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ABSTRACT

High-speed laser diagnostics was utilized for single-cycle resolved studies of the formaldehyde distribution in the combustion chamber of an HCCI engine. A multi-YAG laser system consisting of four individual Q-switched, flash lamp-pumped Nd:YAG lasers has previously been developed in order to obtain laser pulses at 355 nm suitable for performing LIF measurements of the formaldehyde molecule. Bursts of up to eight pulses with very short time separation can be produced, allowing capturing of LIF image series with high temporal resolution. The system was used together with a high-speed framing camera employing eight intensified CCD modules, with a frame-rate matching the laser pulse repetition rate. The diagnostic system was used to study the combustion in a truck-size HCCI engine, running at 1200 rpm using n-heptane as fuel. By using laser pulses with time separations as short as 70 μs, cycle-resolved image sequences of the formaldehyde distribution were obtained. Thus, with this technique it is possible to follow the formaldehyde formation and consumption processes within a single cycle. The combustion evolution was studied in terms of the rate and spatial structure of formaldehyde formation and consumption for different engine operating conditions, e.g. different stoichiometries. Also, the impact on the rate of heat-release was investigated.

INTRODUCTION

Homogeneous Charge Compression Ignition (HCCI) is a hybrid between the well-known Spark Ignition (SI) and Compression Ignition (CI) engine concepts. As in an SI engine fuel and air are premixed in the inlet system into a more or less homogeneous charge. During the compression stroke the pressure and temperature of the mixture increases and reaches the point of auto ignition at several locations simultaneously [1]; i.e. the mixture burns without the help of any ignition system, just as in a CI engine. Since ignition occurs at multiple points, the integrated combustion rate becomes very high. Therefore, highly diluted mixtures or Exhaust Gas Recirculation (EGR) have to be used in order to limit the rate of combustion [2]. Without sufficient mixture dilution, problems associated with extremely rapid combustion and knocking-like phenomena will occur, as well as excessive NO_X production. On the other hand, an overly lean mixture will result in incomplete combustion or even misfire. The big challenge with this combustion concept is auto ignition timing control since this is only depending on the pressure and temperature conditions. Combustion control can be done by adjusting operational parameters as inlet air temperature, fuel amount and EGR rate [3, 4]. The major advantages of HCCI compared to the diesel engine are low NO_X emissions and, depending on the fuel, virtually no soot [5]. The benefit of HCCI compared to the Spark Ignition (SI) engine is the much higher part load efficiency since the HCCI engine is running unthrottled [6]. The toughest challenge is controlling the ignition timing over a wide load and speed range [7, 8]. Another challenge is to obtain an acceptable power density. The power density is limited by combustion noise and high peak pressures. At low loads, the rather high emissions of unburned hydrocarbons (HC) and carbon monoxide (CO), in combination with low exhaust temperatures, present an additional challenge [9]. By applying unthrottled HCCI combustion at part load in SI engines, efficiency can be improved by 40-100%. Emerging technologies for variable valve timing, with the intent of using these as means of controlling the combustion timing in HCCI engines [10], may well lead the way for the first application of the HCCI combustion mode in practice.

Formaldehyde is usually formed as an intermediate species when combusting hydrocarbons. The formation occurs through low-temperature oxidation in an early phase of the ignition process. The generated formaldehyde is then being consumed in the following combustion process. Formaldehyde is also associated with the low-temperature reactions that occur when certain mixtures of hydrocarbon fuels and air are close to the explosion limit. Hence, the low-temperature reactions (cool flames) and the early phase of the main heat release in an HCCI engine can be investigated by probing the formation and consumption of formaldehyde. Conventional planar laser induced fluorescence from formaldehyde, i.e., with one image captured per engine cycle, has been used earlier in investigations of the Controlled Auto Ignition (CAI) combustion concept [11] and for characterization of HCCI combustion [12, 13, 14]. In the latter publication it was reported how the concentration of formaldehyde increased as the Low Temperature Reactions (LTR) progressed. In the same study, the spatial formation and consumption of formaldehyde appeared to be highly heterogeneous. In terms of cycle-to-cycle stability it could be concluded that the formation during the LTR was quite stable whereas the consumption during the main heat release showed substantially more fluctuations. This means that although the cycle-to-cycle variations in terms of in-cylinder pressure are known to be reasonably small, the spatial variations of the combustion from one cycle to another can be quite significant. The heat release when running HCCI is also known to be very rapid. This combination of fast consumption and fluctuating combustion phasing introduces an averaging effect when performing conventional LIF measurements where one image is recorded per cycle. In order to really capture the details of such processes it is necessary to follow a single cycle event.

