Applications of the LIF-method for the diagnostics of the combustion process of gas-IC-engines

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Within the underlying project the task was to develop methods for optical measurements in a hydrogen fueled engine with direct-injection with the goal of measuring the jet-patterns during injection, the stratification of the charge at ignition point and the propagation of the flame during combustion. Therefore the method of planar laser-induced-fluorescence (PLIF) was chosen. In order to apply this technique for the named tasks, particular methods for visualising the fuel and the flame front were developed.

The measurements were carried out on a single-cylinder research-engine installed at the Institute for Internal Combustion Engines at Graz University of Technology. This engine features optical access through a quartz-glass liner and a window in the piston while providing a layout equivalent to modern passenger-car engines and the possibility to operate in fired mode.

As it is hardly conceivable to directly excite hydrogen molecules by means of laser light it is necessary to add a tracer substance to the fuel that provides high fluorescence intensity while not changing the properties of the fuel. Consequently Triethylamine was chosen as a tracer to be mixed to hydrogen at 200 ppm, which allows it to be used up to a maximum pressure of 200 bar while still providing a strong LIF-signal. Due to the excellent linearity of the signal to the local air/fuel-ratio it was possible to develop a method for the calibration of the images in order to compensate for inhomogeneities of the laser beam and staining of the optical access and ultimately allow a quantification of the fuel distribution. The results are images scaled on air/fuel-ratio which can be used for a direct optimisation of mixture formation processes and the validation of CFD-models.

For the analysis of the combustion process the method was adapted with two different approaches. For homogeneous charges a new method was applied by marking the flame front using the tracer within the fuel, so both are burned together. However, as this method is limited to measurements with a homogeneous distribution of tracer within the measured volume an alternative technique was applied for the measurement of stratified charges. In this case a direct visualisation of the flame front was achieved by exciting the OH-radicals formed during combustion. As this method has significantly increased demands on measuring equipment and is more time consuming, both methods are used in parallel on specific measuring tasks.

1 Introduction

To everybody involved in transportation technology one of the greatest challenges for the future is the development of new propulsion systems which are free of the negative environmental effects of today's concepts. One of the proposed solutions is the development of internal combustion engines for the use with gaseous fuels as a clean alternative. The highest potential is attributed to a configuration wherein hydrogen is injected directly into the combustion chamber, giving a whole new set of possibilities for the optimisation of the combustion process. As a consequence in 2002 a cooperation was started between the Institute for Internal Combustion Engines and Thermodynamics at TU Graz and BMW Group Research and Technology to investigate new combustion systems for hydrogen with high-pressure direct-injection (Wimmer et al. 2005). The goal is to develop a drivetrain with zero-impact on the environment, higher specific output than today's gasoline engines and at least equal efficiency compared to modern diesel engines. First tests at TU Graz with a single-cylinder research engine have already shown the high potential of this concept (Wallner 2004). At the same time this requires a deeper understanding of the in-cylinder processes – which can not be easily obtained by CFD-simulation especially in the case of supercritical injection of hydrogen (Kovac et al. 2005) – leading to the need for sophisticated measuring techniques. In which way this task can be fulfilled by the means of laser-optical methods is the focus of this article.

2 Applied measurement technique

Different applications of planar laser-induced fluorescence (PLIF) are established techniques in combustion research by now, but due to their high complexity and costs they are seldom used as standard methods in the development of new engine concepts. For the development of complex combustion systems though, no other method can deliver as much insight into the processes going on within the combustion chamber. The results derived from these optical methods are invaluable especially under conditions where little experience is available yet – as it is with combustion engines with hydrogen high-pressure direct-injection.

Depending on the application the molecules used for fluorescence may be the substance investigated itself or a marker mixed to the main substance, the so called tracer. In the first case it is necessary to set up the laser for the exact excitation wavelength for a specific energy transition of the investigated molecule. Therefore a complex laser system is required which can deliver high pulse energies within a very small band of wavelengths. Most laser systems are capable of producing discrete wavelengths only, thus limiting the choice of excitable molecules. Additional factors like the availability of components and the applicability on the engine test bench lead to further limitations.

2.1 Tracer-LIF in the hydrogen engine

For these reasons the method commonly used for measuring the fuel distribution is the so-called Tracer-LIF. The choice of a suitable tracer substance has to be based on optical and physical criterions. A crucial precondition is a good excitability, preferably by broadband laser light, which implies the existence of numerous energy transitions within a narrow spectral range. Therefore large branched molecules are often used as tracers. At the same time the physical and especially the transport properties of the tracer should be similar to the substance investigated to avoid demixing.

