Near Nozzle High-Speed Measurements of the Intact Core for Diesel Spray

A. Heilig*, M. Kaiser, F. Dinkelacker
Institute of Technical Combustion (ITV)
Leibniz University of Hanover
Welfengarten 1a, 30167 Hannover, Germany

Abstract

The optical connectivity method is applied for the first time for near nozzle measurements of the intact core length of stock high pressure diesel injectors up to 220 MPa (2200 bar) with high speed imaging. The method is based on an approach by Roosen (1991) and the so called optical connectivity method of Charalampous et al. (2009) for the measurement of the intact core length of sprays. To achieve this, the light is guided through an optical access into the nozzle tip to illuminate the liquid jet along its intact core length from inside. So far, this approach has been applied to rather low pressure injectors or specially designed nozzles. For the application on modern common-rail diesel injectors with injection pressures above 200 MPa (2000 bar), two approaches are being evaluated now. In the first approach, an optical fiber is coupled into one of the nozzle holes of a standard heavy duty diesel injector. Doing so, it was possible to determine the intact core length for the hole on the opposed side. First high speed measurements of the unsteady spray behaviour with up to 25 kHz resolution were feasible. In the second approach the light is guided into the sac hole volume through an additionally drilled access on the center of the nozzle tip. Here, the lengths of all spray cores could be measured simultaneously. A stable operation was possible up to injection pressures of 220 MPa (2200 bar). Results with transient high speed imaging measurements are then shown. Additionally, a simultaneous application with high speed Mie scattering imaging of the spray shape is presented within this work.

Introduction

Reduced emissions and fuel consumption are one of the main motives for optimizing combustion engines. Especially for Diesel engines, the injection process is an important key for progress. With increased injection pressure and multiple injections, the typical duration of one injection greatly decreases so that highly transient effects of spray formation and spray break-up are more and more dominant. However, the direct measurement especially in the near nozzle field is difficult due to the small spatial scales, the highly transient processes and the dense spray. The application of optical measurement techniques like phase doppler anemometry for droplet sizing or planar imaging techniques like planar Mie scattering are rather unsuitable particularly in the near field of the spray. On the other hand, numerical methods are developed for the simulation of the flow and spray breakup processes. However, due to the complex nature of the physical processes here, detailed experimental validation methods are mandatory. This is of particular importance as the spray breakup processes determine significantly the mixing of fuel and air in the engine, the ignition and combustion processes, and thus, the efficiency of the engine as well as the formation of pollutants like soot and nitrogen oxides.

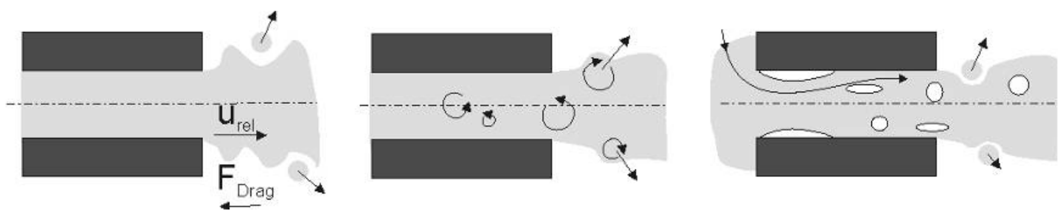

Figure 1. Break-up mechanisms: aerodynamically-induced, turbulence-induced and cavitation-induced break-up (from left to right) [1].

The break up mechanisms shown in Fig. 1 are dominant within the various spray regimes demonstrated in Fig. 2. They are being consecutively passed during one injection cycle when the spray gains speed and a stationary state is being established after complete needle lift.

