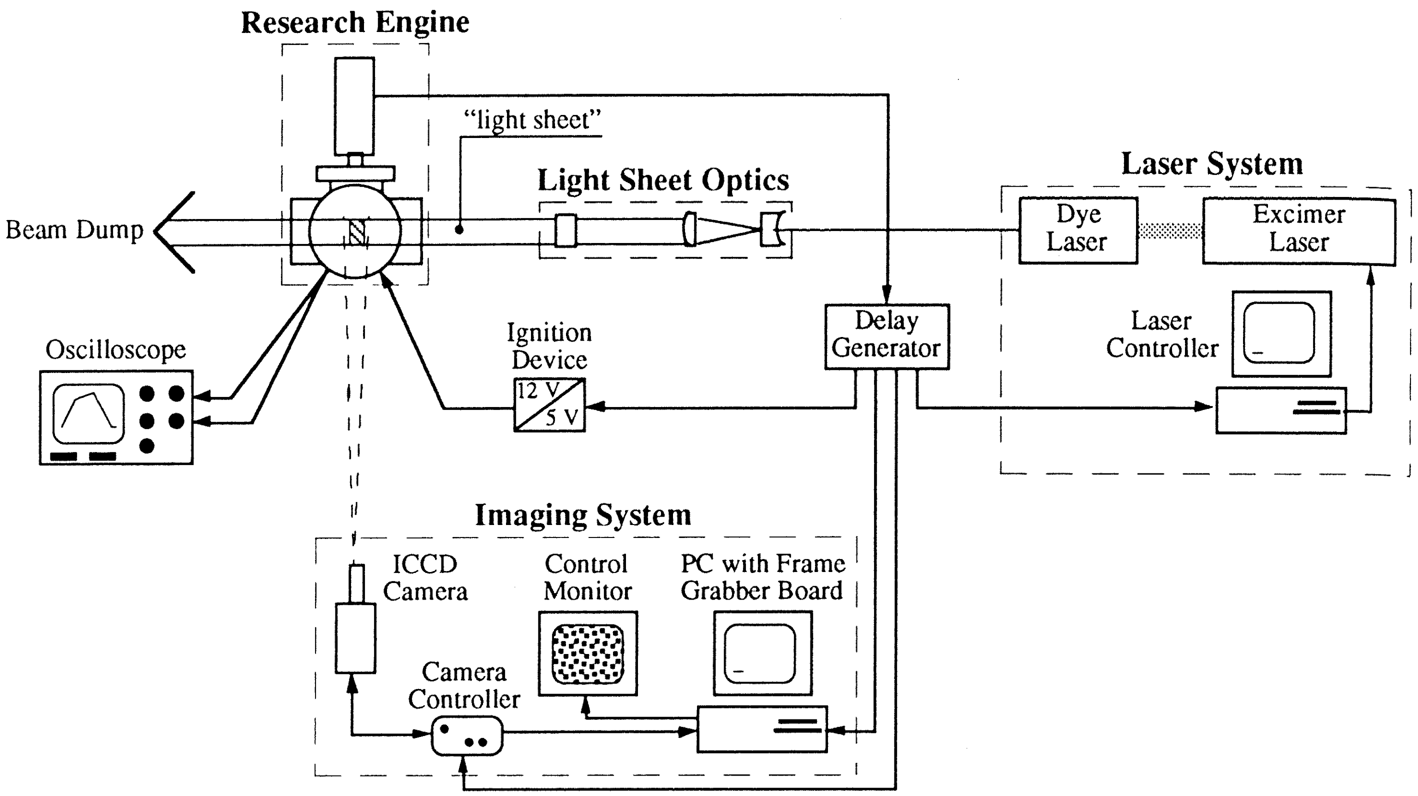

Fig 1: Experimental Set-Up

preliminary experiments the excitation wavelength of 353.19 nm in the near UV was chosen. The emission spectrum, slightly shifted to the red, starts at ≈ 360 nm. The major intensity of formaldehyde fluorescence is found in the range of ≈ 390 to 460 nm.