In the case of hydrogen these two demands are contradictory as no molecule exists with a branched structure and a molecular weight anywhere near that of the hydrogen molecule. Therefore the optical properties of the tracer have to be given priority to allow LIF-measurements.

A further prerequisite for the applicability with high-pressure direct-injection is the possibility to mix the tracer with the main substance over the whole pressure range. In the case of hydrogen this results in a very low concentration of the tracer, so that the partial pressure is always low enough to keep the tracer in gaseous state under all conditions. On the other hand the intensity of the fluorescence signal has to be strong enough to provide sufficient information for a quantification of the results. Based on theoretical considerations and on published information Triethylamine (TEA) was chosen as the tracer for hydrogen (Blotevogel et al. 2003). It was already shown in previous investigations that no noteworthy demixing can be observed (Blotevogel et al. 2005). The excitation by laser light can be realized by using light at a wavelength of 248 nm, thus permitting the use of a KrF-Excimerlaser in combination with this tracer. The fluorescence can be observed in a wavelength range centered at approximately 300 nm (Fröba et al. 1998).

For the applicability of the tracer on mixture formation it is necessary to beforehand investigate on the dependency of the signal strength on the fuel concentration. The fluorescence intensity is primarily dependent on constant factors (laser intensity I_n, Einstein coefficients A, B), and on factors defining the absorption and emission of energy, namely the concentration of active substances (n_{fuel}) and substances involved in quenching processes, which is mainly oxygen (n_{O_2}). The subsequent equation can be written as follows (Reboux et al. 1994):

$$I_{LIF} \approx N_1^0 B_{12} I_n \frac{A_{21}}{a n_{O_2}} \approx b \frac{B_{12} I_n A_{21} n_{fuel}}{n_{O_2}} \quad (1)$$

Provided that the calibration process is carried out under the same boundary conditions as the measurements the constant factors can be neglected, thus leading to the following dependency:

$$I_{LIF} \approx \frac{n_{fuel}}{n_{O_2}} \approx \Phi \approx l^{-1} \quad (2)$$

where Φ is the equivalence ratio and l the air/fuel-ratio, both being factors generally used to describe mixture formation within combustion engines. Therefore the results achieved when employing this method can be directly used in the development of combustion processes.

These theoretical findings also were confirmed by experiments on the optical engine (Figure 1). The measurement series was conducted with helium to allow high concentrations of the measured gas under safe operating conditions. The results were converted to correspondent concentrations of hydrogen and subsequently to equivalence ratios.

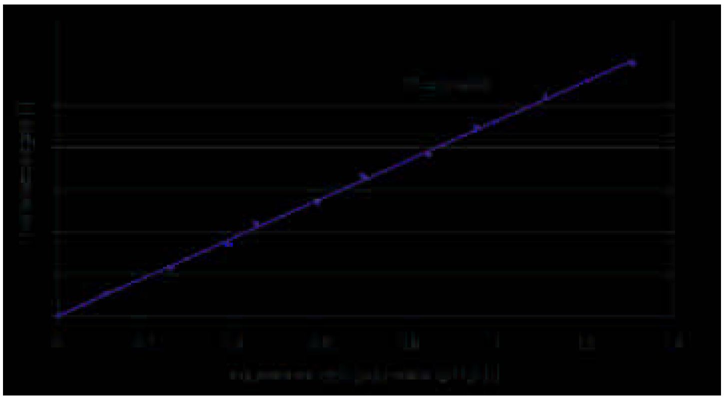

Figure 1: linear correlation of fuel/air-ratio to light intensity

The concept for the quantification of mixture formation measurements derives directly from these findings, as the excellent linearity allows the application of a calibration routine for the complete measured area. This is done by using port injection to produce a homogeneous charge inside the combustion chamber with a defined equivalence ratio. This delivers a value for light-intensity/equivalence-ratio which allows the creation of a calibration line for each pixel. To compensate for the influence of pressure completely and the influence of temperature at least partly it is necessary to perform this calibration for each measured crank angle. Additionally, for each crank angle also a background image is taken to eliminate noise of the camera system and unwanted reflection and fluorescence phenomena.

Yet another application of the Tracer-LIF method can be found in the field of combustion process analysis. As the Tracer consists of hydrocarbons it burns together with the hydrogen, which allows the definition of a burnt and an unburnt zone. The precondition for this method is a homogeneous distribution of tracer within the combustion chamber at ignition point, but this can not be achieved for all operating points when keeping in mind that the tracer is added to the fuel. Another limitation of this method is the uncertainty whether or not the tracer burns at the same time as the hydrogen, which could possibly lead to inaccuracies in defining the flame front.

