Modern optical diagnostics in engine research

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Abstract. Different optical diagnistic techniques are used to gain insight into the single steps forming the functioning chain of the engine combustion process and the complex interplay between these single steps. Examples are given for the application of Mie scattering, laser-induced fluorescence, Raman scattering, CARS and laser-induced incandescence to study diesel engine, SI engine and HCCI combustion processes. The careful adaptation of each optical tool to one part of the engine process makes it possible to get valuable information with minimum change of the process investigated. The paper demonstrates that in addition to conventional engine measurement techniques, a number of different optical techniques must be applied – and sometimes simultaneously – to successfully determine the critical parameters of the processes and to investigate their influences on the performance and the quality of real engine combustion.

1. Introduction

Swooning oil resources, global warming and above all the copious use of combustion engines in passenger cars still give the need and a great influence in improving engine combustion towards higher efficiency and less emission. To reach this a better understanding of all single steps of the functioning chain of engine combustion and their interplay forming all together the engine combustion process is necessary. At the technical level of today's engines and with the complexity of the combustion processes in modern engines, try-and-error-methods can no longer be of any help. To gain inside into the combustion process appropriate optical diagnostic tools must be used. Today, different techniques are available which can help to investigate every single step and its influence on the functioning chain in engine processes (Figure 1).Today we must state that without the use of such an optical insight into modern engine combustion processes no further development and improvement seems to be possible, especially for engines making use of direct fuel injection. At the LTT Erlangen we are active since many years in the development of appropriate optical diagnostic tools and its application for the investigation of engine combustion processes. This paper provides a selection of the modern optical tools we use in engine research.

2. Optical Investigation of Engine Combustion Processes

Engine combustion in general is a process of tremendeous complexity. Already the chemical reaction of the hydrocarbon-mixture we use as fuel is very complex because of the numerous different reactions which take place even under constant ambient conditions. In engine combustion additionally temperatures and pressures change rapidly and the field of reaction is superposed by a complex flow field and governed by the mixing field of fuel and oxidizer. Therefore, ignition and combustion in engines in general are influenced by

- field of reaction => fuel, chemistry
- field of mixing => local equivalence ratio, flow field (macroscopic flow and turbulence)
- ambient condition => temperature, pressure, turbulence, wall-interaction

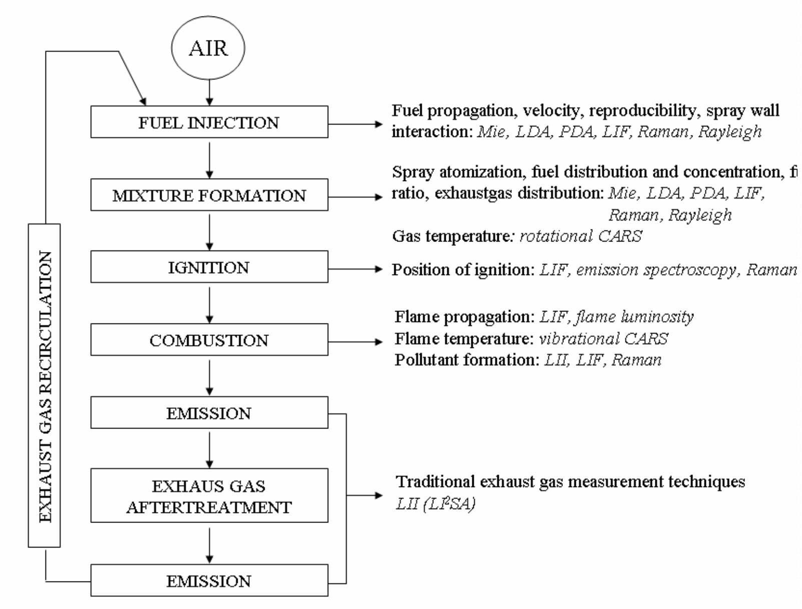

Figure 1. Functioning chain of engine combustion and appropriate optical diagnostic tools. LIF (laser-induced fluorescence); CARS (coherent anti-Stokes Raman scattering); LII (laser-induced incandescence) [1]

