

OH and HCHO LIF measurements in HCCI engine

by

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ABSTRACT

To meet the environmental requirements on the pollutants formation without increasing the fuel consumption level, the car manufacturers have to develop new combustion processes. These new concepts require new insights in the comprehension of the physical and chemical phenomena occurring inside the combustion chamber. One of the most promising concept is the Homogeneous Charge Compression Ignition (HCCI). The HCCI concept can be described as a hybrid of the well known Spark Ignition engine (SI) and the Diesel engine. A premixed air-fuel mixture is used just like in a SI engine but the charge is not ignited by a spark. Instead, the charge is ignited by the compression temperature as in Diesel engine. Earlier studies on this type of combustion system have shown high efficiency and low NO_x and soot emissions. But the emissions of unburned hydrocarbons and CO are reported to be high and the ignition process difficult to control. To optimize this new mode of combustion, the physical and chemical mechanisms occurring during this one - ignition and combustion processes - must be understood. The detection techniques based on the natural emission spectroscopy or direct combustion visualization are not sufficient to obtain the information on the chemical process driving the HCCI process (localization and the nature of the chemical species involved). Laser-Induced Fluorescence (LIF) is a good candidate because it is non intrusive, spatially and temporarily resolved. The ignition and combustion processes can be studied by visualizing the distributions of formaldehyde (HCHO) and formyl (OH) radicals by laser-induced fluorescence. The HCHO molecule is formed as an intermediate specie during hydrocarbons oxidation. The formation occurs through low temperature oxidation in the early phase of the ignition process. HCHO is consumed later in the combustion process. Hence HCHO is an indicator of the first stage of ignition and a marker for the low temperature reactions zones. The OH radical is an important intermediate that is formed during the combustion. OH is formed in flame region with high temperature and is often used as a marker of both flame fronts and burnt regions. In this study, the ignition and combustion phase in an HCCI optical engine are investigated using laser induced fluorescence on HCHO and OH. The measurements are performed on a single cylinder optical engine with port-fuel injection system. A blend of iso-octane and n-heptane is used and the compression ratio is set to 16:1. The images of OH and HCHO are compared along with the heat release calculation derived from the pressure-trace. The results show that OH and HCHO are two different and complementary markers of the combustion process in HCCI engine. HCHO traces the cool flame region and it has been demonstrated that the formaldehyde signal correlates with the beginning of the cool flame heat release and the maximum of HCHO signal corresponds to the maximum heat release on this first phase of the combustion process. OH traces the principal heat release and it has been shown that OH is strongly correlated to high temperature premixed combustion and also the low oxidation of unburnt hydrocarbons. These data will help the optimization of the HCCI concept and also provide valuable data to improve the physical models and CFD calculations.

I. INTRODUCTION

In response to the stringent emission standards which are determined by the ever greater concern for the environment, the automotive industry is continuously investigating new ways of improving engine technologies. One of the main innovations introduced in recent years is Homogeneous Charge Compression Ignition (HCCI) engine. It can provide both diesel-like efficiencies and very low emissions of nitrogen oxides (NO_x) and particulates, Christensen et al. (1999). When running an engine in HCCI-mode the fuel and air are allowed to mix in the intake port, or in the cylinder, in order to create a homogeneous charge. The charge is then compressed until auto-ignition occurs. A characteristic feature with HCCI is that ignition occurs simultaneously at multiple sites, Hultqvist et al. (1999). So a major challenge is the difficulty to control the timing of the ignition so to that the combustion occurs close to TDC. A greater understanding of the complex physical and chemical processes that occur during the various stages of HCCI combustion is required in order to further exploit their potential in terms of pollutant emissions, fuel consumption reduction and combustion control.

The most promising diagnostics to investigate HCCI combustion seem to be Laser Induced Fluorescence (LIF) of combustion radicals or reaction intermediates. The ignition and combustion processes can be studied by visualizing the distributions of Formaldehyde and OH radicals. Formaldehyde is associated with the low temperature reactions that occur when certain mixtures of hydrocarbon fuels and air are close to the explosion. Hence, formaldehyde is an indicator of the first stage of ignition and a marker for zones with low temperature reactions. Planar laser induced fluorescence from formaldehyde has been used earlier for visualization of self-ignition centers in SI-engines, Schiessl et al. (2001), for studying the ignition of Diesel sprays, Kosaka et al. (2000) and for characterization of the Controlled Auto Ignition (CAI) combustion concept, Graf et al. (2001).