2.2 Selective LIF-methods for the detection of minor species

The direct visualization of specific molecules or radicals is made possible by means of selective LIF-techniques. These methods are especially viable for the detection of the flame front, which can be carried out by exciting minor species like formaldehyde or the hydroxyl-radical.

The energy transitions of OH which are used for these investigations are in the A-X (3,0) band system which can be covered by a tunable KrF-excimer laser. The use of this energy transition system is described as laser-induced predissociative fluorescence, as some of the energy of the excited state is lost in predissociation of the molecules. However, this method avoids the loss of energy due to quenching and thus yields a higher fluorescence intensity especially at higher pressures. Thus this technique is favorable for measurements under engine conditions and can also be used for quantified measurements of OH (Andresen et al. 1990). The applicability of this method in a similar measurement layout has already been shown in several publications dealing with the measurement of flames in combustion engines (Andresen et al. 1992) and even the measurements of turbulent structure in flames (Chen and Mansour, 1999).

As it is not possible to directly set the laser used for these investigations to a defined wavelength, it is necessary to perform a scan of wavelengths on a reference flame in order to receive an intensity spectrum for the excitation of the OH-radical. This laser spectrum then can be brought into accordance to a spectrum which was simulated with the software LIFBase 2.0, thus allowing a correlation between laser position and wavelength (Figure 2).

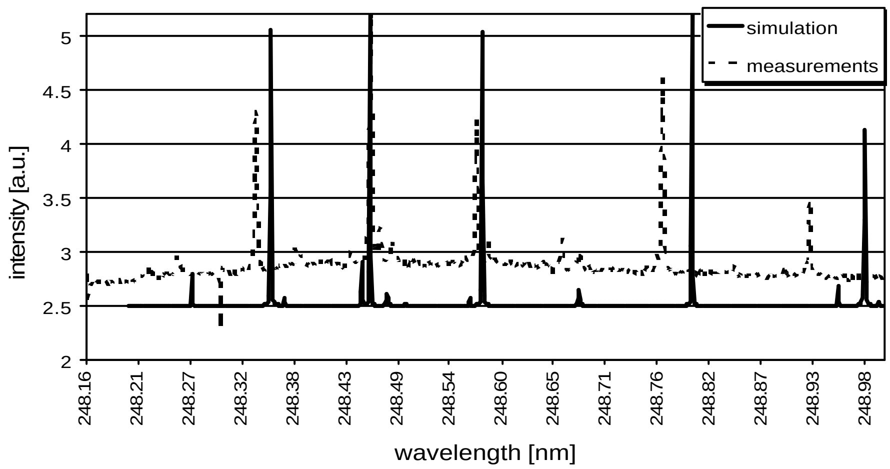

Figure 2: Simulated (LIFBase) and measured LIF-excitation spectrum of the OH-radical

Some differences between those two spectra can be observed which can be attributed to a non-linear behavior of the laser tuning unit. Even though the best signal intensity under ambient conditions is observed at 248.46 nm, for the investigations on combustion inside the engine the laser wavelength was set to 248.35 nm, which corresponds to the A-X (3,0) Q_1 (11) transition (Andresen et al. 1992), which delivered the best results under engine conditions.

3 Experimental setup

3.1 Optical engine

The investigations are carried out on a single-cylinder research engine which allows optical access through a glass cylinder located below the cylinder head and through a window in the piston. The glass cylinder has a minimum height of 44 mm and thus allows insight into the upper half of the combustion chamber. The glass cylinder is formed according to the contour of the pent-roof to achieve full visibility of the area around the spark plug and the injector tip (Figure 3). Due to its thickness of 18 mm peak cylinder pressures of up to 60 bar can be realized, thus allowing realistic operating points in fired mode.

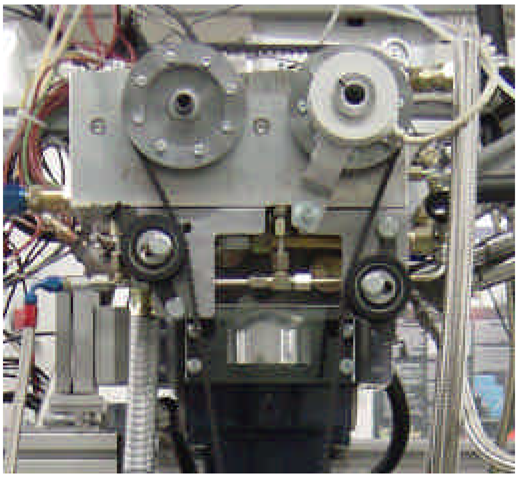

Figure 3: Single-cylinder research engine with optical access into the combustion chamber

3.2 Beam path

In order to achieve an optimized illumination of the combustion chamber for each crank angle it is necessary to split the laser beam into two separate beams. In the configuration currently used one beam passes through the glass ring, the other through the window in the piston. The two beams are expanded in one direction and aligned in order to form a vertical light sheet incorporating the cylinder axis and perpendicular to the crank axle. The plane illuminated includes the two injector positions (central and side) and the spark plug. The complete beam path is shown in Figure 4.

