LIF Laser Scanning with pent roof illumination to Investigate Mixture Distribution in IC Engines with limited Optical Access

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ABSTRACT

Modern IC engines are realized with direct fuel injection, so the mixture formation takes place in the cylinder. Optical accessible engines allow a detailed investigation of the injection and mixture formation process. The measurement technique which is presented in this work is the tracer based Laser-induced fluorescence, which allows to quantify the air-fuel equivalence ratio in the engine. With this technique, only a single plane, which is illuminated by a lightsheet, is investigated. The new approach which is presented in this work is the Lightsheet scanning technique. To realize this approach the lightsheet is shifted laterally and several planes in the cylinder can be investigated. The focus in this work is to estimate the maximal cylinder which can be measured with this principle. Additionally, this idea is combined with a modified optical setup for the lightsheet forming to illuminate the pentroof through the glass ring without using a piston window. Different optical setups are studied to realize the best possible illumination of the pentroof. The chosen setup which was used finally is combined with the lightsheet scanning setup and used for the experiments. To align the optical setup fast and reliable to the different measurement planes, all relevant parts, lenses, mirror and camera, are mounted on electrically driven linear stages.

The engine measurement results show the successful application of the developed method. In detail, two engine operating points are investigated and only the water temperature is varied. The method enables the reconstruction of any cross-sections, so that the spray targeting during the injection is shown in detail and differences between the two operating points are identified. The quality and progress of the mixture formation is evaluated by the uniformity index, which is calculated from every recorded plane. Additionally, the air-fuel ratio is also averaged over every plane and displayed over the crank angle to verify the results.

1. Introduction

Modern IC Engines usually have direct fuel injection and in cylinder mixture formation. The injection and mixture formation are the initial processes that directly influence the combustion and the resulting emissions. An appropriate procedure to investigate the mixture formation is the tracer based Laser-Induced fluorescence to determine the air-fuel equivalence ratio $\lambda$, usually carried out in optical engines with glass ring and piston window. The disadvantages are low possible loads and different heat transfer compared to production engines. Another approach is
to equip a normal engine with endoscopic access which goes along with limited optical access (Goschütz et al. 2015).

A possible trade-off between these two concepts is an optical engine without an elongated piston, only equipped with a glass ring. To enhance the measurement area with this setup, a modified laser lightsheet method with a larger field of view is presented. The LSS method makes use of measuring the fuel distribution in multiple planes and is based on the laser induced fluorescence (LIF). Due to a tomographic evaluation it enables the detection of the spray propagation and mixture formation process, not only for a single plane, but for an extensive, three-dimensional part of the cylinder volume (Fig. 3) (Heldmann (2013), Welss (2015)). The modification is done in the optical setup which enables the illumination of the pentroof through the glass ring. Different optical setups are evaluated to get the best measurement result. The chosen setup is used for a study to compare two different operating points with different engine temperatures. Especially the injection and the mixture formation process are investigated.

2. Experimental setup

The LIF measurement technique is based on the excitation of molecules to a higher energy level due to the absorption of photons. One possibility to leave this excited state, is the emission of a photon (fluorescence). The resulting LIF signal is dependent on pressure, temperature and the concentration of the active species. In the experiments presented a combination of the non-fluorescent model fuel isoctane and the fluorescent tracer Triethylamine (TEA) enables the quantitative determination of the air-fuel equivalence ratio $\lambda$ in a transparent engine using an appropriate procedure described in (Fröba (1998) and Mederer (2013)). The investigations are carried out on an optically accessible engine with direct injection and spark plug ignition. For the optical access, the elongated and slotted piston is equipped with a quartz glass window. Additionally, the upper 40 mm of the cylinder are built of a quartz glass ring. Fig. 1 shows the Assembly of the optical engine. The characteristics of the engine are based on the BMW “Prince” engine with gasoline direct injection and turbocharging. This setup of the transparent engine allows investigations of mixture formation with a vertical laser light sheet and recording through the glass ring and a horizontal light sheet, acquiring the images through the piston window and a mirror (Fig. 1). For the results presented which are presented in this work, only experiments with a vertical light sheet are done.
The optical setup for the LIF measurements with a vertical laser light sheet is shown in Fig. 2. The light source is a KrF excimer laser with 248 nm wavelength. The laser emits a beam of a rectangle profile with a height to width ratio of 0.5. The beam is guided by three mirrors and is shaped by a Kepler telescope containing two cylindrical lenses with focal lengths of $f=250$ mm and $f=328$ mm. The next two mirrors align the light sheet vertically to the combustion chamber. To focus the lightsheet in the center of the cylinder, a cylindrical lens with $f=750$ mm is used. The setup of the optical components produces a thin light sheet and illuminates a defined plane in the combustion chamber. The camera is orientated perpendicular to the incoming lightsheet. To realize in addition the pent roof illumination, the optical setup is changed. The detailed configuration for the pentroof illumination is described later in detail. To combine LightSheet Scanning and the pentroof Illumination, the optical setup is mounted on electrically driven motor stages which enable a fast and reliable adjustment of the laser lightsheet.
First results of the lightsheet scanning method (LSS) were published (Welss and Bornschlegel (2015)). Objective of this work is to enlarge the measurement volume for the method and the illumination of the pentroof. The width of the measurement volume normal to the vertical planes Fig. 3 in is 25 mm to 30 mm (Welss and Bornschlegel (2015) Welss and Mederer (2015)). The modified setup allows a width of 50 mm for a cylinder bore of 77 mm and therefore to acquire the mixture distribution in about 35 % of the 399 cm³ cylinder stroke volume.

