Studies of Flame Propagation in an SI-engine using Laser-induced Fluorescence of CH$_2$O

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ABSTRACT

Visualization of the unburnt fuel-air mixture has been performed in a spark-ignition engine using planar laser-induced fluorescence of formaldehyde. Formaldehyde (CH$_2$O) is naturally formed in the first stage of the two-stage ignition process in the end-gas, and the fluorescence was detected after excitation using the Nd:YAG-laser wavelength 355 nm. Thus the contour of the fluorescing area indicated the position of the flame front. The flame propagation was measured in each cycle by recording a fluorescence image from each of two subsequent laser pulses. The merits and limitations of this technique for engine applications are discussed.

INTRODUCTION

Still in the year 2003 the transportation sector relies heavily on the use of fossil fuels. During the last decades increasing concern has been raised regarding the fuel consumption and the emissions of combustion engines and the research have to face these aspects as well as the reliability, durability and overall performance of the engine.

In all combustion engine types the performance, fuel consumption and emission formation is strongly dependent on how the combustion process develops in time and space. In spark-ignition (SI) engines a flame kernel is formed emanating from the spark plug and propagating towards the cylinder walls. This flame propagation process is closely related to engine parameters such as fuel-air mixture and combustion chamber design, and can thus be regarded as an important link between these properties and engine performance.

Laser diagnostic methods [1] have during the last decades evolved as a powerful tool for measurements of both chemical and physical properties in the combustion chamber. For example, temperature measurements using Coherent Anti-Stokes Raman Spectroscopy (CARS) has proven to be very useful [2]. Laser-Induced Fluorescence (LIF) has been used both for visualization of radicals and of the fuel distribution by adding a suitable tracer element (see for example [3] and references therein). In laser-induced fluorescence, molecules are transferred to an excited state by incoming laser radiation. The molecules will very fast transfer back to the ground electronic state while emitting radiation – the fluorescence signal.

The addition of tracers introduces a potential source of error into the measurement situation because the combustion process may be affected. By probing a naturally occurring species this uncertainty can be circumvented. Many radicals are present at different stages and at different locations during the combustion process and some of these radicals, such as OH,
have often been used as a flame front marker. Another naturally occurring species is formaldehyde (CH$_2$O) that is formed in the unburnt mixture during the so called cool-flame chemistry that foregoes the real combustion. Since formaldehyde then is consumed, the presence of this species indicates unburnt areas of the combustion chamber. Formaldehyde and other species formed in the cool-flame region have also been used to detect self-ignition centers [4-6] – a process that may lead to engine knock.

In this work we have studied the flame propagation by using a double laser and camera setup and recording two images of the formaldehyde distribution during each engine cycle.

**EXPERIMENTAL SETUP**

Two Nd:YAG lasers were used for excitation of formaldehyde at the wavelength of 355 nm. The beams were shaped to 4 cm wide sheets using cylindrical lenses and led through a quartz ring situated at the top of the cylinder wall of the port-injected AVL 5411 single-cylinder research engine. This is illustrated in Fig. 1a. The signals were detected perpendicular to the incoming laser sheets through a piston window via an aluminium mirror located below the piston. In Fig. 1b the view through the quartz window in the hollow piston is shown and the details of the pent-roof combustion chamber is evident. The observable area was 65 mm in diameter as opposed to the bore at 83 mm. This comes from the fact that the cylinder is hollow and its steel walls partially block the view.

![Fig. 1](image)

*Fig. 1  a) Experimental setup. b) The view through the piston window.*

The fluorescence images were captured on two separate ICCD cameras by separating the signal using a beam splitter. Two long pass filters (GG385) were used to suppress the laser wavelength. The pulse energy was 70 mJ for both lasers. The fuel consisted of a mixture of n-heptane and iso-octane (RON 60) and the engine was run at a constant speed of 1200 rpm. One advantage of the system was that the two laser-detector setups were triggered independently. This enabled us to choose time separation between recorded images arbitrarily. For measurements of flame propagation we decided to use the separation 1.5 CAD, which corresponded to 200 $\mu$s.

**RESULTS**

An example from a measurement series is shown in Fig. 2. The white areas are formaldehyde signal from the unburned fuel-air mixture and the dark ones correspond to the areas where the flame already have passed and consumed the formaldehyde. These images were captured at -2CAD and -0.5CAD, respectively, as indicated in the corresponding pressure trace.
Fig. 2  a and b) Laser-induced fluorescence images of formaldehyde (white areas) in the AVL engine. c) Pressure trace for the cycle shown together with the time positions where the images were recorded. The oscillations that are observed to start at +3CAD indicate the engine knock phenomenon.

The LIF signal was studied spectrally using a spectrometer, and formaldehyde peaks were identified. The spectra looked similar to those presented in previous studies in the same engine [7], and it cannot be ruled out that other molecules formed in the cool-flame chemistry contribute to the detected signals.

From image pairs such as the ones presented in Fig. 2 the average flame propagation velocity can be estimated. By using a contour recognition program and subsequently also a routine that calculates the distance between points in the two contours, the flame velocity field can be calculated. This is illustrated in Fig. 3 for the image pair in Fig. 2.

Fig. 3  The contours of the image pair from Fig. 2 along with parts of the calculated velocity field.

Using the treatment discussed above the average flame speed in the illustrated region was found to be ~15 m/s. Of course this assumes the third dimension (the height of the combustion chamber) to give negligible contribution to the velocity. Since a pent-roof design was used, this must not necessarily be true. However, near the edges where the formaldehyde signal most often appeared, the height of the chamber is much less than in the middle regions and the approximation of two-dimensional flame propagation is believed to be sufficient. Unfortunately the possibility of studying cycle-to-cycle variations for stable operating conditions was limited in the present measurements since the engine temperature increased during operation.
DISCUSSION

The main advantages of using formaldehyde as a flame front indicator are that it is a natural intermediate species and that it is conveniently excited using the third harmonic of an ordinary Nd:YAG laser at the wavelength 355 nm [7]. Drawbacks are that formaldehyde only is present in large enough quantities to be detected if the temperature and pressure is sufficiently high for its formation. This prevents detection of flame propagation early in the cycles. It should also be noted that the formaldehyde signals obtained during our experiments showed very good signal strength despite the fact that the wavelength 355 nm is not the optimum choice to get a strong absorption in formaldehyde.

The use of formaldehyde as a flame front marker was compared with the added fuel tracer 3-pentanone excited at the laser wavelength 266 nm. The tests showed that the signal-to-noise ratio was lower for the 3-pentanone images when using equal pulse energy in the beams. It was also found that the structures in the 3-pentanone images and the formaldehyde images coincided when the laser-detector systems were used with no time separation.

To summarize, in this work laser-induced fluorescence has been used to study flame propagation in an optical SI-engine with a real geometry pent-roof design. Species formed during the cool flame chemistry, among them formaldehyde, were probed, thus acting as a marker of the unburnt gas regions. The dual laser and detector setup made it possible to record two images with arbitrary time separation from which the flame propagation velocity could be calculated. The standard laser wavelengths used simplified the setup, and the signal-to-noise ratio was good using laser pulse energies around 70 mJ.

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REFERENCES