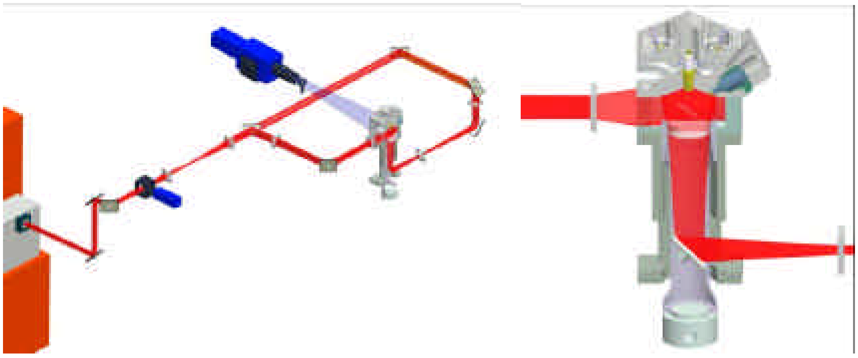

Figure 4: Beam path of LIF-measuring system

3.2.1 Laser

The investigations were carried out employing an excimer laser system by Lambda Physik, model Compex 150T. With its special layout incorporating two separate laser tubes (oscillator and amplifier) it is capable of providing laser light with a very narrow bandwidth of < 3 pm within a range of 0.8 nm – a precondition for the suitability for selective LIF methods. When using the amplifier tube only it is possible to produce UV laser light with maximum pulse energies of more than 400 mJ, which allow the efficient use of the laser for Tracer-LIF techniques. The layout of the system is shown in Figure 5.

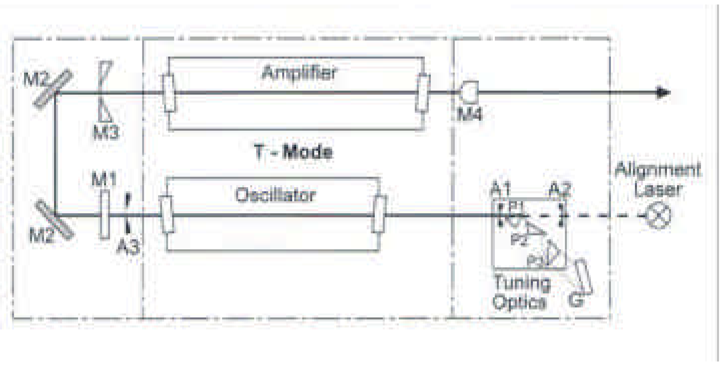

Figure 5: Layout Compex 150T

The angle of the grating (G) within the tuning optics is varied by means of setting a step motor position and therefore can not be directly set for a certain wavelength. Therefore and due to a certain sensitivity of the tuning optics to ambient conditions it is necessary to regularly perform a wavelength calibration for narrowband operation.

3.2.2 Camera

The camera system utilized for the measurements is a modular system by LaVision, consisting of a cooled CCD-camera (model Imager 3s) and an image intensifier (model IRO). The maximum resolution is 1280x1024 pixel but for LIF measurements the camera is used with 2x2 binning to increase signal strength and frame rate. The quantum efficiency of the intensifier is approx. 15 % at 300 nm. A bandpass filter (307±25 nm) is installed in front of the camera for blocking unwanted scattered light and reducing chemiluminiscence deriving from the combustion. To further reduce noise the exposure time of the image intensifier is set to 200 ns.

3.2.3 Reference burner

In order to be able to perform calibration scans without the necessity of running the engine in fired mode a reference burner is installed within the beam path. The burner is fed with hydrogen and oxygen to achieve high temperatures within the flame at atmospheric pressure.