In this work the early phase of ignition and main combustion in an HCCI engine were investigated with high-speed laser-induced fluorescence, LIF, of formaldehyde. For this purpose a tailor made YAG-laser cluster combined with a high speed framing camera were used. This approach was used to generate unique single-cycle resolved measurements.

EXPERIMENTAL

ENGINE SETUP

The engine used for the work presented was an inline six-cylinder, 2.0 liter/cylinder *Scania* D12 diesel engine, converted to single cylinder HCCI operation.

Type:	Four-valve diesel engine
Displaced volume:	1966 cc
Bore:	127.5 mm
Stroke:	154 mm
Compression ratio:	11.2:1
Exhaust valve open:	34° BBDC @ 0.15 mm lift
Exhaust valve close:	6° BTDC @ 0.15 mm lift
Inlet valve open:	2° BTDC @ 0.15 mm lift
Inlet valve close:	31° BBDC @ 0.15 mm lift
Valve lift exhaust:	14.1 mm
Valve lift inlet:	14.1 mm
Inlet valve diameter:	44 mm
Exhaust valve diameter:	41 mm

Table 1. Data for the Scania D12 optical engine.

In order to provide for optical access the engine was equipped with an elongated piston and a 30 mm high quartz liner. The engine was also modified to operate with port-fuel injection, which generates a principally homogeneous charge. To have an optically transparent and non-fluorescent fuel, pure n-heptane was used. The compression ratio was set to 11.2:1 and the engine was run with lambda values between 3.2 and 4.5. The engine runs reported in this work were performed with a fixed inlet air temperature of 38° C.

A water cooled Kistler pressure transducer, placed 50 mm from the centre of the bore axis, was used for in-cylinder pressure capture. A photo of the engine can be seen in Figure 1 and a table containing some vital engine specifications of the *Scania* D12 is shown in Table 1.

The inlet air was preheated with an electrical heater to initiate HCCI combustion with the selected compression ratio and fuel type. The experiments on the engine were conducted under the operating conditions shown in Table 2. The rich limit was limited by too rapid combustion and high in-cylinder pressures.

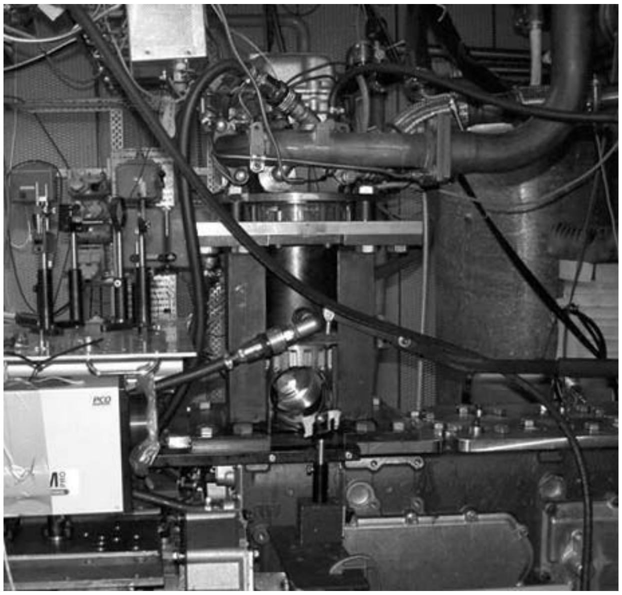

Figure 1. The modified Scania D12, the engine used for all the experiments conducted.