OH is appropriate to localize the burned gas regions during the high temperature combustion phase, Dec and Coy (1996). Although the separate use of each of the two techniques is useful in developing our understanding of HCCI combustion, both techniques have the potential to yield information concerning the different phases of the typical combustion process that occurs and have thus been exploited in the present study. Indeed if OH visualization allows the localization of both the reaction and burnt gas zones, Bokle et al. (2000), the localization of the reaction zone alone requires the application of both techniques together, Paul and Najm (1998).

In this work the ignition and combustion phases for a HCCI engine are investigated with laser-induced fluorescence on formaldehyde and OH. Both technique are used consecutively in an optical single cylinder engine to understand the physical and chemical phenomena occurring inside the combustion chamber.

II. EXPERIMENTAL SETUP

Optical engine

The work presented is performed on an 0.5 l single cylinder optical HCCI engine, the technical specifications are summarized in table 1. The engine is equipped with port fuel injection system to generate an homogeneous charge. A set of blend fuels (n-heptane and iso-octane) is used. The compression ratio is set to 16:1. The horizontal optical access in the upper part of the cylinder liner is obtained through a full sapphire ring with a height of 10 mm. An elongated piston and a 45-degree mirror provided for optical access through a piston window with a diameter of 55 mm (figure1).

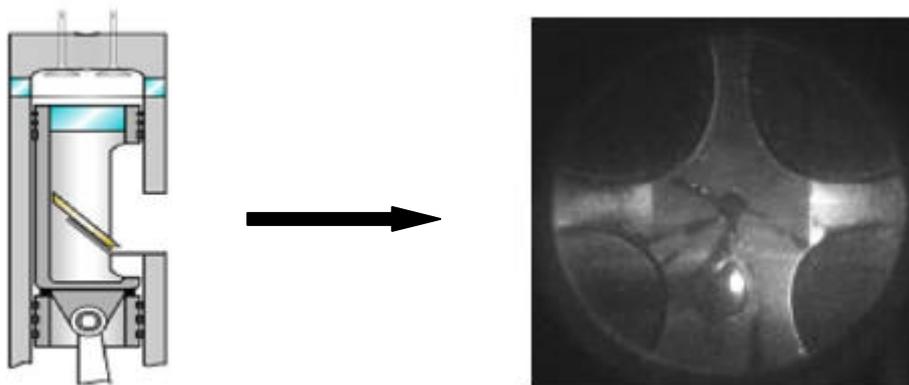


Figure1. Elongated piston scheme and camera view through the piston window.

Type	Four-valve diesel engine
Engine speed	1200 rpm
Displacement	0.5 l
Bore	85 mm
Stroke	88 mm
Con rod length	145 mm
Compression ratio	16 :1
Fuel	50% Iso-octane / 50% n-heptane
Injection	Port fuel injection

Table 1. Specifications of the test engine.

Optical setup

OH LIF

The experimental set-up used for the OH LIF experiment is presented in figure 2. A frequency-doubled (532 nm) Nd:YAG-laser pumped a dye laser (Rhodamine 590) which frequency is doubled to 283 nm to excite the $Q_1(6)$ OH transition of the $Q''=0, Q'=1$ band of the $A^2\Sigma^+ - X^2\Pi(1,0)$ system. Excitation of the $N''=6$ level is selected to minimize the temperature sensitivity of this population within the absorbing level, Croonenbroek (1996). The laser system provides pulses of 7 ns duration, with a mean energy of 40 mJ at 283 nm. A set of cylindrical and spherical lenses are used to obtain a 20 mm width, 1mm thick laser sheet that entered the engine through the sapphire ring.

The OH PLIF signal is collected using a 512x512 array PI -Max intensified CCD camera equipped with a 105 – mm f/4.5 UV-Nikkor lens and two filters (low pass : WG 305 and band pass : UG5). The detected OH fluorescence signal corresponded to the (1,1) and (0,0) transition bands near 309 nm.