2.1. Diesel Engine Processes

In diesel engines especially at higher revs and loads, injection, mixture formation, ignition and combustion take place in parallel, which means that the combustion process is only to a certain extend a premixed combustion but a relevant part of the combustion is controlled by diffusion. This means that in addition to temperature, pressure and turbulence which effect premixed combustion processes the evolution of the diesel engine combustion process is controlled by local mixing properties. Therefore, the injection process which controls the mixing (via atomization => evaporation => mixing, spray-momentum => local distribution => mixing) has a dominant influence on the entire diesel combustion process. It is this "spray-controlled-combustion" which allows the diesel combustion process to reach high combustion efficiency and to handle even highest loads. Even at very high temperatures and pressures the combustion speed in diesel engines can be controlled by the mixing defined by the spray. This is an important difference to SI engines where the combustion tends to get out of control (knocking combustion) if loads get too high.

Additionally, the spray injected with high fuel pressures up to 200 MPa (in interaction with the swirl flow) creates the turbulence affecting the combustion speed as well. For that reason basic understanding of the spray and its evolution under different conditions is required. The complexity of the spray itself gets visible in the Mie scattering experiments done with high spatial resolution in the region of the nozzle orifice using a long-distance microscope as being represented in Figure 2. These measurements demonstrated for the first time that a two-phase flow already exists at the nozzle exit being caused by cavitation processes inside the nozzle tube. A spray model derived from the measurements is represented in the figure, too [2].

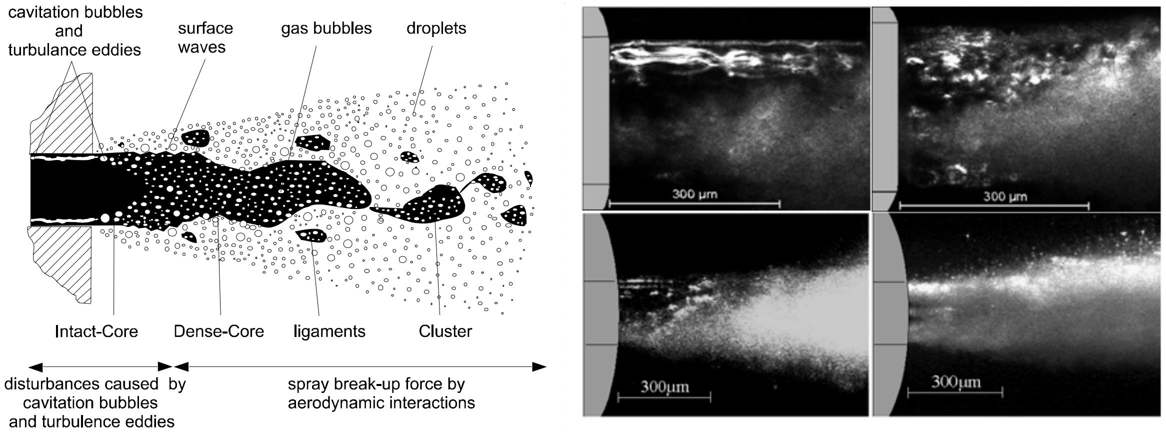

Figure 2. Spray model (left) developed from measurements near the nozzle´s exit; some images of the two-dimensonal measurements (right)[2]

The following evolution of the spray is caused by the interaction of the primary spray with the surrounding while differences in the ambient conditions have a great impact on the spray. Again relatively simple Mie scattering experiments can be used to show how variations in temperature and pressure influence the spray under modern engine conditions (Figure 3). It is obvious that realistic conditions reaching 10 MPa and 1000K are necessary for representative results. In engines, the rapid change of the conditions, the complex interaction of many parameters and difficult optical access make it hard to study sprays directly inside of running engines. For that reason a high-pressure-high-temperature injection cell was used enabling investigations up to 100 bar / 1000K and providing constant ambient conditions for spray research.