4 Application inside the hydrogen engine

4.1 Investigation on jet patterns

Due to its effects on the whole mixture formation and consequently the combustion process it is vital to understand the behavior of the fuel at the outlet of the injector nozzle. In this case it is not necessary to calibrate the images, as in this first phase of the injection there are hardly any mixing processes within the jet. On the other hand these measurements require an increased resolution of the image, which can only be achieved by reducing the investigated area, i.e. by moving the camera towards the measured volume. Additionally the increment of the time steps has to be reduced in order to be able to investigate the hypersonic flows at high-pressure injection. The minimum increment is 0.25° CA which results in a time step of 41.7 µs for an engine speed of 1000 rpm.

The main distinction between different nozzle concepts is the number and placement of bores, whereas an increased number of bores generally has a positive effect on mixture formation but leads to increased production costs. Therefore investigations were carried out with a multi-hole injector in order to investigate the behavior of single jets with supercritical injection. As the light sheet also is situated in the plane of symmetry the two bores located in the center of the nozzle can be observed. One of the two subsequent jets is inclined downwards, the other parallel to the pent roof. The results are shown in Figure 6. Start of injection (SOI) trigger is at 120° crank angle (CA) before top dead center (bTDC), the actual SOI is slightly delayed due to the mechanical properties of the injector.

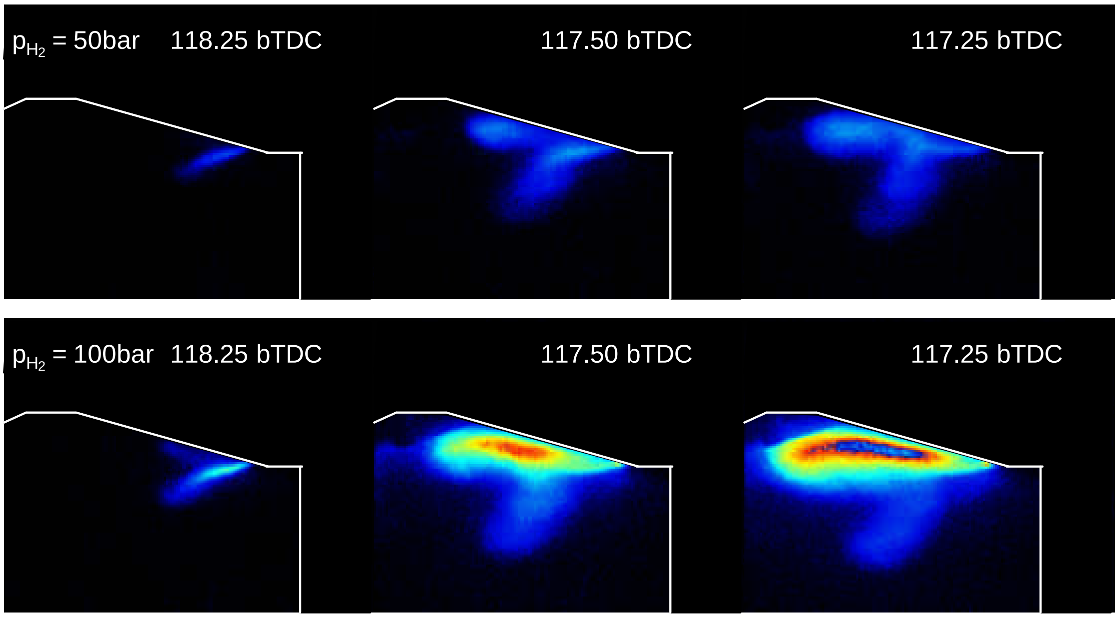

Figure 6: Application of non-quantified LIF-measurements: Comparison of jet patterns for variations of fuel pressure

It can be seen that in the early phase of the injection the two single jets can be distinguished, whereas only a short time afterwards the lower jet is merged with the upper jet due to the Coanda-effect occurring in supersonic flows (Nasr and Lai 1997). The same effect also causes the merged jet to be drawn towards the pent roof wall (Nasr and Lai 1998). In the later stage of injection a slowly dissipating cloud of hydrogen can be observed right to the center of the combustion chamber which is the result of the lower jet during the early phase. The overall behavior of the jets is practically identical for the two hydrogen pressures investigated, though differences can be observed in light intensity and intrusion depth due to the different densities of hydrogen within the jet. To be able to investigate the intrusion speeds the maximum penetration depth of the single jets is measured along the direction of the nozzle bores, the results are shown in Figure 7.