EXPERIMENTAL

Main item of the experimental set up is the research engine which has especially been adapted to the demands of 2D-LIF measurements. The complete experimental set up is shown schematically in Fig. 1. In principle, the rig consists of four principle units, i.e., the laser system including the light sheet optics, the research engine, the imaging system, and an engine data acquisition system. The shaft encoder of the engine provides a trigger signal to the delay generator (Spectroscopy Instruments SR 250). All remaining units are controlled by this delay generator in order to assure exact timing.

Laser System and Light Sheet Optics

The laser system consists of an PC-controlled excimer laser (Lambda Physik LPX 205i) which pumps the dye laser (Lambda Physik FL 3002). The excimer laser is a XeCl-type working at 308 nm with pulse durations of 28 ns (nominal) and maximum energies of 420 mJ. In order to meet the excitation wavelength of formaldehyde, the dye laser is equipped with BMQ-dye tunable from 335 to 375 nm. The conversion rate of the dye at the excitation wavelength of 353.19 nm is ≈ 6%.

The light sheet optics consisting of three quartz cylinder-lenses shapes the output beam of the dye laser into a two-dimensional plane of measurement (light sheet). The first two lenses make up a Galilean telescope and produce a beam width of ≈ 50 mm. The third lens focusses the light sheet into its plane obtaining a minimum thickness of less than 60 μm.

Research Engine and Data Acquisition

The research engine is a redesigned industrial one cylinder two-stroke engine (ILO L 372) with an 80 mm bore and a stroke of 74 mm. A two-stroke engine was chosen due to the fact that neither valves nor camshafts fitted in the cylinder head disturbe full optical access to the combustion chamber from above. To meet the demands of the LIF-technique, i.e. clean windows, no broadband absorption of lubricant, no soot formation, etc., the engine runs "dry". The oil usually added to the fuel is replaced by MoS_2-grease in order to ensure lubrication between piston and cylinder wall. This grease was found to produce no fluorescence signal in the relevant range of excitation. Figure 2 shows a partly schematic cross section of the modified research engine. Arrows illustrate the directions of the light sheet (excitation) and the fluorescence (signal). The engine has undergone modifications of the piston, the cylinder, and the cylinder head. In particular, cylinder and cylinder head have been altered in the region of top dead centre (TDC) in order to obtain constant temperatures via oil instead of air cooling. A quartz-ring window of 4 mm height allows the light sheet to enter the combustion chamber. A cylindrical quartz top window replaces the cylinder head and assures full optical access to the combustion chamber from above. The piston, originally crowned, has been planed and fitted with an aluminium disc. Except for a small pocket for the ignition electrode which is passed through the cylinder wall

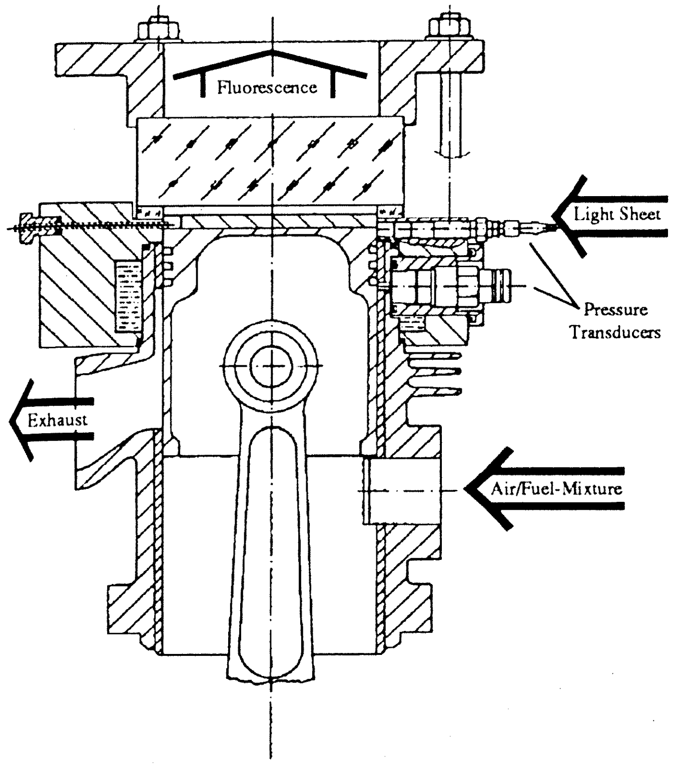

Fig. 2: Cross-Section of the Research Engine

from aside the combustion chamber exhibits disc shape. This, combined with a clearence height of slightly less than 4 mm ensures mainly two-dimensional flame propagation.