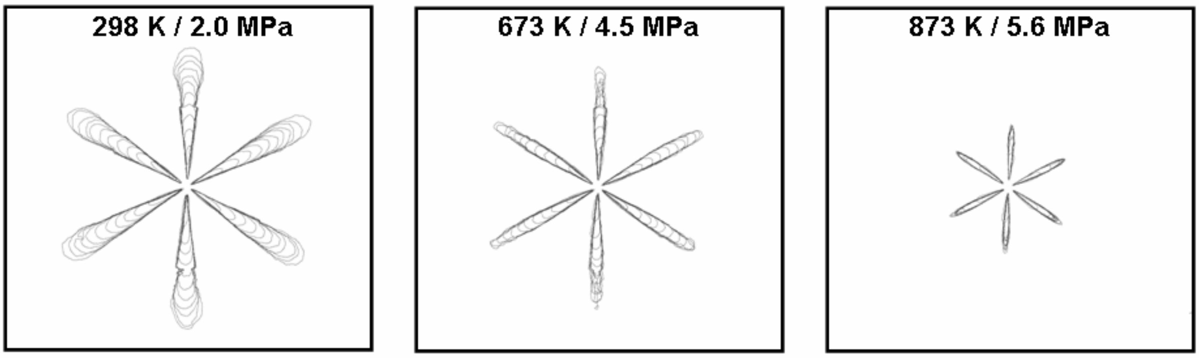

Figure 3. Formation of a Diesel spray under constant density but different temperatue conditions [3]

At the same time as there is the need for fundamental investigation of sprays, the engines have to be run under very different operating conditions. This means optical tools that are used in research and pre-development have not only to provide a deep insight into the processes but have to be able to investigate huge parameter fields.

During the spray formation process in engines also a complex mixing with the ambient air and pre-reactions take place. Optical tools can help to study even these overlapping. In the last years Raman techniques have become a tool that can be used in rough technical conditions like spray processes and that delivers quantitative results on a single-shot basis which allows statistical evaluations that can not be delivered by other techniques (Figure 4). In addition to the fuel-air-ratio the cool flame region and combustion start could be detected by the simultaneous detection of the different types of the H_2CO fluorescence spectrum.

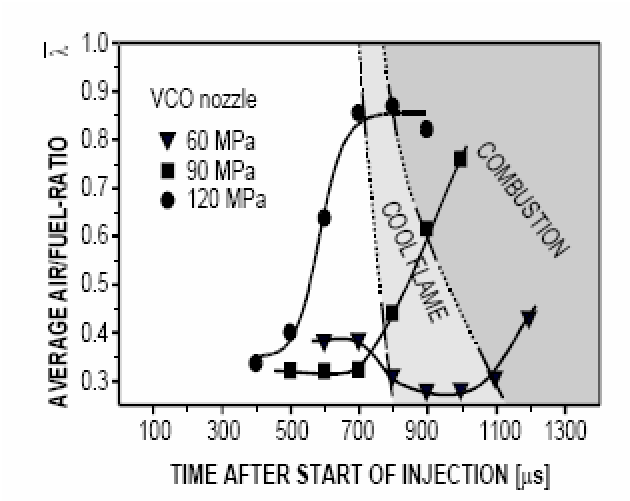

Figure 4. Temporal evolution of the averaged air/fuel-ratio at different rail pressures measured with the Raman technique; fuel: n-Dodecane [4]

Looking from the single steps of the functioning chain towards the interplay of injection, mixture formation, ignition, combustion and pollutant formation the simultaneous application of more than one measurement technique becomes relevant. Figure 5 gives sample results of a laborious study on an optical accessible diesel engine using simultaneously 5 different measurement techniques. To run such an application a lot of work has to be done, but it can show cause and effect inside of a single engine process.