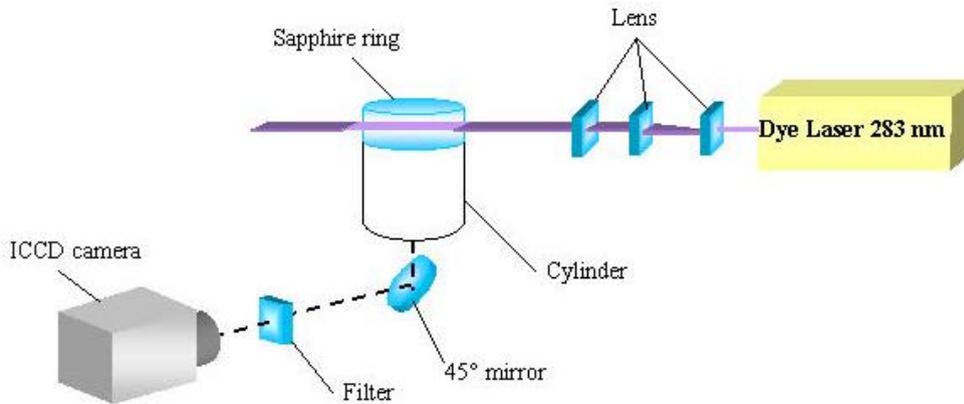


Figure 2. Experimental setup for OH LIF measurements

HCHO LIF and Direct visualization of combustion

A Nd:YAG laser (1064 nm), tripled to 355 nm is used to excite the rotational transitions within the absorption band $\tilde{A}^1A_2 - \tilde{X}^1A_1 4_0^1$. Using high laser power is very easily achievable at this wavelength to obtain a high signal-to-noise ratio. The laser provides pulses of about 7 ns duration, with a mean energy controlled in the range of 80 mJ. However, unlike the OH LIF fluorescence, the excitation system is not tunable and does not allow selective excitation. Furthermore, other species such as PAH might also fluoresce at this excitation wavelength. Therefore, a special care will be taken before analyzing the results in order to determine the origin of the fluorescence signal. Direct visualizations of combustion are realized in order to obtain global information on the combustion process. The chemiluminescence emission are directly collected by the intensified camera.

The experimental set-up is presented in figure 3. The laser beam of a tripled Nd:YAG laser was formed into a 25 mm width, 1 mm thick laser sheet by a set of cylindrical and spherical lenses. The sheet enters the engine through the sapphire ring. Two cameras are used : The first camera (Sensicam, A), is delayed slightly with respect to the laser illumination in order to collect the naturally-emitted light from combustion via the 45° mirror. The second camera (Princeton, B) is used to collect the fluorescence emission. Camera A and camera B are equipped with a 105–mm f/4.5 UV-Nikkor lens. A combination of a 385-nm high-pass and a 450-nm low-pass filters is used to separate the HCHO LIF signal from the natural combustion emission.

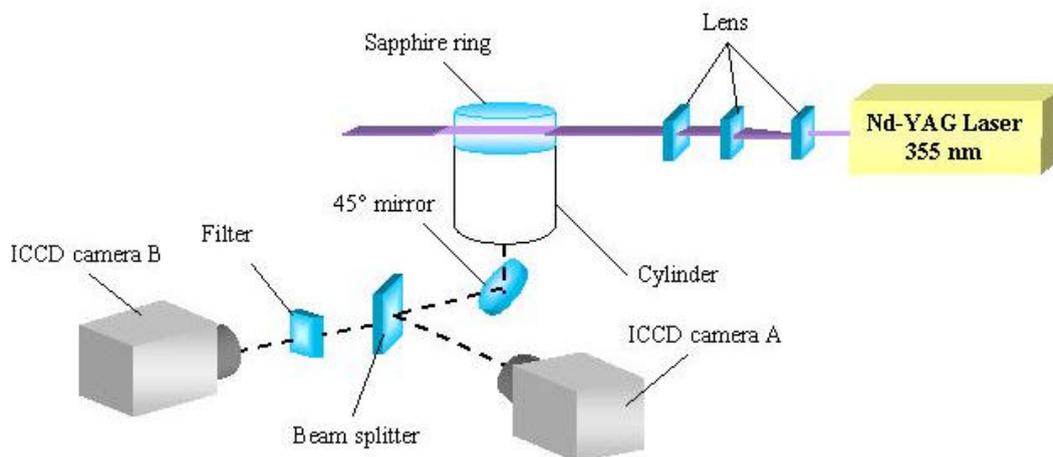


Figure 3. Experimental setup for HCHO LIF measurements + direct visualization of combustion

Image acquisition and processing

For every measured crank-angle position background images, from the corresponding motored case, are collected. These background images are subtracted from the measured direct images. Measurements are performed in a wide time range, starting before the onset of the low temperature region, through all combustion and until late in the expansion stroke. For every measured crank-angle position 20 images are collected.

Spectral investigation

Formaldehyde can be detected by LIF and several possibilities exist regarding the choice of excitation wavelength, Shin et al. (2000), Klein Douwel et al. (2000). One possibility exploits the third Nd:YAG harmonic at 355 nm, Harrington and Smyth (1993). The collected signal is spectrally analysed in order to confirm that it corresponds to the formaldehyde transition. This investigation is performed by replacing the ICCD-system collecting the formaldehyde-LIF by a spectrograph. The obtained spectrum, in figure 4 (red), show the LIF signal obtained. Figure 4 indicates that this spectrum is in good agreement with laminar premixed flame emission spectra (blue spectrum) obtained in a previous study and the theoretical emission spectra of formaldehyde Collin et al. (2003), Harrington and Smyth (1993). The experimental spectrum has a broad band structure compared to similar spectra obtained at lower temperatures and also contains a continuous emission structure. The effects are due to the additional fluorescence and overlap of the spectral lines of formaldehyde emission. However, formaldehyde is clearly identified as being the visualized specie.