A large size fly-wheel is fitted to the engine crank shaft to stabilize its speed; braking and driving the engine is done by an electronically speed controlled dynamometer.

In-cylinder pressures are detected by a quartz pressure transducer (Kistler 6001) and are stored together with the trigger signal in a digitizing oscilloscope (Tektronix 11201).

Imaging System

The imaging system digitizes, stores, and processes the recorded formaldehyde fluorescence signal. It comprises an intensified CCD-camera with its control device, a PC equipped with a frame grabber board and respective software.

The ICCD-camera (Proxitronic Nanocam) features ultra-short exposure times down to 5 ns. It is equipped with a CCD-chip of 12.8 by 9.6 mm². The lens is a common camera lens (Nikon Makro f 4/200 mm) due to the fact that the formaldehyde fluorescence signal is obtained in the visible blue. The laser excitation wavelength and occuring stray light are blocked by a band pass filter (transmission 400 to 450 nm). The camera video signal (CCIR-type) is digitized with a resolution of 8 bit by the frame grabber board (Matrox, MVP-AT) in a PC. The employed software allows recording, processing, and presentation of the frames.

RESULTS AND DISCUSSION

Frames of formaldehyde fluorescence taken in different non-knocking and knocking cycles, respectively, are presented here. In both cases the engine has been driven at a speed of 1000 rpm on primary reference fuel (PRF) of 90 ON (90 % iso-octane and 10 % n-heptane). Non-knocking conditions were as follows: ignition set at 21° crank angle before top dead centre (CA BTDC) and two skipped cycles (i.e., only every third cycle is fired), whereas under knocking conditions ignition was set at 24° CA BTDC with three skipped cycles. Due to high rates of residual gases of previous fired cycles, skip-firing was introduced to ensure good cylinder filling.

The limit of one frame per cycle is founded on the facts of both limited repetition rate of the excimer laser (max. 50 Hz) and the time it takes to read out the CCD-chip. However, the effects observed at a certain time or crank angle, respectively, are typical for all frames be they taken in knocking or non-knocking cycles. Hence, this allows to explain general features of autoignition in the unburnt end gas.

Figures 3-7 show 2D-LIF of formaldehyde in non-knocking (Fig. 3) and knocking (Figs. 4-7) cycles, respectively. The frames are taken through the full-size top window looking into the combustion chamber from above. The camera exposure time was 100 ns and fully enclosed the laser pulse (28 ns). Originally, the frame grabber board produces black-and-white frames (256 grey values). These grey values are assigned to a false colour code where 0 is denoted by black and 255 by red. This achieves an enhanced impression of the fluorescence signal.

Figure 3 shows a blue area on the left representing the fluorescencing end gas within the laser light sheet. The frame is taken in a non-knocking cycle at 12° CA ATDC. The upper and lower straight transitions from blue to black represent the borders of the light sheet travelling from the right to the left. The annular transition on the left represents the cylinder wall whereas the wrinkled one on the right represents the flame front originating from the spark electrode. Near this flame front there are found no black spots within the end gas region which might have occured due overlapping and advancing turbulent flame fronts, respectively. The black spot in the middle of the light sheet next to the cylinder wall results from deposited grease on the inside of the top window. The annular stroke on the right, finally, originates from reflections of the quartz ring window. It results from poor glass quality. However, this reflection yet again represents the cylinder wall.

Figures 4-7 show fluorescening end gas in knocking cycles taken at 6° CA ATDC, i.e. 5 ms after ignition. Again the light sheet travels from the right to the left and the just recognizable upper and lower transitions indicate its borders. In Fig. 7 the hazy tiny spots distributed on a circular area represent the combustion chamber. They result from reflections of particles on the piston top. The spark electrode is situated at the cylinder wall in the upper right corner of the frame.

Figures 8-11 show the corresponding pressure traces to Figs. 4-7. The drawn in vertical bars indicate the respective triggers relative to their pressure traces.

The frame shown in Fig. 4 is taken at an early stage of autoingnition. This can be seen from the trigger bar in Fig. 8 which lies before the pressure rise originating from autoignition. The rather large end gas region shows relatively homogeneous distribution of fluorescence intensity. In the lower region of the detection area one small hot spot is visible in form of a black spot.