Fig. 4 shows clearly the benefit of the LSS method. The cylinder midplane (right, Fig. 4) gives only few information about the targeting of the used injector. With the calculated cross-section (left, Fig. 4) the targeting information can be extracted clearly.
3. **Pentroof illumination**

To realize the pentroof illumination and to find an ideal configuration for the optical setup, the raytracing tool SMARTOPTICS in CREO 3.0 was used. The selected setup is shown in Fig. 5 in the center. The laser beam is divided in two single beams with a 50/50 % beam splitter. The two resulting beams are directed towards the engine once upon the other. The upper beam guided horizontally to illuminate the engine the ordinary way. The lower beam is guided over two mirrors to the pent roof area. The additional lens with a focal length of $f=208$ mm next to the mirrors diffuses the light sheet, so that whole pentroof is illuminated.

![Fig. 5 different Optical setups for pent roof illumination (CAD Drawing)](image)

Fig. 6 shows the resulting pictures with homogeneous fuel mixture in the combustion chamber excited by the laser with the optical setups from Fig. 5. The setup chosen for the experiments is concept two. Compared to the concept with only two beams and one mirror (1, Fig. 5) it enables illumination of the complete combustion chamber. The concept with only one beam and one mirror (3, Fig. 5) would also give a complete view of the engine if a lens with a short focal length of $f=50$ mm is used. Due to the short focal length, the resulting picture shows very low intensity
in the boundary area due to the scattered beam. For concept two, the two laser beams are clearly recognizable and deliver sufficient illumination intensity for the whole combustion chamber.

Fig. 6. Homogeneous Images in the combustion chamber, realized with the optical setups of Fig. 5

The resulting images of concept one and two for the mixture formation process are shown in Fig. 7 for a crankangle position of 40° CA BTDC. Compared to the shown image without pentroof illumination additional information can be gained in the spark plug area shortly before spark timing. The mixture formation can be investigated until 40° CA BTDC. The image shows a very good contrast and a complete view of the mixture composition in the combustion chamber.

Fig. 7 resulting images for the different optical setups, recorded at 40° CA BTDC
4. **Lightsheet Scanning measurement area**

Another objective beside the pentroof illumination was the determination of the possible measurement area for the lightsheet Scanning. When the lightsheet is shifted from the center, it does not impact normal to the Glass ring surface and is refracted. To evaluate the refraction and the position of the single lightsheets in the Glass ring, also the raytracing with SMARTOPTICS was used. Fig. 8, (left) shows the progress of the incoming laser beams depending to the offset to the center. The beams show a sloping progress in the glassring to the outside with increasing offset.

![Fig. 8 deviation through refraction of the laser beam (left), View from the camera through the glass ring](image)

The effect that the beams are diverging is also recognizable in the resulting pictures because of the refraction in the ring (Fig. 8 (right)). The result is that the images are distorted on the left and right edge. Fig. 9 (left) shows the plane far from the camera. Its picture size is equal to the drawn contour. The image Fig. 9 (right) shows the plane far from the camera. Its picture size is equal to the drawn contour. The image Fig. 9 (right) should have the same width as the left picture. But it is enlarged on the left and right edge. Fig. 8 (right) shows the refraction to the camera which causes the enlargement of the images acquired near to the camera.

![Fig. 9 resulting images of LSS with pentroof illumination](image)
5. Engine measurements

Table 2 shows the essential operating parameters of the investigated operating points at an engine speed of 1200 rpm. Start of injection and start of ignition were constant. The air mass flow is set to 5.9 kg/h for all OP’s. The engine was run with a stoichiometric equivalence ratio, therefore the injection timing is varied due to the different injector properties.

Both OP’s are recorded with a crank angle section from 220° - 200° BTDC in steps of 2° CA for the fuel injection and 200° - 40° BTDC with 10 °CA steps for the mixture formation. To realize the LSS method the mixture distribution was acquired in eleven planes with a distance of 5 mm. For each plane the mixture distribution was measured in 5 succeeding engine cycles and the results from the different cycles were averaged. For OP 1 the water temperature was set to 70°C and for OP2 for 45°C. Objective of this experiment is to show the ability of the LSS method to identify the spray targeting and the progress of the mixture formation. The other engine parameters used are shown in Table 1.