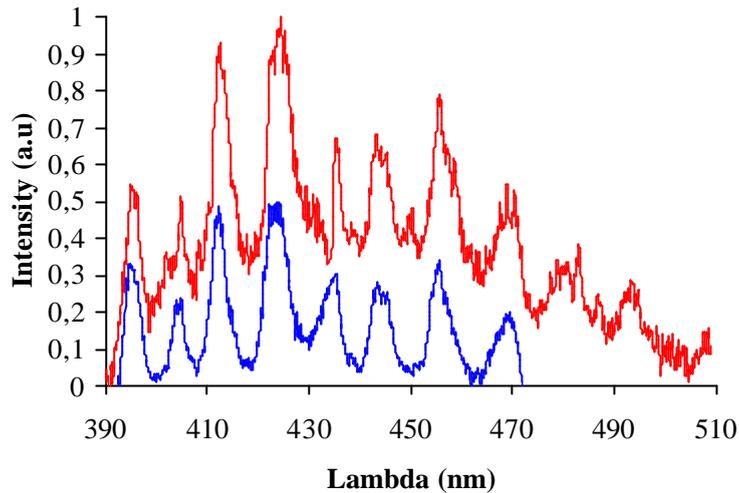


Figure 4. LIF emission spectra obtained with 355 nm excitation : the red spectrum originates from measurements in HCCI engine and the blue spectrum has been obtained in a laboratory premixed flame.

III. RESULTS

Combustion analysis

During all imaging events, the cylinder pressure is recorded simultaneously with the image acquisition. The cylinder pressure is processed to derive the engine heat release. The figure 5 indicates that the HCCI combustion process can be divided into two consecutive parts : a cool flame (C) and main heat release (M). Both parts are visible on the pressure trace and the rate of heat release. The cool flame(s) is characterised by low oxidation of hydrocarbon. This region is strongly dependant on the fuel formulation, Westbrook (2000), Minetti (1996). In our case a blend of iso-octane and n-heptane is used.

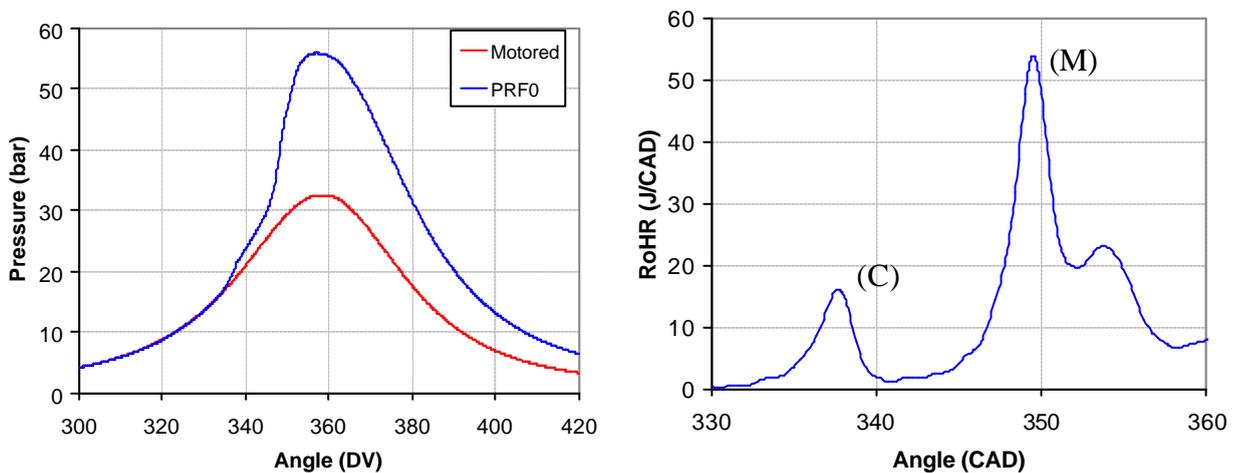


Figure 5. Pressure trace and rate of heat release (RoHR)

The main region is characterised by a distributed reaction throughout the combustion chamber. The distributed reaction appear to be inhomogeneously progressing in the combustion chamber. This effect can not be observed from the average images as seen in figure 6 but are clearly depicted in the instantaneous acquisitions. This inhomogeneity is due to the temperature and concentration fluctuations.