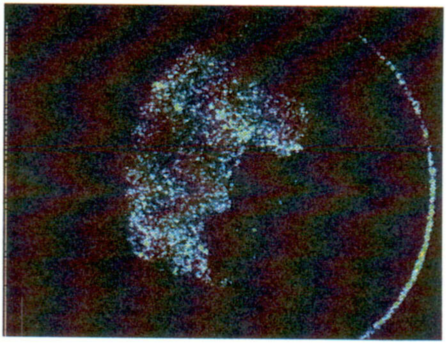

Fig. 3: 2D-LIF of Formaldehyde in Non-Knocking Cycle

False Colour Code

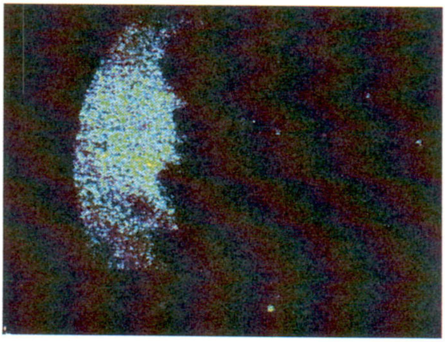

Fig.4: 2D-LIF of Formaldehyde in Knocking Cycle (a)

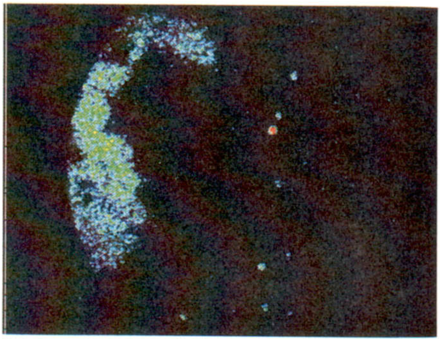

Fig. 5: 2D-LIF of Formaldehyde in Knocking Cycle (b)

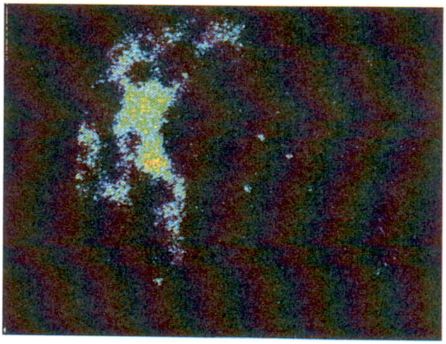

Fig. 6: 2D-LIF of Formaldehyde in Knocking Cycle (c)

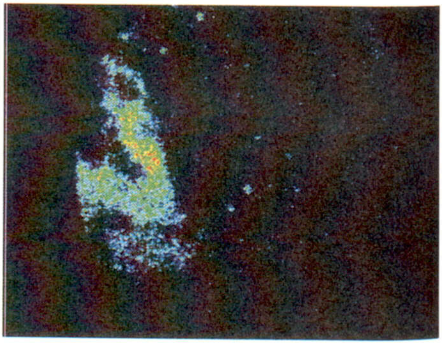

Fig. 7: 2D-LIF of Formaldehyde in Knocking Cycle (d)