Engine speed:	1200 rpm
Lambda:	3.2 – 4.5
Inlet air temperature:	38° C
Inlet air pressure:	1 bar absolute
Fuel:	N-Heptane

Table 2. Operational parameters.

OPTICAL SETUP

The formaldehyde LIF measurements were performed by exciting the formaldehyde molecules in the A-X^1_0 band, using the third harmonic (355 nm) from the multi-YAG cluster. The laser cluster consists of four separate laser channels of Nd:YAG type, each operating with a repetition rate of 10 Hz and with a fundamental laser wavelength of 1064 nm. For superimposing the four beam paths and for frequency tripling of the laser radiation to 355 nm, a specially designed beam combining scheme was used, shown in Figure 2. In this scheme the beam from laser 1 was frequency doubled to 532 nm in a second harmonic generating (SHG) crystal, after which the frequency doubled beam together with the remaining part of the fundamental is mixed in a third harmonic generating (THG) crystal to generate laser radiation at 355 nm. The tripled beam is separated from the doubled and fundamental beams by means of a dichroic mirror. The frequency doubled beam from laser 2 is then combined with the tripled beam from laser 1, by using a second dichroic mirror reflecting in the UV and transmitting in the green and IR. The beams are directed through a second THG where the tripled beam from laser 1 passes unaffected while the fundamental and doubled beams from laser 2 are frequency tripled. This procedure is repeated for all the four lasers, and thus the laser system has a single optical output from which the pulses at 355 nm from the four lasers are emitted. The laser system allows for opening of the Q-switch twice during one flash lamp discharge, extending the number of pulses from four to eight. The eight pulses can be emitted in a rapid succession, and the time separation between two consecutive pulses can be set to values as short as 6.25 μs.

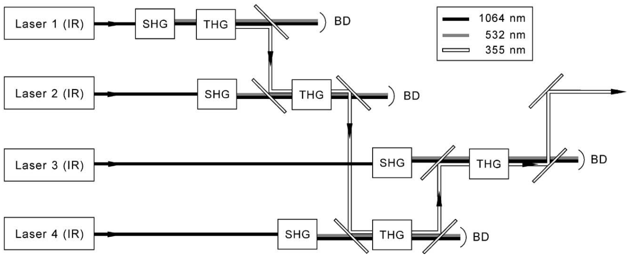

Figure 2. The beam combining scheme for generation of laser radiation at 355 nm with the multi-YAG laser system.

In order to detect the fluorescence generated by the rapid laser pulse burst, a high-speed framing camera was used. The framing camera employs a single optical input in front of which a Bernard-Halle camera lens (f=+100 mm, f#=2) is mounted. An image intensifier is placed at the optical entrance of the camera in order to enhance the sensitivity of the detector. The intensified signal is split up with an eight-facet prism onto eight individual intensified CCD modules. Each module consists of a CCD image sensor (384x576 pixels) and a micro channel plate (MCP). The MCP further intensifies the signal and it also functions as an electronic shutter. To enable exposure of the CCD image sensors in a rapid succession, the MCPs are synchronized with the laser pulse train. In the configuration presented, the detector system can acquire image sequences with an image time separation down to 1 μs.

To gain two-dimensional information of the formaldehyde distribution the laser beam from the multi-YAG laser system was passed through an f=-100 mm cylindrical lens and an f=+500 mm spherical lens to form a narrow, laser sheet. The laser sheet, approximately 40 mm in width, was directed into the HCCI engine through the quartz cylinder liner and focused in the center of the combustion chamber. The fluorescence signal from the formaldehyde was imaged perpendicular to the sheet,