*Corresponding author: heilig@itv.uni-hannover.de

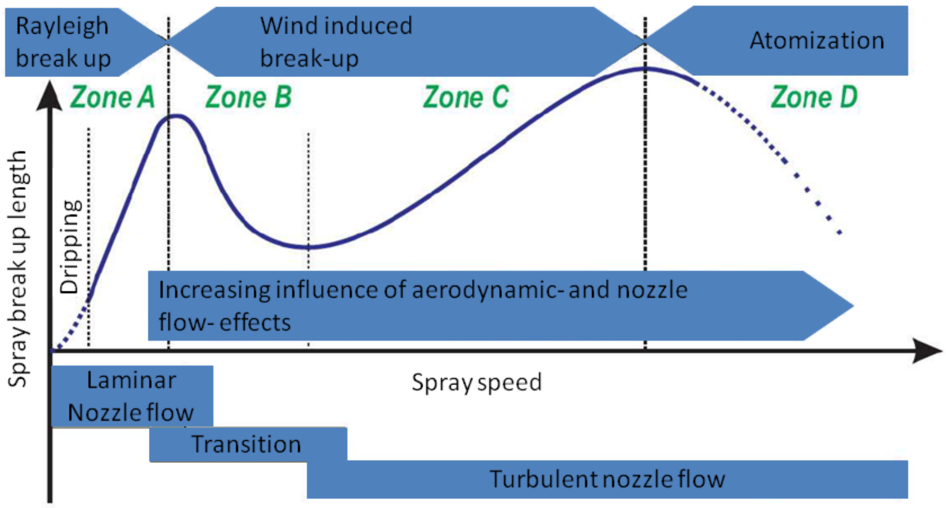

Figure 2. Break up mechanisms according to spray speed and break up length [2].

Unfortunately, especially the influence of the cavitation-induced break-up is not well understood, yet it is of increasing importance for high performance injection systems operating at pressures above 200 MPa (2000 bar). Various optical measurement methods have been applied on sprays in the past. But standard optical diagnostic methods in the near nozzle field are known to fail due to the high optical density of the diesel spray. Spray observation of [3] applied with a pulsed ND:YAG laser light sheet revealed an intact core in the near nozzle area for a $d = 200\ \mu m$ cylindrical nozzle hole. The length in that case was estimated to be about $l_{lc} = 200\ \mu m$ surrounded by strong cavitation bubbles at an operation point of $p_{Rail} = 15\ MPa$. Another idea to illuminate the intact core was described by [4] in 1991. It was applied on a modified diesel injector nozzle. Here, the laser light is guided into the injection nozzle to illuminate the liquid jet from the inside. The spray break-up interrupts the light transfer within the liquid phase and thus limits the illuminated area to the liquid core. More recently, Charalampous et al. [5], [6] developed again this approach with the name "Optical Connectivity Technique", and optimized it to measure the length of the intact liquid core in sprays generated by a two-component jet. An example for the validation of this technique is given in Fig. 3. In both cases ([4],[6]) a fluorescence tracer was added to the fuel to distinguish the liquid core from the spray.

In this work the optical connectivity method was used without seeding, as the stray light emitted from the fuzzy structure of the dense core provided a sufficient signal. Furthermore, first experiments in [7] also proved that at very strong illumination intensities by a Q-switched Nd:YAG-laser, there is a sharp, clearly distinguishable signal gradient at the phase transition border between liquid core and spray.

While so far, a specially designed injector was necessary [4],[5] and the injection pressure was rather low, the aim of the current development is the application of this technique to stock high pressure diesel injector systems operating up to 200 MPa (2000 bar) and above. A second goal was to prevent modifications to the injector as much as possible, as this would potentially allow to establish an additional indicator for the experimental evaluation of real injector systems. Additionally, the application of high speed imaging in the 25 kHz range should be tested to measure transient spray breakup effects.

In this work, two approaches are described. In the first approach the idea is followed to use an unmodified stock injector where the light is coupled into the sack hole of the injector through one of the existing spray holes. Promising results of this approach have been presented recently [7]. A second approach was a symmetric illumination through an additional hole in the center of the nozzle tip. This approach allows a more uniform illumination of the dense cores for all spray holes. As this additional hole is custom made, its diameter can be adapted for an optimized coupling of the optical fiber. Both approaches are described together with the first obtained results.