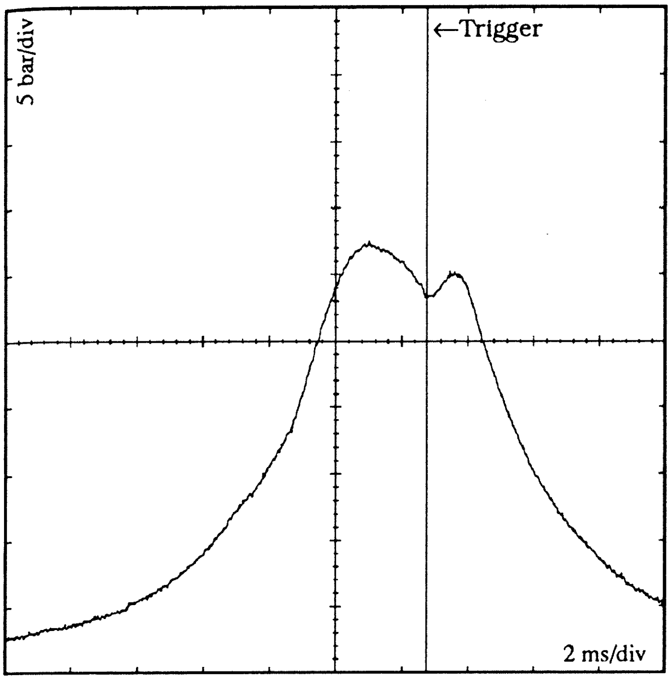

Fig. 8: Corresponding Pressure Trace to Fig. 4

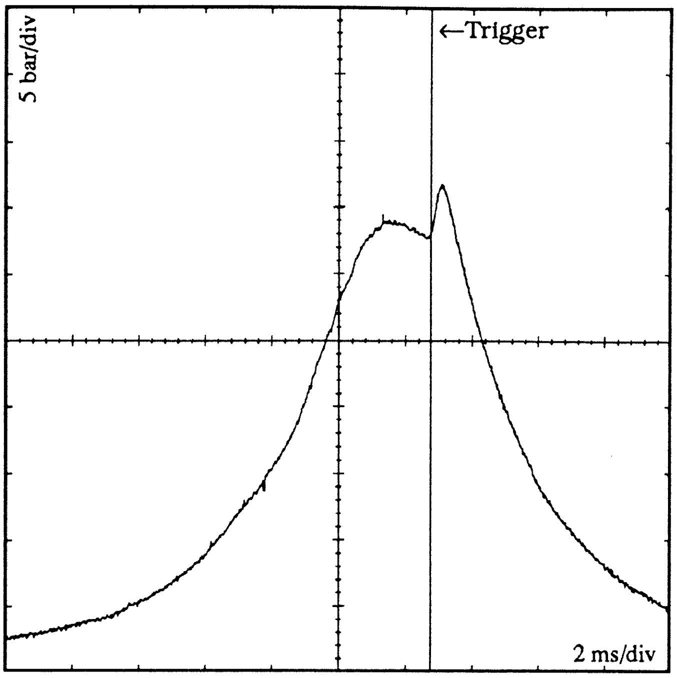

Fig. 9: Corresponding Pressure Trace to Fig. 5

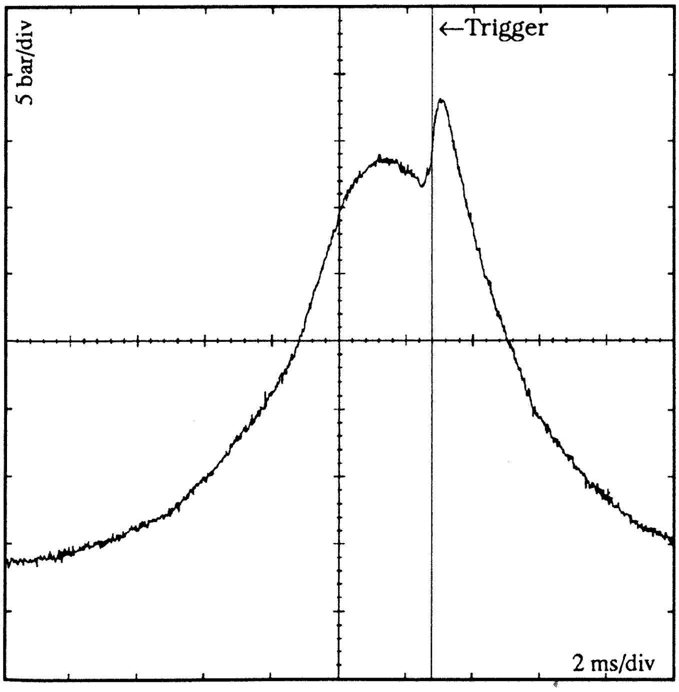

Fig. 10: Corresponding Pressure Trace to Fig. 6

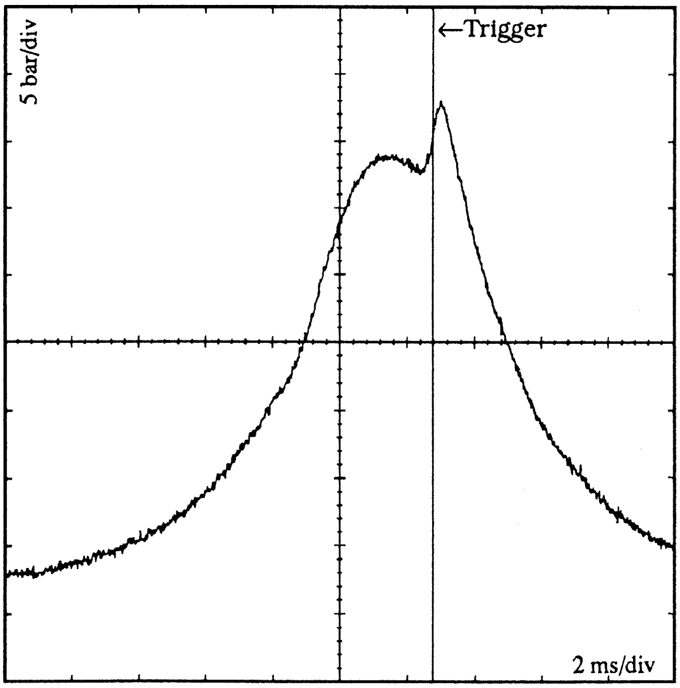

Fig. 11: Corresponding Pressure Trace to Fig. 7

This results from the absence of formaldehyde due to beginning autoignition. The wrinkled right hand border again shows the regular flame front.

In Fig. 5 a frame is shown taken slightly later than the one before, right at the beginning of the sharp pressure rise (Fig. 9). It shows a small end gas region with higher fluorescence intensities in its centre. Just below the middle there are three small hot spots, one right at the cylinder wall. A much lager ETC can be seen just above the fluorescening region in the upper part of the detection area. Size and shape of this hot spot suggest that it could have been two small ones that already have ignited and merged.

Figure 6 shows a frame taken during knock, at a time, where the gradient of the knock originated pressure rise is highest (Fig. 10). The crescent shape of the end gas region is hardly recognizable due to expanded autoignition areas. In the centre, again, fluorescence intensity has increased compared to Fig. 5. In the lower part of the light sheet there is a very large structure at the cylinder wall connected with the one just beneath the fluorescening region. Another large structure can be seen in the middle between cylinder wall and fluorescening "centre". Some smaller ETCs in the upper region seem to be already connected to the regular flame front coming from the right. The large size and the overall area caught in combination with the timing (Fig. 10) suggest that autoignition already has taken place and some hot spots have grown. It can also be seen that the regular flame front has lost a little of its wrinkles compared to Fig. 4.