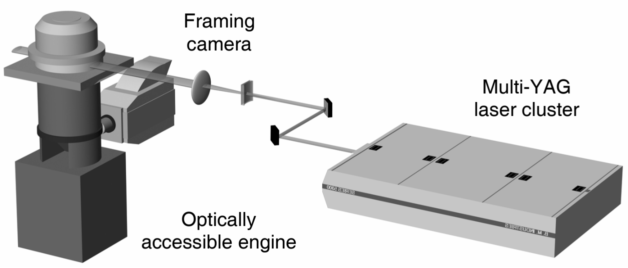

Figure 3. Schematic of the experimental setup.

through the quartz piston via a UV enhanced mirror in the piston extension onto the high-speed framing camera. In front of the camera two optical filters were mounted, a long-pass filter, GG385, to eliminate the laser scattering at 355 nm, and a short-pass filter with a cut-off wavelength at 500 nm to avoid interference from the remaining 532 nm laser light. A schematic of the experimental setup for the formaldehyde LIF measurements is shown in Figure 3. In Figure 4 the field-of-view of the camera is shown, and the dashed line corresponds to the area of the laser sheet.

In order to synchronize the engine with the laser/detection system the engine speed was kept constant at 1200 rpm, corresponding to a combustion cycle frequency of 10 Hz. This matches the overall repetition rate of the laser system. A pulse from a crank angle encoder was used to fire the laser system at the desired position.

The multi-YAG laser system was operated in double pulse mode, resulting in an energy of approximately 45 mJ per pulse at 355 nm. The time-separation between two consecutive images was kept constant at 70 μs, corresponding to 0.5 CAD (crank angle degree), throughout the measurements. In order to suppress the background radiation, the camera exposure time was set to 50 ns for each image acquisition. Due to one malfunctioning CCD module in the framing camera, only seven images were acquired in the present study.

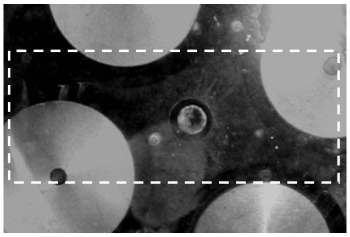

Figure 4. Image of the field-of-view. The dashed box show the LIF detection area, with dimensions 35 mm x 90 mm.

RESULTS

Seven pulse LIF sequences of the formaldehyde distribution within one stroke in the HCCI engine were recorded. The combustion development was studied in terms of the rate of formaldehyde formation and consumption for different load conditions, i.e. by varying the stoichiometry (lambda value). The formaldehyde formation occurs in the early low-temperature reactions (cool flame) of the ignition process, while the consumption is located at the early phase of the main heat release. The imaged region inside the combustion chamber corresponds to an area of 35 mm x 90 mm. To be able to subtract the undesired laser scattering from the formaldehyde LIF measurements, also images without combustion present were acquired. The fluorescence signal was approximately ten times stronger than the background level, providing a satisfactory signal-to-noise ratio. In order to compensate the LIF images for imperfections in the laser intensity profile, these profiles were also recorded [15]. This was done by recording LIF image sequences in a CAD range were the formaldehyde distribution was uniform, thus between the completion of the formaldehyde formation and the beginning of the consumption.

In Figure 5 image sequences of seven images showing the formaldehyde consumption within one cycle event for λ=4.5, λ=4.0, and λ=3.5, are presented. In the images the formaldehyde consumption can be followed within the main combustion process for the different running conditions. Regions where formaldehyde consumption has occurred appear dark, while bright regions indicate the presence of formaldehyde. From the images it is evident that the formaldehyde consumption becomes more rapid as the fuel mixture becomes richer. This is in agreement with traditional heat release analysis which shows an increased rate of heat release for richer mixtures. It can also be seen that the consumption process occurs at an earlier stage for fuel richer mixtures. From earlier experiments it is known that the ignition temperature decreases slightly with lambda. This implies that the combustion phasing becomes more advanced for richer mixtures if the inlet temperature is kept constant. The spatial structure of the formaldehyde distribution during the consumption phase looks quite similar to what was found in an earlier investigation using high-speed fuel tracer LIF [15], indicating that visualization of formaldehyde, under certain circumstances, can be an alternative to fuel tracer LIF. In that paper [15] it was shown how the combustion progressed through distributed reactions throughout the entire bulk volume and this without traditional flame front propagation. Supporting those results, the formaldehyde images also clearly show that the ignition occurs at multiple points simultaneously and as can be seen, also the consumption of formaldehyde is lacking normal flame propagation.