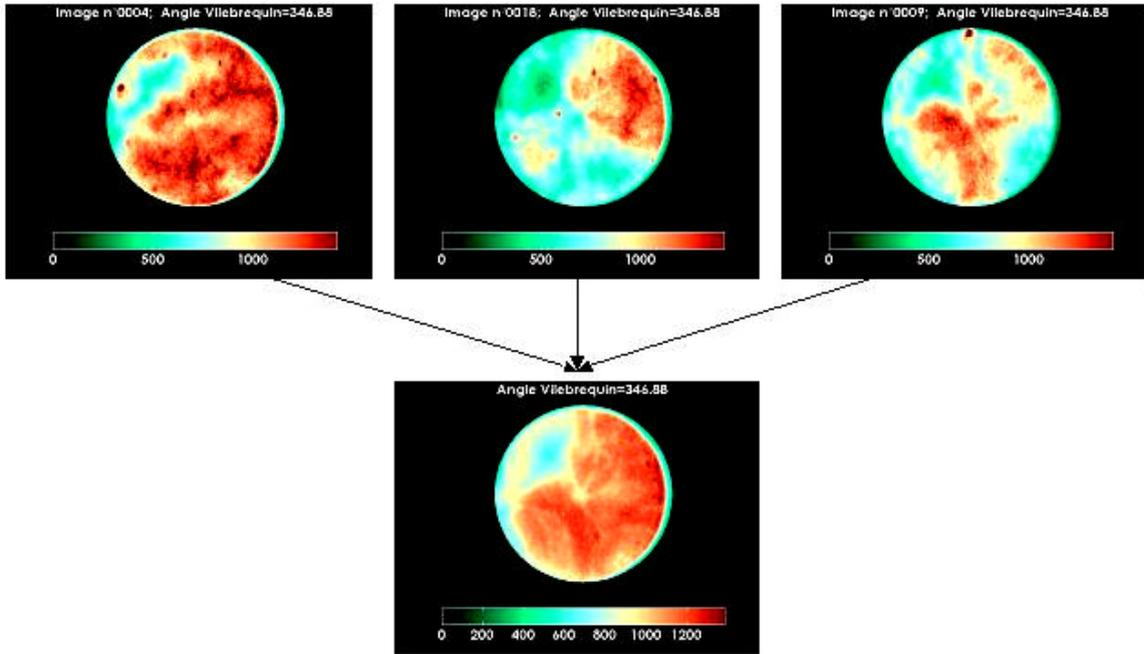


Figure 6. Comparison between instantaneous and averaged images

Figure 7 show the cool flame instantaneous emissions. The cool-flame reaction progresses rather homogeneously without any protruding structure. The signal level during the cool flame is very weak compared to the main heat release. This fact limits the image analysis since the signal to noise ratio is not favourable using the natural emission visualization.