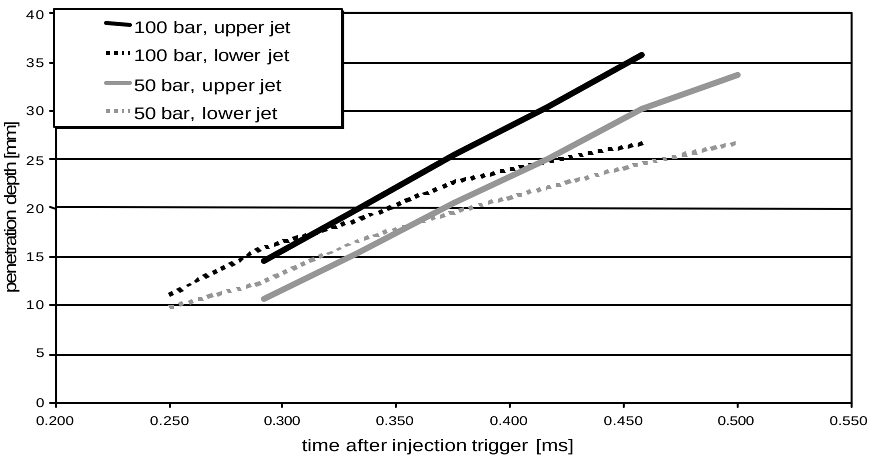

Figure 7: Measurement of intrusion depths

Whereas the intrusion speed of the lower jet shows a clearly degressive tendency due to the lower back pressure caused by the merging of the two jets, the penetration depth of the upper jet shows a linear behavior for both pressures throughout the investigated range. Therefore it is viable to derive the speed of the jets, which results in values of 127 m/s and 112 m/s respectively. Thus it can be concluded for applications of this configuration that an increase in gas pressure only has a minor effect on penetration speed and depth, as a doubling of the back pressure only resulted in an increase of jet speed of approximately 13 %, an effect that has to be taken into account when developing injection strategies for stratified charges.

4.2 Mixture Formation

The main goal in developing injectors and injection strategies for modern combustion processes is the ability to provide a wide range of different mixture distribution concepts within one layout to cover the whole operating range. Depending on the operating point it can be advantageous to provide a homogeneous charge at ignition point whereas other operating conditions require stratified charges with the fuel concentrated around the spark plug (Gerbig et al. 2004). Therefore quantified LIF-measurement providing information on fuel distribution at any given time during mixture formation form an ideal basis for the evaluation of new concepts.

4.2.1 Methodology for quantified measurements

The Tracer TEA is mixed with hydrogen at a concentration of 200 ppm. In order to achieve the homogeneous charge necessary for signal calibration, an injection unit is installed in the intake manifold in addition to the DI-injectors. Due to the comparatively long distance between the port-injection unit and the intake valves, a well homogenised mixture with the intake air is achieved. For an optimised quality of the results, a series of images is recorded for each crank angle, with 50 images recorded respectively for the investigated operating point, the homogeneous charge for calibration and the background noise. These recordings are averaged. The images of background noise then are subtracted from the recordings of both direct-injection and port-injection. Finally the results of direct-injection are calibrated with the images of homogeneous charge. The increment of each time step is between 1° CA at start of injection up to 10° CA later on till the ignition point.

4.2.2 Measurements of mixture formation

In the following the influence of the start of injection (SOI) is investigated. The injector again is equipped with a multi-hole nozzle and positioned on the side of the combustion chamber. SOI is at 120° bTDC and 30° bTDC respectively, the pressure of hydrogen is set to 140 bar. The engine is operated at 1000 rpm and an indicated mean effective pressure (IMEP) of 3 bar. The results are shown in Figure 8 with the images for early injection on the left hand side and those for late injection on the right hand side.

Due to the fact that the laser beam coming from the side is partly shadowed by the piston some inhomogeneities in the light sheet can be observed for late injection which are compensated by the calibration of the images but are still slightly visible.