Experimental Methods

The experiments were conducted at the high pressure injection chamber of the Institute of Technical Combustion in Hannover [8], which is operated at ambient temperature. It is suitable for research on the macroscopic

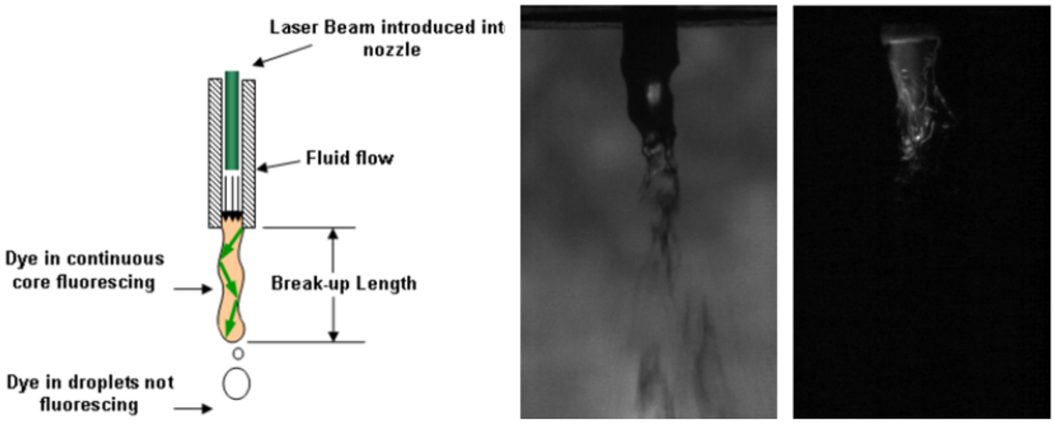

Figure 3. Principle of the optical connectivity method (l.) and simultaneously captured pictures of background shadowgraphy visualizing the whole spray and of fluorescence imaging visualizing the liquid core length(r.) [5].

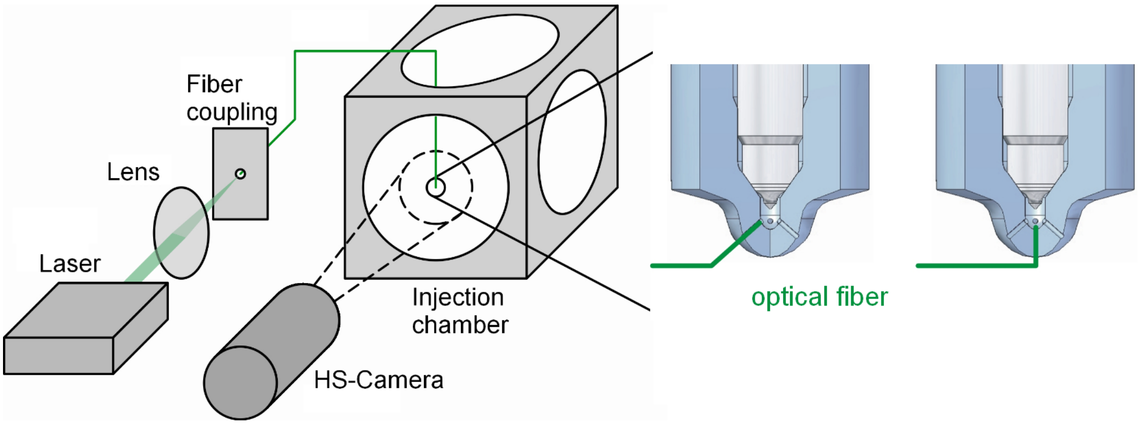

Figure 4. Optical setup with enlarged scheme of the injector cross section and inserted optical fibre through one injection holes (l.) respectively central coupling through an additional hole in the nozzle tip (r.)