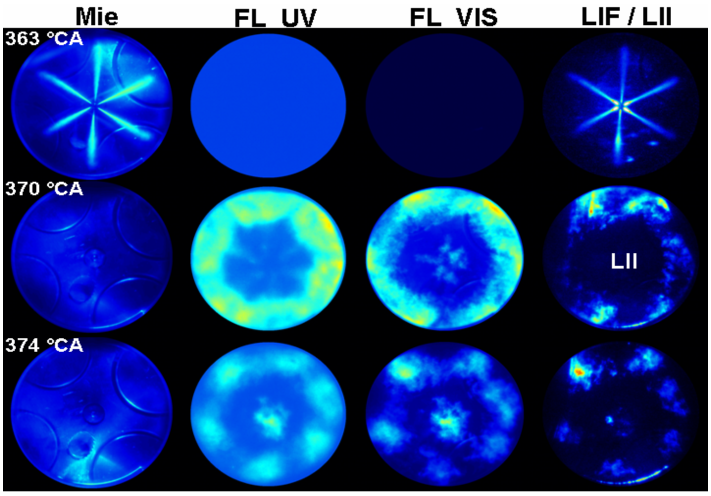

Figure 5. Application of simultaneous optical diagnostics. Mie (Mie scattering); FL_UV (flame luminosity ultra-violet spectral range); FL_VIS (flame luminosity visible spectral range); LIF (laser-induced fluorescence); LII(laser-induced incandescence) [5]

In pollutant formation and exhaust emissions optical diagnostics are currently becoming tools that replace conventional exhaust gas analysers because of new parameters that become accessable. First of all the high temporal and spatial resolution that optical tools provide is advantageous since more and more of the engine emissions are caused during transient operation phases. As an example Figure 6 displays the soot volume concentration measured during a standard transient ETC test in the exhaust of a truck engine. The example shows that the time resolution of 20 Hz used in the measurements is sufficient to resolve the variations in the transient test cycle.

2.2. Spark Ignited Engines Processes

Generally and in contrast to diesel engine combustion, SI engine combustion used not to be controlled by local mixing properties. Classical SI engines tried to prepare a homogeneous mixture prior to combustion start, while the combustion itself was controlled by the ambient conditions and the turbulence resulting from the in-cylinder charge motion (tumble). Coming to gasoline direct injection using stratified charge, this is no longer true. Newest applications using spray controlled stratified charge strategies tend to control not only the charge stratification but also the mixing and combustion by multiple injections [7] even in SI engines. These complex developments need optical insight into the spray, mixing and combustion process.

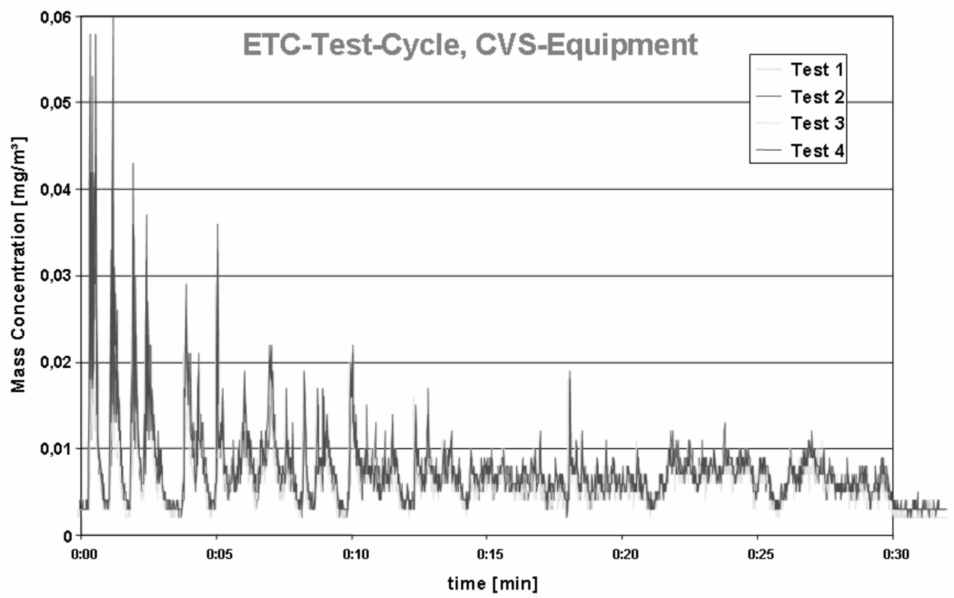

Figure 6. Measurement of the EC mass concentration during 4 consecutive runs of the ETC test cycle of CRT equipped heavy duty truck engine [6]