The frame shown in Fig. 7 is taken late during knock. The trigger bar in Fig. 11 shows that the peak pressure of knocking combustion is nearly reached. In the centre of the end gas region the fluorescence intensity has increased again (red and yellow areas). A very large autoignited structure at the cylinder wall stretching towards the regular flame front can be seen in the centre. Smaller ones in the upper and lower areas reached by the light sheet. Finally, in this frame the regular flame seems to have straightened what can be seen from the course of the right hand border of the fluorescening area. Ultra-high speed Schlieren frames (up to 720,000 frames per second) taken during a joint CEC-project (same engine type) by König et al. [9,10] exhibit the same phenomenon.

CONCLUSIONS

To counter-measure against knocking combustion the underlying mechanisms must be understood before. Model calculations based on detailed reaction mechanisms usually assume homogeneous end gas which more or less autoignites simultaneously at a given critical temperature. On the one hand high speed Schlieren frames show that these assumptions are not perfectly valid, on the other hand numerical calculations showed that local temperature fluctuations as small as 20 to 30 K are sufficient for partially autoigniting the end gas.

Numerical simulations as well as early papers on engine knock, e.g. [4], show that large amounts of formaldehyde are formed in processes prior to knock. But this formaldehyde is completely consumed during the following combustion phase. Hence, formaldehyde is a suitable natural tracer for following early stages of knock and ETCs, respectively.

The results presented here show frames of two-dimensional laser induced fluorescence of formaldehyde taken in a one cylinder two-stroke engine during non-knocking as well as knocking combustion. The formation of formaldehyde in the end gas region is clearly shown. Hot spots at different stages of knocking combustion have been detected as non-fluorescent areas within the fluorescening end gas region. Their number and size correspond well with these stages which are related to the course of the pressure trace.

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