spray shape as well as on the microscopic effects of spray break-up. Air densities up to 60 kg/m^3 allow high pressure spray experiments to be conducted under realistic conditions comparable to those in diesel engines at the beginning of the injection.
For the first approach, to apply the optical connectivity method, an optical fibre was coupled into the injector through one of the existing nozzle holes (Fig. 4). Here, a hard cladding multimode fibre was used. In the first application, [7] it was possible to illuminate the dense core length especially of the jet opposite to the coupled side. Also, the jets adjacent to this were illuminated with a lower intensity. Measurements were possible also with high speed illumination and observation. The measured time dependent signal of some of the spray holes indicated the possibility of a tumbling injector needle. To eliminate this possible influence, an automotive injector was also used which is known to work without a tumbling needle. The injector has a hydraulic flow rate of $\dot{Q} = 705 ml/min$ and eight conical nozzle holes with a diameter of $d = 105\ \mu m$ while the k-factor is k = 3.5. A first evaluation for comparing the present measurements to those from [7] is described later.
As a second approach, a central light coupling through an additional hole in the nozzle tip was applied. For adapting the optical fibre with a core diameter of $d = 230\ \mu m$ the nozzle tip was slightly modified by eroding a suitable access hole for the fibre. A new hole with a diameter of $d = 500\ \mu m$ was used because of the experience that the fibre application is more durable with larger holes. Due to this, it was possible to apply the technique for rail pressures up to $p_{Rail} = 220\ MPa$ for the first time.

For illumination two combined cw laser modules were used. Each module consists of a 1 W-semiconductor laser emitting at $\lambda = 445\ nm$ and a coated collimating lens. The polarized beams (4 mm x 2 mm) are superimposed with a polarizing beam splitter cube and by perpendicularly adjusting the polarization planes. A digital high

speed camera (Vision Research Phantom V711) was used, configured to a frame rate of 25 kHz at a resolution of 512 x 512 pixels. With a 130 mm lens system with F = 2.8 at an operational distance of about $480\ mm$, a spatial resolution of $r = 50\ \mu m/px$ was realized. With exposure times down to 20 μs, the signal-to-noise ratio was still acceptable and the temporal resolution was sufficient for time resolved measurements of single injection cycles.
In a post-processing step the core length of the different spray holes was determined for each single shot image. This was done by an algorithm, which detects the illuminated area of the liquid dense core phase by binarizing the image and then taking the farthest point from the injector center to calculate the absolute penetration depth. In a second step, the radius of the pitch circle of the nozzle holes was subtracted to calculate the actual core length.
The hydraulic behaviour of the injector was analyzed separately by an IAV Injection Analyzer N-050-50, for every rail pressure, to determine the mass flow rate as well as the effective duration of the injection.

Results and Discussion

Nozzle hole coupled fibre

The quality of these measurements has been evaluated by means of the achievedspatial resolution, the signal-to-noise ratio and also with the fluctuation of the determined dense core length. For the latter point the two described injectors have been benchmarked. The injection pressure could be increased up to 80 MPa. For higher pressure, the light fibre was ejected. Due to the cw-laser illumination, it was possible to capture time resolved images of the intact core with the high-speed camera. In the first measurements a heavy duty injector was used with $p_{Rail} = 40\ MPa$ at ambient pressure. Fig. 5 shows the results of these measurements where the light was coupled through the nozzle hole in the 6 o'clock direction. These time resolved pictures show the core length (red contour) in relation to the overall spray shape visualized by Mie scattering which were overlaid by post-processing. Here, four of seven possible spray jets revealed a sufficient signal strength to be clearly detected.

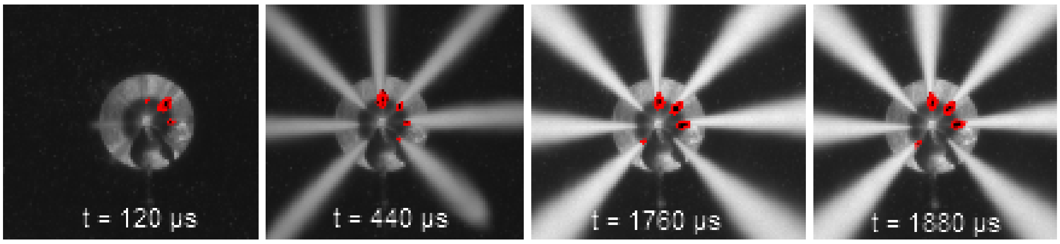

Figure 5. High-speed Mie-scattering spray pictures with overlay if the liquid spray core (red contour)