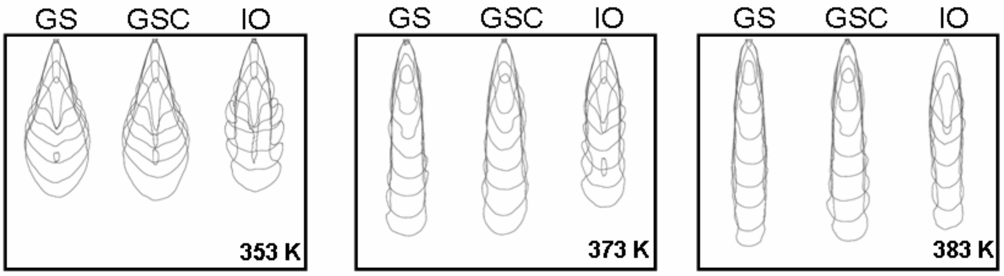

Figure 7. Investigation of the temperature influence on the spray behaviour of different fuels. GS (Gasoline Super); GSC (Gasoline Super Colourless); IO (Iso-Octane)

Since spray and gas phase mixture formation in a gasoline engine are more separated than in Diesel engines the optical access to the process is to a certain extend easier. Therefore, a lot of techniques, e.g., on basis of laser-induced-(exciplex)-florescence LI(E)F have been developed and used to study gasoline sprays and mixture formation. Most of these techniques do not allow using conventional gasoline and therefore use, e.g., a single component test fuel in combination with a tracer providing a well defined fluorescence signal.

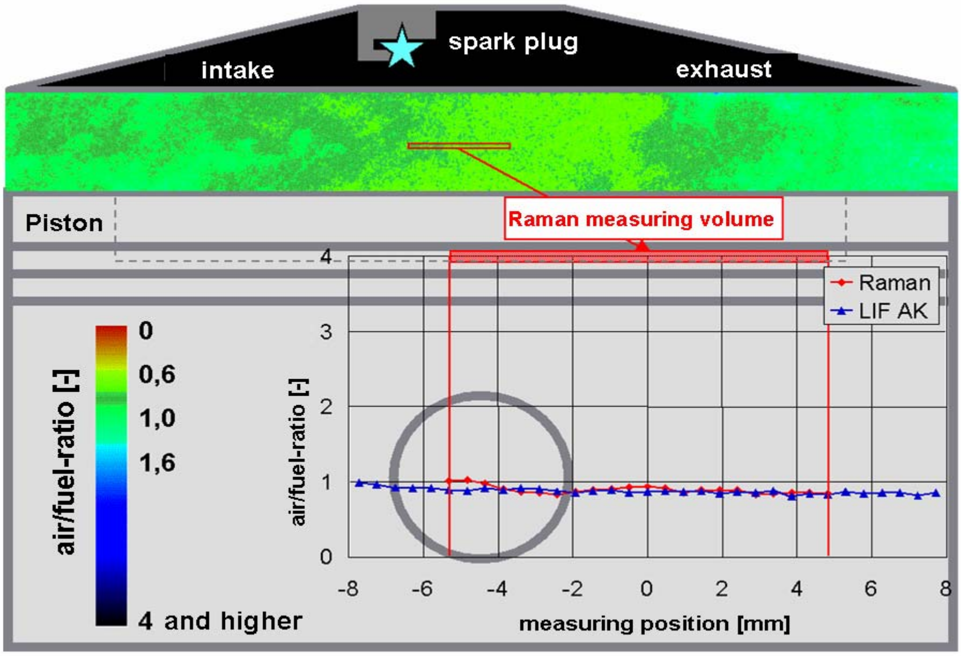

Figure 8. Comparison of quantitative Raman measurements with LIEF inside a GDI engine [8]