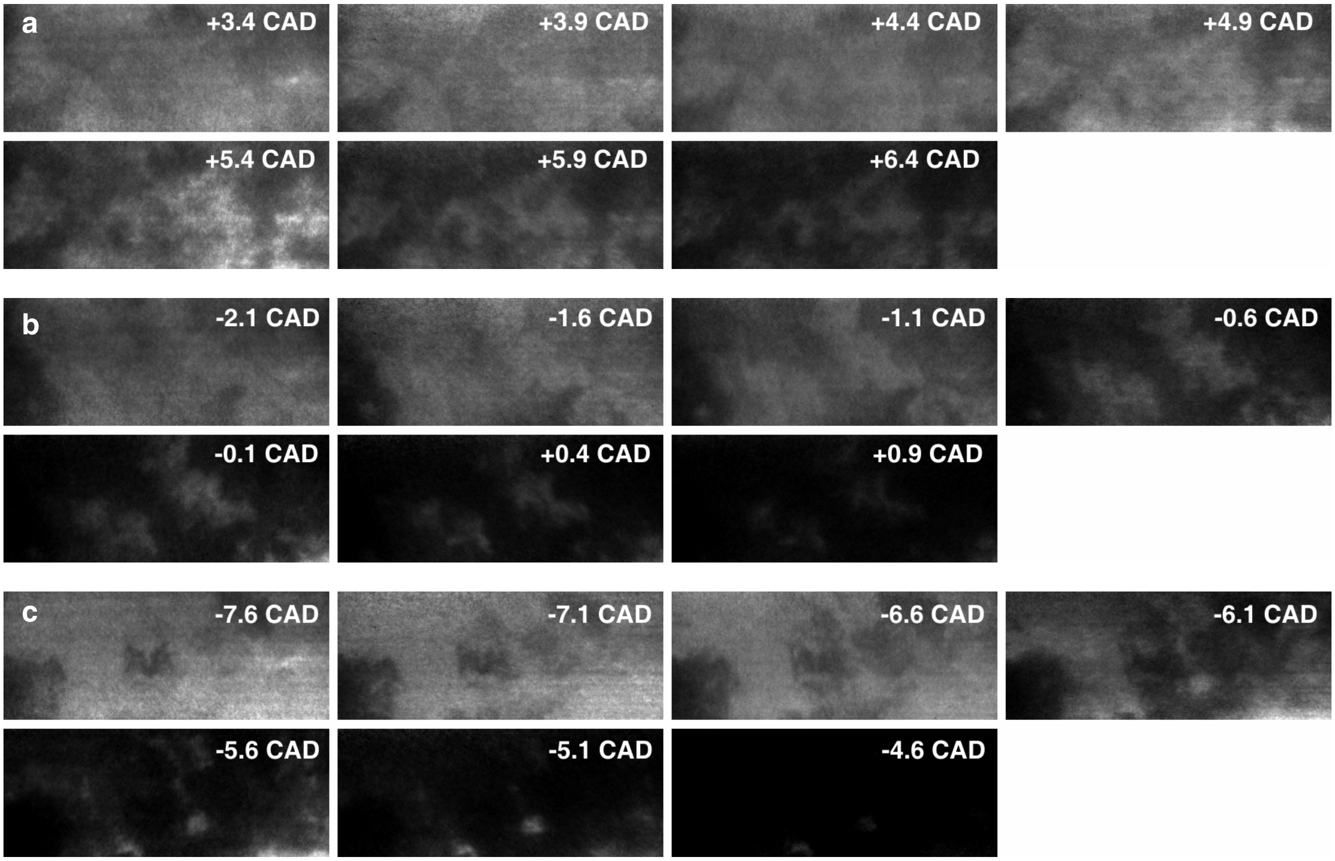

Figure 5. A sequence of seven single-shot PLIF images showing the formaldehyde consumption is depicted for each the three stoichiometries λ=4.5 (a), λ=4.0 (b), and λ=3.5 (c).