With high speed imaging at 25 kHz, the temporal fluctuation of the detectable spray cones and also of the dense cores is observable. Measurements have been made with two injectors to find out whether these fluctuations are related to the optical coupling method or to the injector setup. Also, some first attempts have been made towards simultaneous measurement of the dense core length with the optical connectivity method and of the spray structure with Mie scattering. In Fig. 6, where the fibre coupling through one nozzle hole was realized, some examples are shown with very good signal quality. The pictures were inverted for a higher visual contrast. The simultaneous measurement of the spray cone and of the dense core was feasible, as the signal from the dense core was drastically higher than the Mie signal and thus, was distinguishable. The increase and decrease of the dense core length as well as fluctuation of the spray shape is clearly visible.

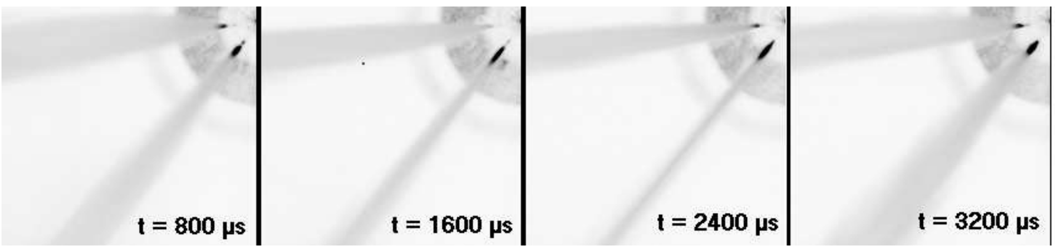

Figure 6. Simultaneous visualization of the dense core and the spray geometry at $p_{Rail} = 40\ MPa$ and $\rho_{K1} = 1\ kg/m^3$, inverted

The standard deviation of the first results is significantly lower compared to that of the obtained results from the injector used in [7]. In contrast to the heavy duty injector, fluctuations have not been observed with this setup. This was potentially a matter of needle tumbling. In conclusion, it is found that this approach with the directly adapted light fibre is applicable. A reasonable SNR is obtainable for the hole opposite to the coupling side. No additional tracer to the diesel fuel was necessary. However, the determined lengths depends, to some extent on the selected spray hole. It is also possible that the coupling method leads to an imbalance of the fuel pressure inside the nozzle tip, as one of the holes is closed for the fuel flow.

Nozzle tip coupled fibre

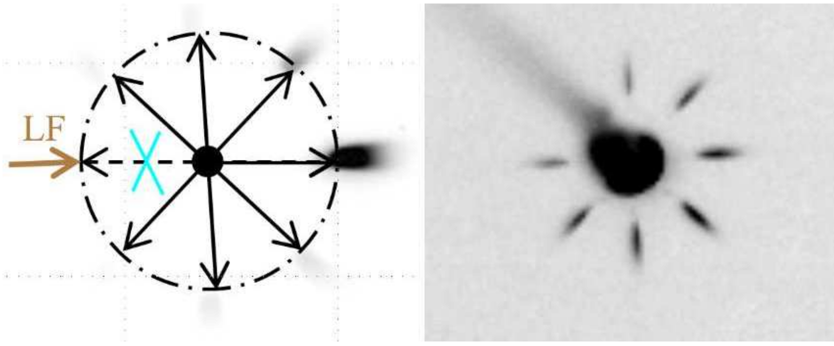

Figure 7. Exemplary, inverted raw pictures: inserted light fibre (LF) through the 9 o'clock nozzle hole (additionally visualized pitch circle of nozzle holes respectively direction of the remaining holes) (l.) and centrally coupled light fibre through nozzle tip (r.) (spray core at the 11 o'clock position is hidden by the slightly off focus fibre in the foreground)

In the second approach, a slightly modified injector has been investigated. Here, an additional hole is eroded into the nozzle tip (see also Fig. 4). The apparent difference between the two different coupling methods is clearly visible in the examples shown in Fig. 7. It can be seen that the the coupling through the nozzle tip leads to a very homogeneous illumination of all dense cores. But it is also found that the intensity of light is lower, possibly due to the distribution of the injected light to all eight nozzle holes.