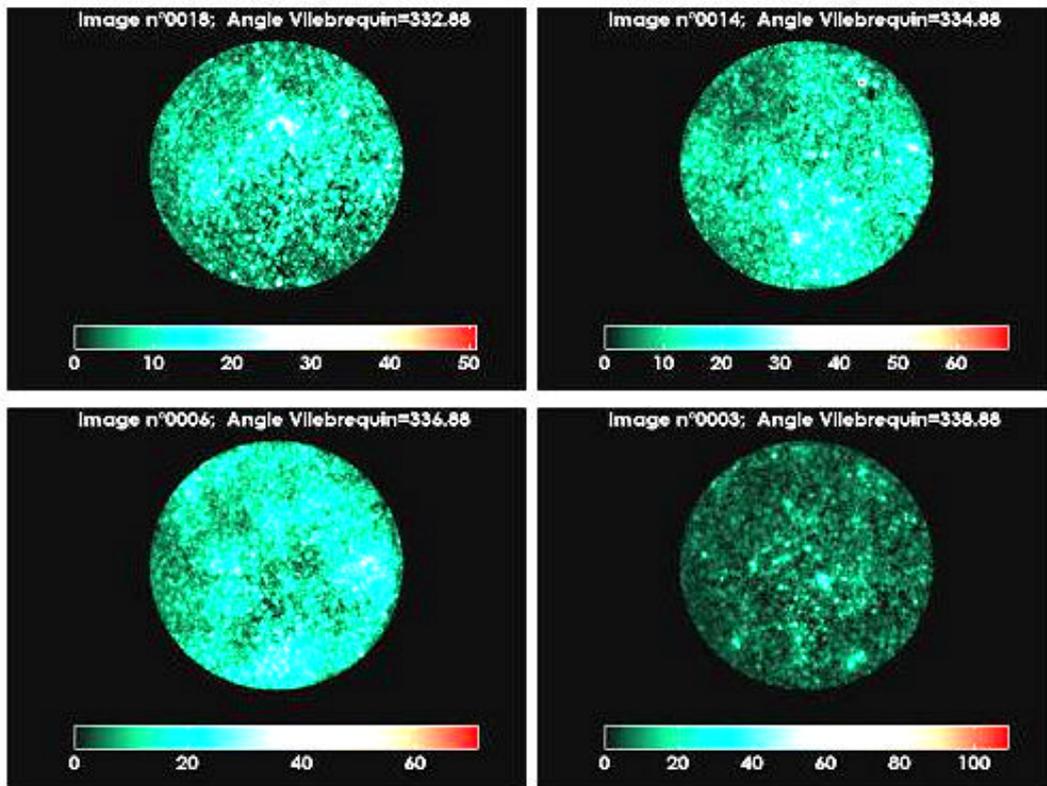


Figure 7. Sequence of cool flame natural emission in the HCCI engine

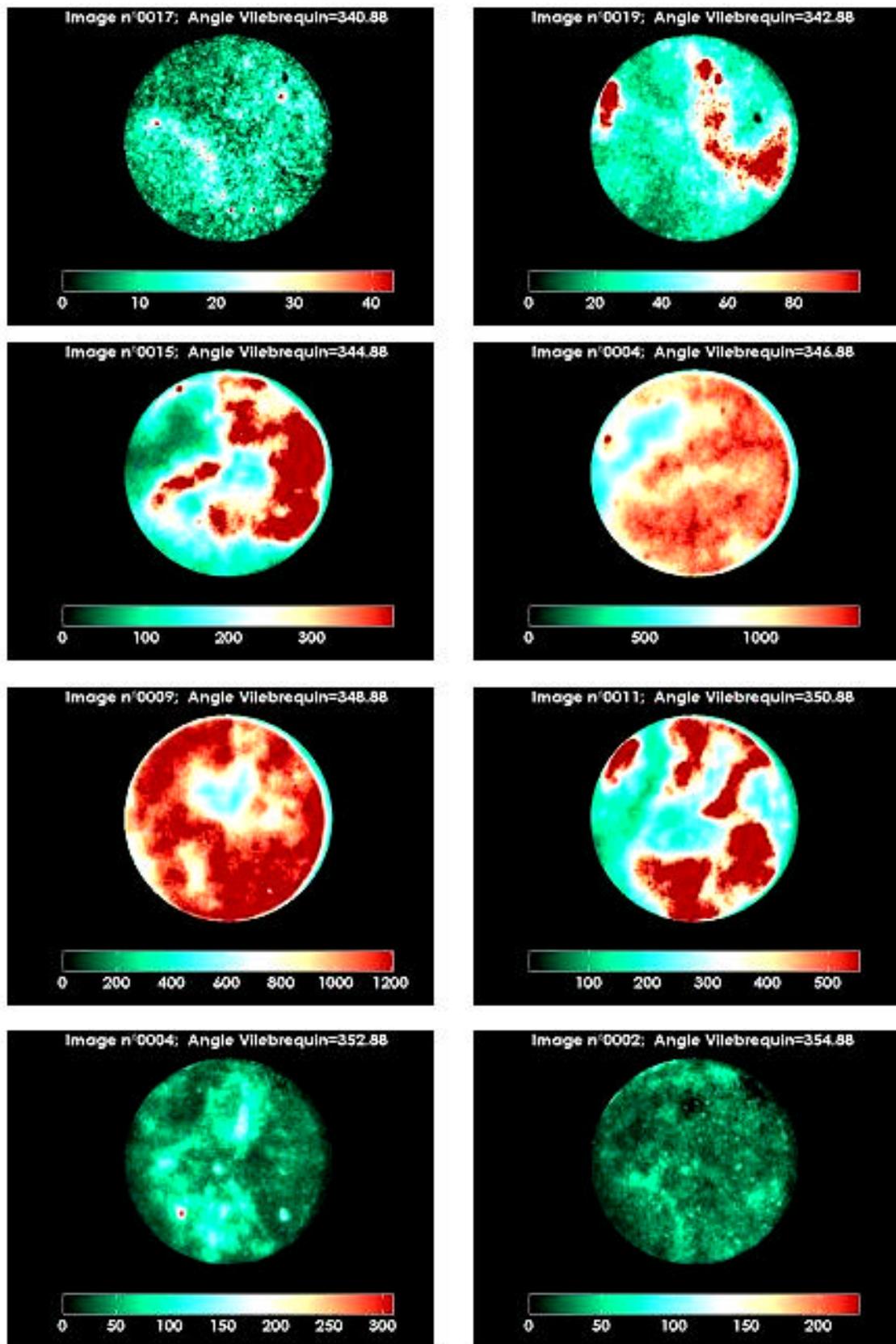


Figure 8. Sequence of the main heat release natural emission in the HCCI engine

Figure 8 shows the timings corresponding to the main part of the heat release.