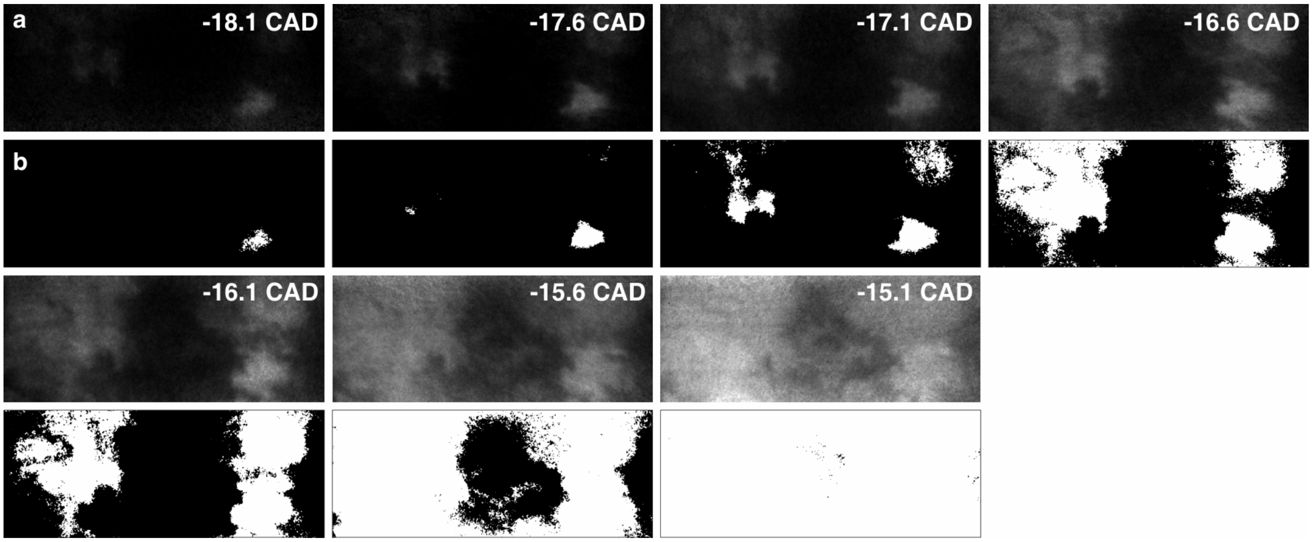

Figure 6. Binary images (b) were accomplished by applying a threshold to the grayscale images (a), marking image areas containing LIF signal as white, and leaving areas lacking signal as black. An example is shown for the formaldehyde formation running the engine at λ= 4.5.

For the purpose of studying the spatial distribution during formaldehyde formation and consumption in the engine, the surface fraction of LIF signal covering the imaged area was determined. To determine the surface fraction binary images, rather than grayscale images, are desired. Binary images were accomplished by applying a threshold to the grayscale images, marking image areas containing LIF signal as white, and leaving areas lacking signal as black. The threshold level was placed just above the noise level of the detector and equally set for all sequences evaluated. In Figure 6 an example is shown for the formaldehyde formation running the engine at λ=4.5. It should be noted that thresholding does not always provide a perfect representation of the signal areas in the images. However, even in the case of λ=4.5, which is the leanest mixture used in the present study and thus the formaldehyde LIF signal-to-noise ratio is the lowest, thresholding still gives an acceptable result.

To illustrate the cycle-to-cycle variations, the heat release traces from 25 independent cycles (black curves) and the corresponding mean heat release trace (white curve), are presented in Figure 7. As can be seen, the cycle-to-cycle variations are larger for the main heat release compared to the heat release of the cool flame, confirming the low temperature reactions to be more stable. These variations support the need for single-cycle studies of the formaldehyde formation and consumption processes.