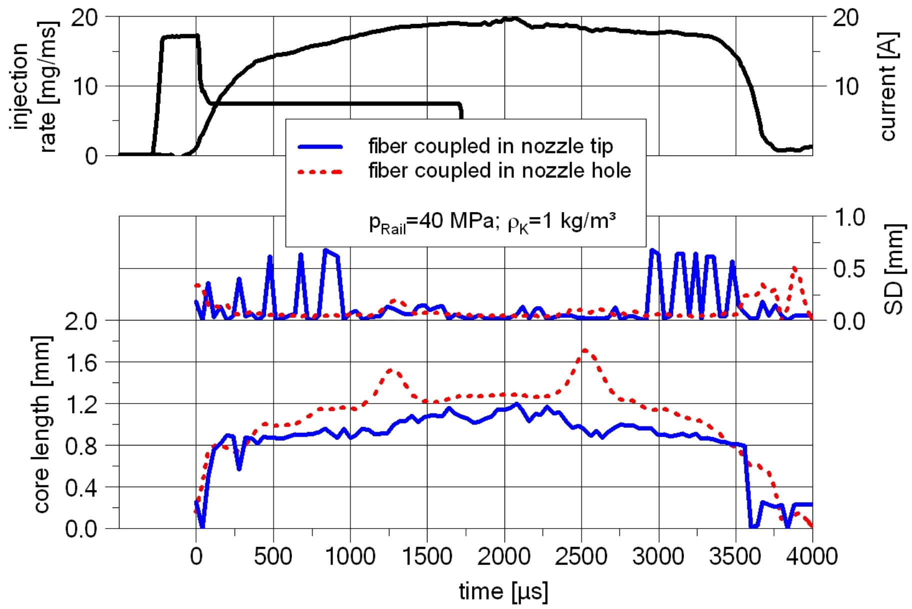

Figure 8. Injector current, injection rate (upper graphs), SD (middle graphs) and statistically averaged liquid core lengths over time for fibre coupling through the nozzle tip respectively through one nozzle hole (lower graphs)

Fig. 8 shows an example of the time depended injection process, where both approaches have been compared.

The injector current and the injection rate are shown in the upper graph. After an offset of about $t_{SOI} = 240\ \mu s$ between electrical and hydraulic start of injection, the electrical duration of injection of $t_{DOI} = 2000\ \mu s$ leads to an actual injection time of about $t_{Inj} = 3800\ \mu s$, due to the delayed closing dynamic of the needle at low fuel pressures. At the bottom of Fig. 8, the measured core length and the standard deviation (SD) is plotted over time for both approaches. The data was obtained from 10 individual injections and one spray cone for the side-coupled fibre. For the nozzle-tip-coupled fibre, the data was calculated from two individual injections over all 7 visible spray cones. The average standard deviation of the dense core length for the hole-coupled fibre is $SD_{mean1} = 0.08\ mm$ with $SD_{max1} = 0.51\ mm$. The result for the other coupling method, with an average standard deviation $SD_{mean2} = 0.11\ mm$ with $SD_{max2} = 0.67\ mm$ is slightly higher. An explanation for this higher SD value obtained at the nozzle tip coupled experiments is again the more even distribution of the total light energy to more nozzle holes. This results in critically low light intensities per hole which leads to poorer SNR's (compare Fig. 8). However, the stability during the steady-state phase of the injection is quite good. Here, a stronger illumination would be helpful. The quantitative signal histories show a nearly similar behaviour for both methods. In both cases, the initiation and end of the measured dense core is rather similar as well as the temporal trend. For the method with the off-center coupling of light, two local maxima at $t = 1750\ \mu s$ and $t = 2500\ \mu s$ are visible. They were not reproducible in a second experiment, so they are assumed to be of statistical nature. It was observed that for the nozzle-hole-coupled measurement approach, the signal levels occasionally went down, especially during the initial and the final stage of an injection. A possible explanation is that the light-guiding cross section inside the injector was too small when the needle was closing or that the light was blocked by strong cavitation effects. For the centrally illuminated approach, such phenomena have not been found.