The following steps can be derived from the visualisation of the main part of the heat release in Figure 8 :

1. Image 1 : The initial combustion onset, which is very evenly distributed, with no flame propagation.
2. Images 2 - 3 : An increase of the chemical activity is observed. As the chemical reactions start, the temperature increases. At the most favourable positions in terms of temperature and air/fuel ratio, kernels are formed and ignite. The number and locations of kernels are dependent upon the global parameters like distribution of air, fuel, inert gas and temperature. The initial kernels grow larger as combustion progresses.
3. Images 4 - 8 : As the combustion progresses the kernels tend to grow and merge with others.

HCHO LIF analysis

In figure 9 a selected series of single shot LIF images obtained at different crank angles are shown to exemplify the formation and consumption of HCHO.

In figure 10 the average rate of heat release for 100 individual cycles collected together with the LIF images is depicted and correlated to the HCHO signal during the cycle. This signal is obtained through the calculation of the mean values of the total sum-up intensity for the 20 single-shot images obtained at each crank angle position. These mean values are normalized to the maximum value of the HCHO-signal.

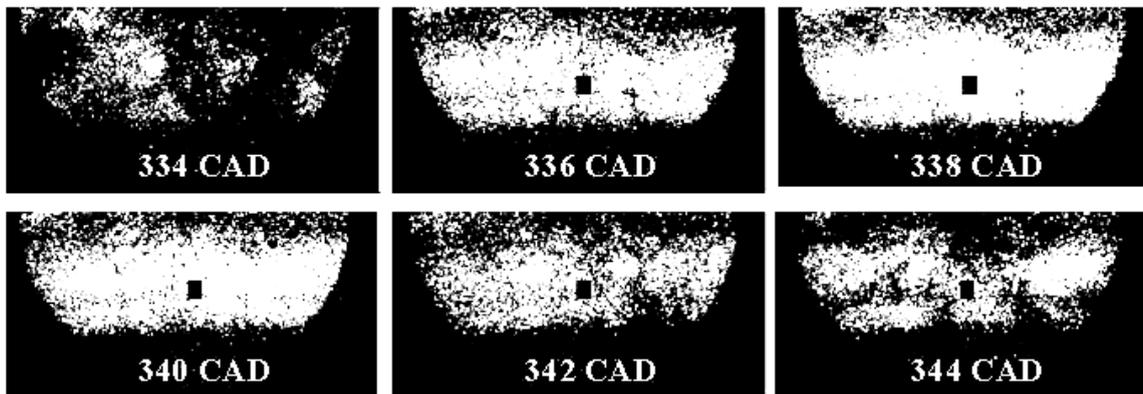


Figure 9. Single-shot images of formaldehyde.

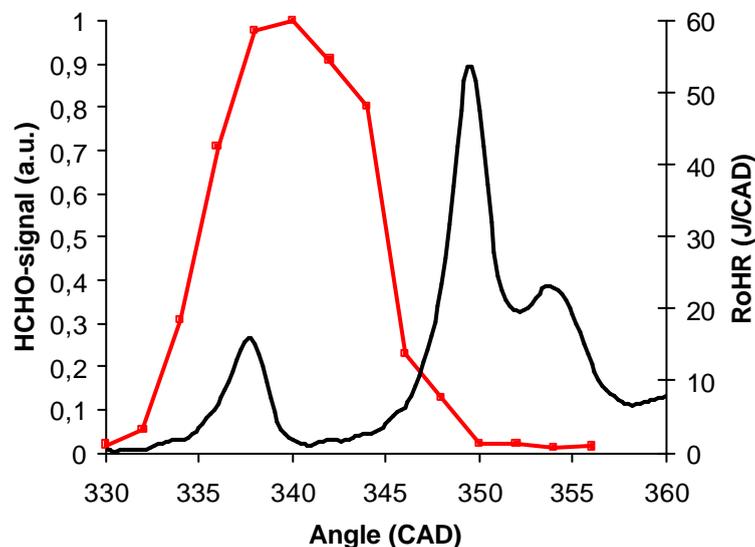


Figure 10. Average rate of heat release (black line) and average formaldehyde signal (red line)
 From figure 9 and 10 it can be seen that the formaldehyde location correlates with the cool flame location. The rise in the formaldehyde signal correlates with the beginning of the cool flame heat release at fairly 334 CAD. The maximum of HCHO signal corresponds to the maximum heat release of this first phase of the combustion process. HCHO signal exhibits a small plateau until the main heat release starts. The fact indicates that the cool flame heat release initiates the chemical processes leading to the main heat release. This cool flame acts as a chemical catalyst of the main heat release.