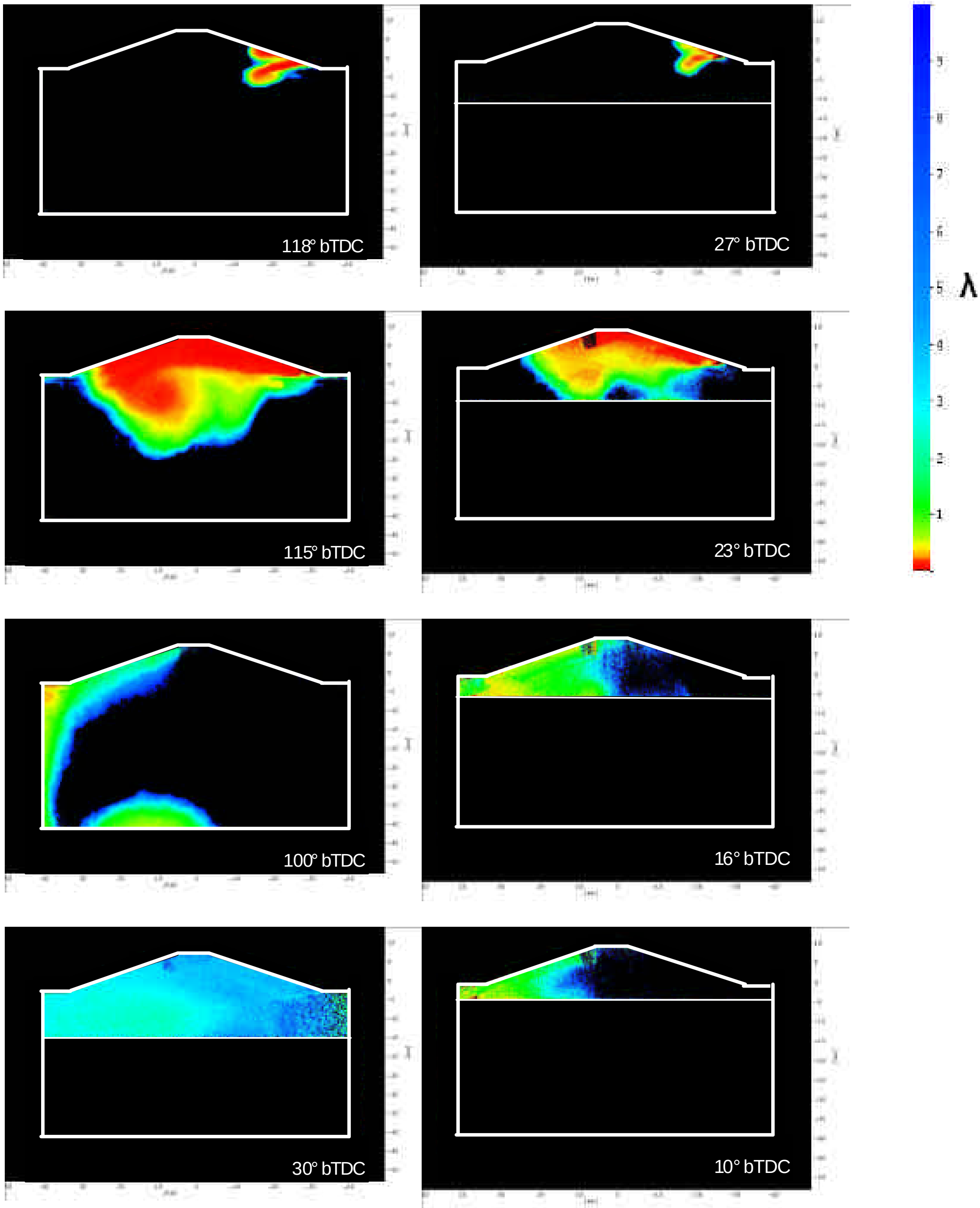

Figure 8: Typical application of quantified LIF-measurements: Comparison of early (left) and late (right) injection

Even though the overall impression of the jet's shape is rather similar in the early phase of injection, the resulting distribution of fuel is completely different. In the first case the tumble induced by the impulse of the hydrogen jet leads to a nearly complete homogenisation of the fuel. In the second case the space is limited by the piston, therefore no tumble is induced and the cloud of hydrogen is concentrated at the side opposite of the injector of only leaving a small amount of fuel around the spark plug.

4.3 Combustion process

The course of the combustion is crucial for the main targets in the development of new engine concepts: increasing efficiency and reducing emissions. Therefore a deeper knowledge of the combustion process is needed, whereas measurements of the flame propagation are needed especially for the calibration of 3D-CFD-models which furthermore can also be used for the simulation of the formation of pollutants during combustion.

Additionally to the OH-LIPF measurements described here the method of using the tracer within the fuel for marking the flame front was also used similarly to the measurements of mixture formation. Thereby the tracer is consumed by the flame which allows fast and efficient evaluation of the progress of the combustion by defining a burnt and an unburnt zone (Kirchweger et al. 2005).

4.3.1 Laser-induced fluorescence of the OH-radical inside the hydrogen engine

The OH-radical is a commonly used indicator for the passing of the flame front, as its concentration rises steeply in the flame front at the start of the reactions, making it easy to define the local start of reactions (Arnold et al. 1997). As the OH-radical is still present after the passing of the flame, only the start of the combustion reactions can be measured employing this method, but due to the lack of formaldehyde in the combustion of hydrogen the visualization of the OH-radical is the method of choice for this task. The measurements were carried out as described in 2.2.