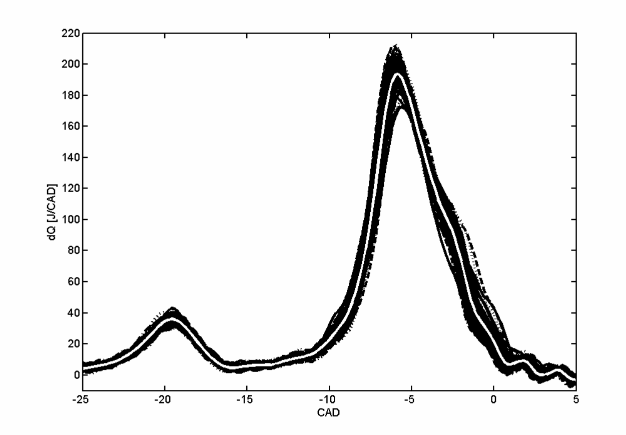

Figure 7. Heat release traces from 25 independent cycles (black curves) and the corresponding mean heat release trace (white curve) for λ=3.5.

In Figure 8 one can see how the phasing of the combustion changes with lambda. With increased amount of fuel the cool flame combustion phasing advances. Note that the duration for the cool flame seems to be constant for the different stoichiometries studied, thus independent of load. It is expected that the heat release rate during the cool flame increases, when additional fuel is injected. However, this effect can be seen only as a slight increase of the peak values in Figure 9. In spite of this, the amount of heat released during the cool flame period compared to the heat released during the main combustion is lower with higher load. The heat release for the main combustion advances and the rate of heat release increases with increasing amount of fuel. This can be explained by the faster kinetics following a more fuel-rich mixture. In addition, the greater amount of heat released in each cycle increases the cylinder temperature, thus advancing the combustion.

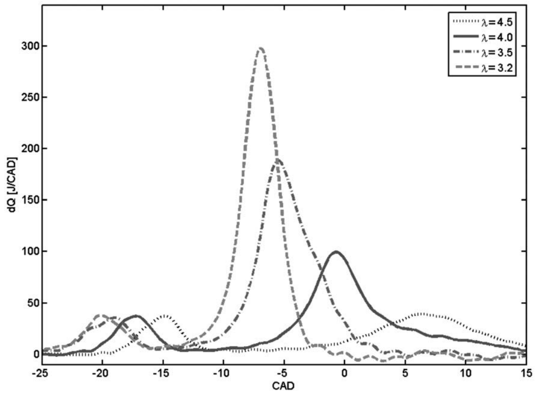

Figure 8. Mean heat release traces for the four different stoichiometries studied.

The binary images were integrated in order to determine the fraction of surface covered by formaldehyde signal. The cycle-resolved surface fraction was plotted together with the corresponding rate of heat release curve for each of the four stoichiometries studied. In Figure 9 this is shown for the formaldehyde formation. Figure 10 shows the cycle-resolved surface fractions and the corresponding heat release curves for the formaldehyde consumption. Cycle-to-cycle variations cause fluctuations in the formation/consumption phasing; hence the complete process is not always covered by the seven laser pulses. However, the variations are sufficiently small to not influence the mutual order of the curves for the stoichiometries studied.

As previously mentioned, the combustion phasing advances as the fuel/air-mixture becomes richer. As can be seen in the upper part of Figure 9, this yields for the formaldehyde formation as well. However, this is not the case for λ=3.2, since this condition is close to the fuel-rich limit of operation, and therefore instabilities in engine operation induces uncertainties in measurement data. Figure 9 also shows that the rate of formaldehyde formation increases for fuel-leaner stoichimometries. A probable cause could be that since the cool flame has a later phasing, the cylinder has reached a higher temperature at the start of the low-temperature reactions, resulting in a more rapid formaldehyde formation.