<table>
<thead>
<tr>
<th>Description</th>
<th>OP 1</th>
<th>OP 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine speed</td>
<td>1200 rpm</td>
<td>1200 rpm</td>
</tr>
<tr>
<td>Injection pressure</td>
<td>150 bar</td>
<td>150 bar</td>
</tr>
<tr>
<td>IMEP</td>
<td>~ 2.5 bar</td>
<td>~ 2.5 bar</td>
</tr>
<tr>
<td>Start of injection (SOI)</td>
<td>220 °CA BTDC</td>
<td>220 °CA BTDC</td>
</tr>
<tr>
<td>Equivalence ratio</td>
<td>λ = 1</td>
<td>λ = 1</td>
</tr>
<tr>
<td>Ignition</td>
<td>18 °CA BTDC</td>
<td>18 °CA BTDC</td>
</tr>
<tr>
<td>Range of LIF images</td>
<td>220 °CA to 40 °CA BTDC</td>
<td>220 °CA to 40 °CA BTDC</td>
</tr>
<tr>
<td>Water temperature</td>
<td>70°C</td>
<td>45°C</td>
</tr>
<tr>
<td>Number of planes</td>
<td>p = 11 planes, 5 mm distance, 50 mm total</td>
<td>p = 11 planes, 5 mm distance, 50 mm total</td>
</tr>
</tbody>
</table>

Fig. 9 and 11 show a comparison of the injection process for the two OPs. The LSS method gives the opportunity to calculate the spray targeting in different cross-sections. Four different cross-sections for each OP at a selected crankangle position of 214 °CA BTDC are presented. The images show the principal capability of the LSS method to reconstruct the spray targeting inside the optical engine for different views. Due to the recording of eleven planes the height of the cross-section is 50 mm, compared to 25 or 30 mm in former experiments. It is recognizable that the whole spray is visible in the cross-section.
By comparing the Injection of the two operating points, two main parameters are identified: The spray cone angle and the penetration depth. The cold engine has a wider spray cone angle than the warm engine. The penetration depth for OP2 is slightly lower than for OP1.
All cross section views show lower intensities on the lower side. At least a part of this is an effect of the experimental setup, as the images were detected from the top side which is closer to the camera. This is why a lower signal intensity due to signal extinction effects of the LIF signal by liquid phase fuel appears on the lower side (Welss and Bornschlegel (2015)). This effect can be eliminated by using two cameras for the image acquisition (Heldmann et. al (2013)). In the mixture formation process, when the fuel is evaporated, no effect of signal extinction is recognizable.

The quality and progress of the mixture formation is shown in Fig. 12 with the uniformity index displayed over crank angle. The principle and calculation of the uniformity index is described in Mederer et. al (2013). Equation (1) shows the calculation for the uniformity index. Where \( n \) represents the number of pixels and \( p \) the number of measurement planes which are recorded. So, one uniformity graph is averaged over eleven images. Both operating points deliver a good mixture formation, almost with the same progress. At the end at 50° CA both points show an equivalent homogenization.

\[
\gamma = \sum_{i}^{p} \left( 1 - \frac{\sum_{i=1}^{n} A_i \cdot \sqrt{(\lambda_i - \bar{\lambda})^2}}{2 \sum_{i=1}^{n} (A_i \cdot \bar{\lambda})} \right) / p \tag{1}
\]

![Mixture formation uniformity index](image)

**Fig. 12** Uniformity index for OP1 and OP2

To evaluate the air-fuel ratio Fig. 13 shows the averaged AFR over all planes over crank angle. The calculation is done by (2). At the end both operating points show a stoichiometric mixture. In the beginning of the mixture formation the air fuel mixture disappears out of the
measurement volume due to the tumble charge motion and causes the high AFR ratio values. If the Piston moves towards TDC, the whole cylinder charge is located in the measurement area, and equals to AFR 1.

\[
\gamma = \sum_{i=1}^{n} \frac{\sum_{i=1}^{n} \lambda_i}{n} / p \quad (2)
\]

![Mixture formation AFR averaged](image)

**Fig. 13** Averaged AFR over crank angle

### 6. Conclusion

This work shows the successful application of the LSS method to investigate the injection and mixture formation process. This process enables a volume reconstruction and the calculation of several horizontal or vertical planes. Furthermore, the pent roof illumination represents a promising concept to enlarge the measurement area. By combining the LSS method with the setup of the pent roof illumination, a very large and relevant area of the cylinder volume is considered.

For future work, there are several interesting concepts depending on the intended use. It is possible to transfer this setup to determine the temperature distribution in the engine with appropriate tracers and light sources (Lind et. al). As well, the Method enables a complete view of the spray propagation in the engine. So the interaction with the charge motion represents a very useful approach because spray measurements from constant volume chambers can be connected with investigations in the engine.
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References