4.3.2 Results of OH-flamefront measurements

In the following the consequences of a stratified charge on combustion as presented in 4.2.2 are shown. The injector again is equipped with a multi-hole nozzle and positioned on the right hand side of the combustion chamber. SOI is at 40° bTDC, the pressure of hydrogen is set to 100 bar. The engine is operated at 1000 rpm and an indicated mean effective pressure (IMEP) of 5 bar. These operating parameters lead to a high concentration of fuel on the left hand side, the following combustion is shown in Figure 9.

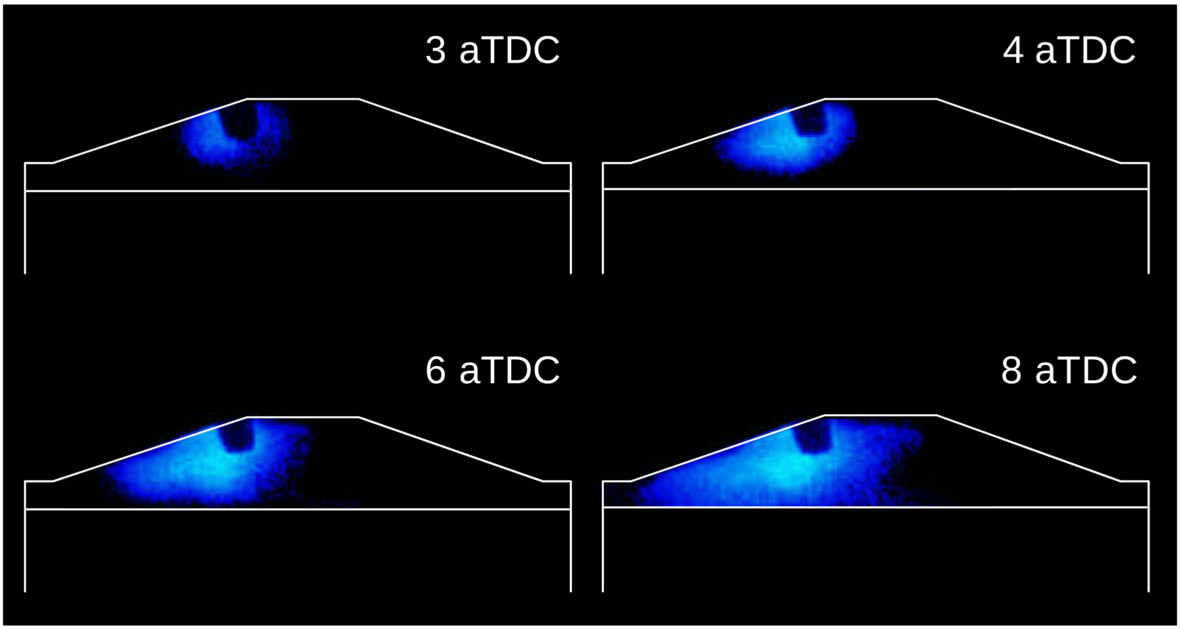

Figure 9: Application of combustion analysis: Visualization of flame propagation for non-homogeneous charges

Due to the very inhomogeneous distribution of fuel the combustion only takes place in part of the combustion chamber. Due to rather high cyclic variations during combustion the averaged images tend to show a soft-focus effect at the edges of the combustion zone, nevertheless the overall propagation of the flame front can be visualized quite clearly.

5 Conclusions

The method of laser-induced fluorescence was successfully applied for the measurement requirements in the field of development of innovative combustion processes for hydrogen engines. The tasks of providing measurement techniques for each the analysis of jet patterns at the injector nozzle, the measurement of the fuel distribution at ignition point, and the visualization of the flame front propagation could be fulfilled by adapting the LIF-technique for the particular conditions inside a combustion engine with high-pressure gas injection.

One main goal achieved was the development of methods suitable for quantified measurements of the fuel distribution during mixture formation. The excellent linearity of the LIF-signal when using Triethylamine as a tracer lead to the development of a very time efficient calibration routine, which can be used as a standard procedure for measurements of mixture formation. The resulting images provide an essential data basis for the development of new mixture formation concepts and the verification of 3D-CFD models.

The other goal was to apply a method for the measurement of the flame propagation, whereas OH-LIPF has provided the best accuracy, whereas the method of measuring the flame front with a tracer has shown great potential for giving a quick overview of the effects of variations in combustion parameters.

Used in combination these, techniques provide the tools for further improvements in the field of hydrogen engines and therefore can help to advance clean mobility for the future.

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