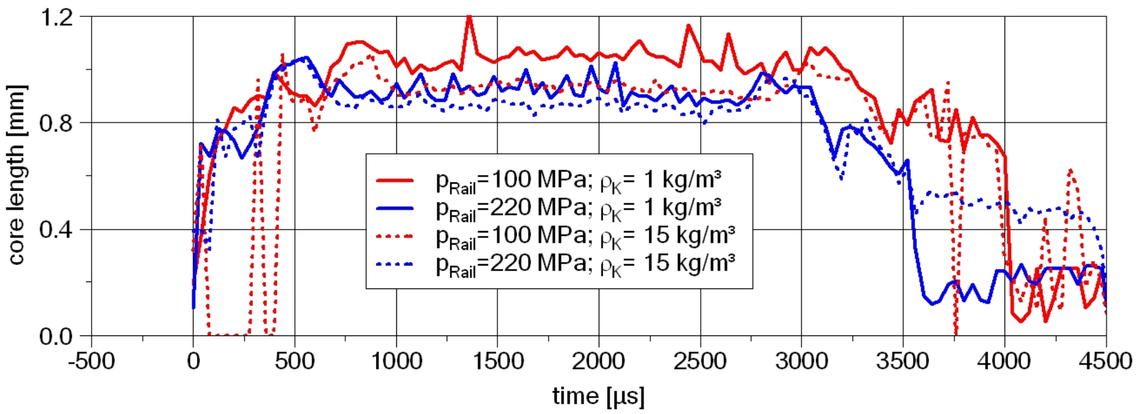

Figure 9. Mean liquid core length for various rail pressures and chamber densities

For the method with central illumination of the sack hole more measurements have been done, also for higher injection pressures at two different densities of $\rho_1 = 1\ kg/m^3$ and $\rho_2 = 15\ kg/m^3$ in the injection chamber. (Fig. 9). It was possible here, to do experiments with varied rail pressure up to $p_{Rail} = 220\ MPa$. At a first glance, the dense core length is only slightly affected by either injection pressure or chamber density. In all cases, the dense core length is found in the order of $l_{lc} = 900\ \mu m$ to $l_{lc} = 1100\ \mu m$ during the steady state of the injection process. A more detailed statistical evaluation of the mean dense core length has been done for the range between $t = 1500\ \mu s$ and $t = 2500\ \mu s$ (Fig. 9). It is found that the core length decreases with higher rail pressure and also with higher chamber densities.

These first measurements show that the optical connectivity method can be applied also to real high diesel injectors from the stock even at high injection pressures, with only slight modifications of the injector. Both approaches (illumination through one of the spray holes or through an additional centrally placed hole) provide rather similar measurement data. The second approach allows more equal illumination conditions for the different spray holes. Here, even higher injection pressures have been realized, as the application of the fibre to the injector was more stable. In both cases, it would be constructive, to increase the illumination power. Here, more work is planned. Also the simultaneous application with high speed Mie scattering imaging has been shown to be feasible and a gain in the signal quality seems realistic.

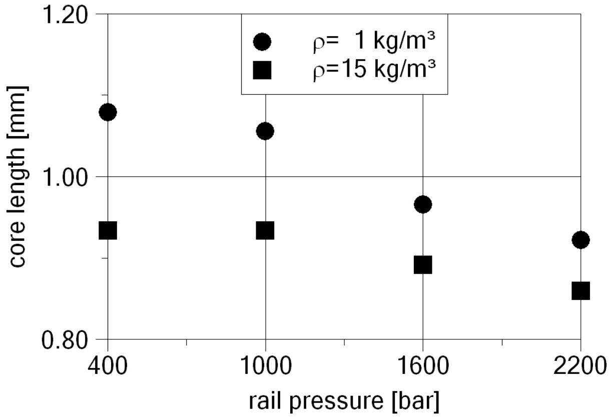

Figure 10. Mean values between $t = 1500\ \mu s$ and $t = 2500\ \mu s$ for variation of rail pressure and density