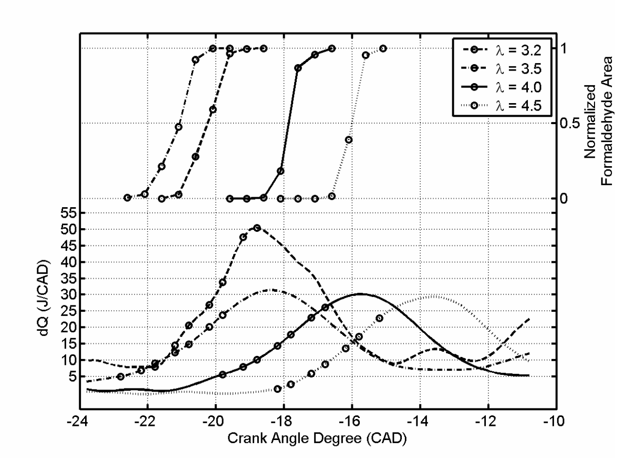

Figure 9. The cycle-resolved surface fraction acquired at formaldehyde formation is shown together with the corresponding rate of heat release curve for each of the four stoichiometries studied.

In Figure 10 it can be seen how the surface fraction with formaldehyde signal shrinks with increasing rate for lower lambda values. Earlier experiments performed with one image captured per engine cycle revealed similar trends. However, by employing high-speed single-cycle resolved measurements the averaging effect introduced by the jittering of the combustion phasing from cycle-to-cycle is avoided.

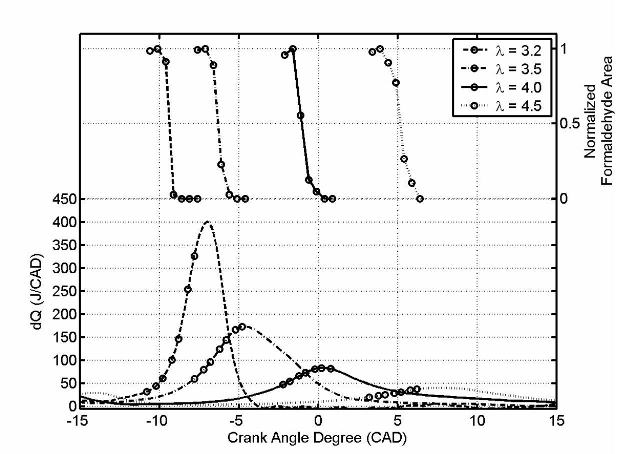

Figure 10. The cycle-resolved surface fraction acquired at formaldehyde consumption is shown together with the corresponding rate of heat release curve for each of the four stoichiometries studied.

SUMMARY AND CONCLUSION

1. Two-dimensional visualization showing the formation and consumption of formaldehyde was performed in an optical engine, within a single cycle, using a high speed PLIF system.

2. By utilizing high-speed diagnostics, the averaging effect introduced by cycle-to-cycle variations of combustion phasing could be avoided.

3. By resolving a single cycle event it could be verified that the formation and consumption of formaldehyde occurs gradually through distributed reactions. The phasing of these reactions varies for different parts of the combustion chamber, resulting in the heterogeneous structure.

4. The decay of the formaldehyde concentration is clearly more rapid for richer mixtures, whereas the duration in CAD's in which formaldehyde is being formed seems to be less dependent on stoichiometry.

5. The spatial structure of formaldehyde LIF recorded in the consumption phase show properties similar to that of fuel LIF. This strongly indicates that visualization of naturally occurring intermediates such as formaldehyde, under certain circumstances, can be an alternative to fuel tracer LIF. This is especially interesting when running heavier fuel fractions considering that no suitable tracers exist for this purpose.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CI	Compression Ignition
CO	Carbon monoxide
EGR	Exhaust Gas Recirculation
HC	HydroCarbons (unburned)
HCCI	Homogeneous Charge Compression Ignition
IMEP	Indicated Mean Effective Pressure
NO_X	The sum of nitrogen oxides
SI	Spark Ignition
λ	Relative air-fuel ratio