OH LIF analysis

As in this previous figures, figure 11 and 12 represent a selected series of OH LIF images obtained at different crank angles, the heat release cycle evolution and the variation of the OH signal.

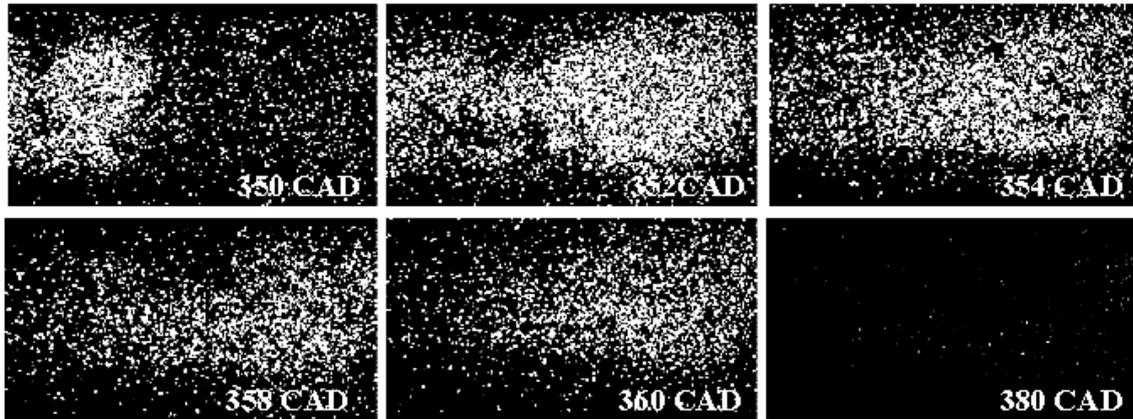


Figure 11. Single-shot images of OH

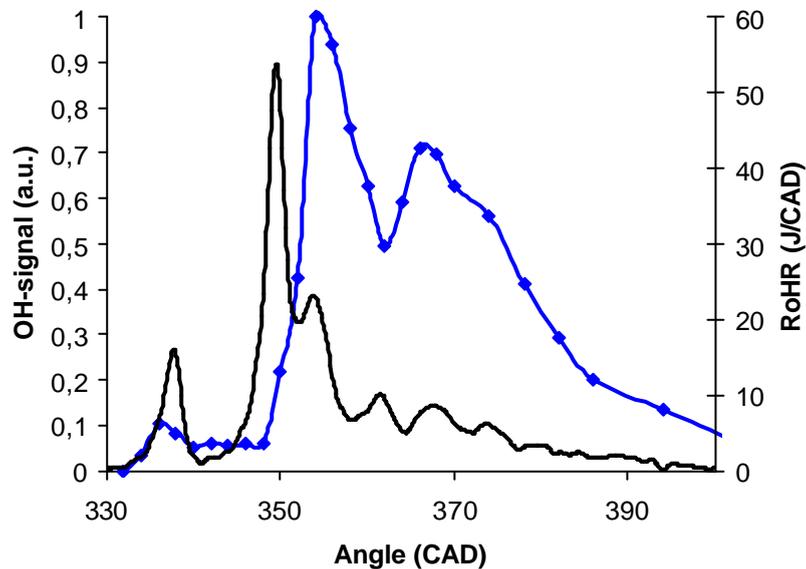


Figure 12. Average rate of heat release (black line) and average OH-signal (blue line)

From figure 11 and 12 it can be seen that OH is formed during the main heat release in the high temperature region. The OH signal starts to increase during the main heat release. The maximum of the signal is shifted from the maximum heat release probably due to the fact that the OH is convected in the burn gas region. The second peak in the OH signal is correlated to the second peak in the main heat release. The fact is explained by the combustion of pockets of previously unburnt fuel/air mixture which ignites due to favourable temperature and mixture conditions. These conditions are generated by the first peak in the heat release which lead to an increase of local temperature along with an increase of turbulence and mixing.

IV. CONCLUSION

The results presented in this study have shown that the combination of OH and HCHO are two different and complementary markers of the combustion process in HCCI engine. HCHO traces the cool flame region and it has been demonstrated that the formaldehyde signal correlates with the beginning of the cool flame heat release and the maximum of HCHO signal corresponds to the maximum heat release on this first phase of the combustion process. OH traces the principal heat release and it has been shown that OH is strongly correlated to high temperature premixed combustion and also the low oxidation of unburnt hydrocarbons. These data will help the optimization of the HCCI concept and also provide valuable data to improve the physical models and CFD calculations.

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