Summary and Conclusions

The optical connectivity method is applied for the first time on high speed near nozzle measurements of the intact core length of real high pressure diesel injectors up to $p_{Rail} = 220\ MPa$. This is a significant progress compared to earlier applications on low pressure injection systems by Roosen or later by Fath et al. For the application of the optical connectivity method to stock injectors, the light is being guided through an optical fibre into the nozzle tip to illuminate the liquid jet along its intact core section from the inside. Two approaches have been compared. In the first approach, an optical fibre is coupled into one of the nozzle holes of a standard heavy duty diesel nozzle. It was possible to determine the intact core length especially of the sprays on the opposite side of the injector. First high speed measurements of the transient behaviour with up to 25 kHz temporal resolution were conducted. In a second approach an additional hole in the center of the nozzle tip has been introduced. Here again with high speed resolution nearly all of the spray core lengths could be measured simultaneously. A stable operation was possible for this configuration up to injection pressures of $p_{Rail} = 220\ MPa$ ($p_{Rail} = 2200\ bar$). The approach and first results are presented. A simultaneous application with high speed Mie scattering imaging of the spray shape has been shown. Compared to the determined liquid core length of [3], although there were other spray conditions in this experiment, typically longer liquid core lengths are found with the optical connectivity method. Here, measurements with the different techniques at the same injector would be of strong interest.

For further investigations, it would be necessary to increase the illumination power to improve the signal quality. Also, measurements with a transparent nozzle are planned. It is expected that this new technique can provide additional data for modeling and validation experiments of high pressure injectors.

Nomenclature

BOI	begin of injection
d	diameter [m·10^{-6}]
DOI	duration of injection
F	force [-]
f	light strength [-]
k	conicity of nozzle hole [-]
λ	wave length [m·10^{-9}]
l	length [m·10^{-6}]
LF	light fibre
p	pressure [MPa]
ρ	density [kg·m^{-3}]
$\dot{Q}$	hydraulic flow [ml·min^{-1}]
r	resolution [m·10^{-6}] /px
ρ	density [kg/m^3]
SD	standard deviation [m·10^{-3}]
SNR	signal noise ratio
t	time [s·10^{-6}]
u	spray velocity

Subscripts

Ch	in the chamber
DOI	duration of injection
Inj	injection
lc	liquid core
r	resolution
Rail	in the Rail
rel	relative
SOI	start of injection

References

[1] L. Zigan, *Kraftstoffeinfluss und Spraymodellierung," in Grundlagen und moderne Anwendungen der Verbrennungstechnik*, Eds. F. Dinkelacker, L. Zigan, A. Leipertz, ESYTEC Erlangen, 2012, p. 469.

[2] B. M. Schneider, *Experimentelle Untersuchungen zur Spraystruktur in transienten, verdampfenden und nicht verdampfenden Brennstoffstrahlen unter Hochdruck*, Dissertation, ETH Zürich, 2003.

[3] A. Fath, K.-U. Münch, A. Leipertz, *Proc. of ICLASS '97, August 18-22, Seoul*, 1997.

[4] P. Roosen, *Einspritzstrahlstruktur vor Dieseldüsen, Motortechnische Zeitschrift*, Vol. 52 (1991) pp. 526-531.

[5] G. Charalampous, C. Hadjiyiannis, Y. Hardalupas, *Proc. 24th European Conference on Liquid Atomization and Spray Systems, Estoril, Portugal*, 2011.

[6] G. Charalampous, Y. Hardalupas, Taylor, *AIAA Journal* Vol. 47, No. 11, pp. 2605 - 2615 (2009).

[7] M. Kaiser, A. Heilig, F. Dinkelacker, *The 8th COMODIA International Conference on Modeling and Diagnostics for Advanced Engine Systems, Fukuoka, Japan*, July 2012 (preliminarily accepted).

[8] A. Heilig, F. Dinkelacker, *Vierter Workshop Optische Technologien*, Hannover, Germany, November, 2010.