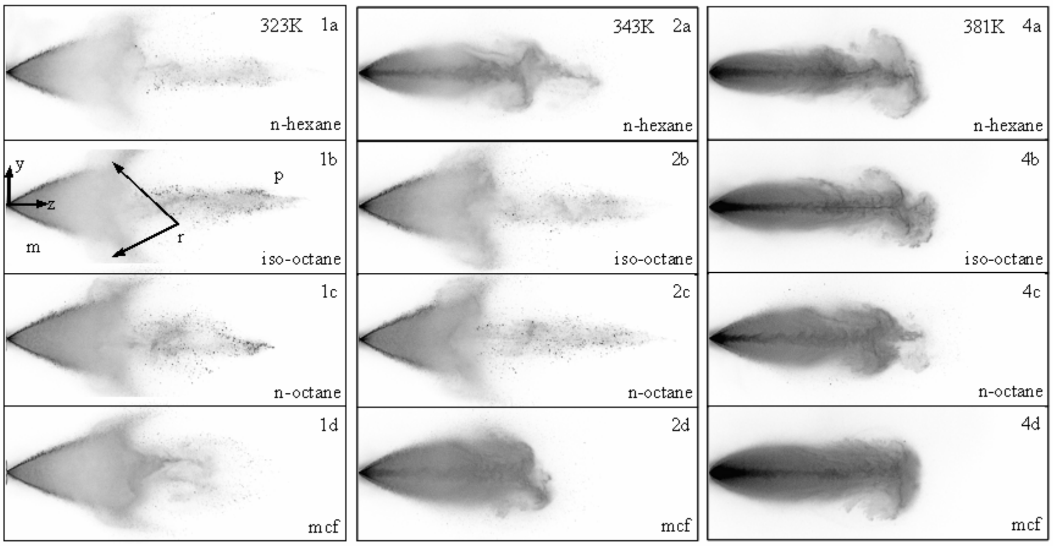

Figure 9. Influence of the injector temperature on the spray structure (m = main spray, r = recirculation zone, p = pre-spray) for four substitutional fuels (pRail = 8 MPa, pChamber = 50 kPa, TChamber = 323 K, tExposure = 1.0 ms) [9]

To do so it is important to choose a test fuel providing properties close to gasoline (Figure 7) and calibrate the tracer fluorescence in a wide range of temperature and pressure. Having the appropriate test fuel, a well calibrated tracer, a calibration procedure linking the tracer calibration and the engines test, two-dimensional quantitative investigations of the mixture formation process in gasoline engines are possible (Figure 8).

A special effect in gasoline direct injection is “flash-boiling” caused by ambient conditions exceeding the boiling conditions of the fuel injected (figure 9). Flash-boiling changes the spray structure of the injected fuel spray, even for very different injectors.

2.3 New Engine Processes

Especially for new combustion concepts optical diagnostics can help to gain a basic understanding of the process. As an example Figure 10 represents measurements done in a homogeneous charge compression ignition (HCCI) engine using Coherent Anti-Stokes-Raman-Scattering CARS to simultaneously measure residual gas fraction and temperature inside of the combustion chamber. Cylinder pressure indication was used to measure the in-cylinder pressure trace and calculate the heat release of the combustion.

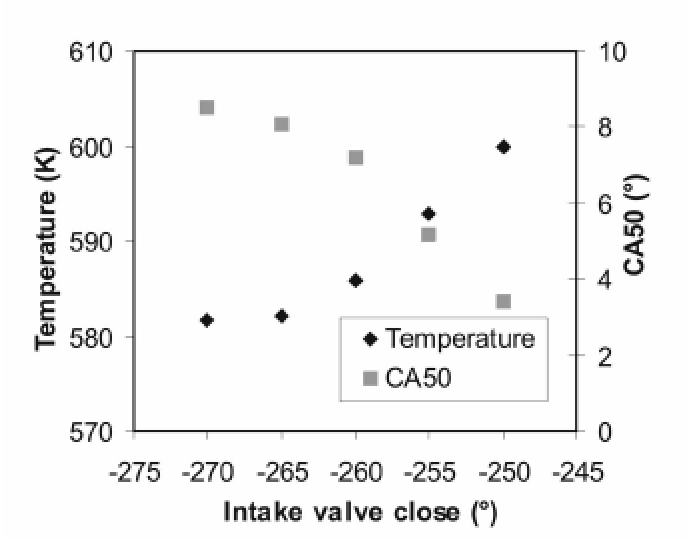

Figure 10. Measurements at -90 °CA with a variation of intake valve closing time. Temperatures are mean values of more than 96% of the 500 measured spectra with the CARS technique. Additionally shown is the crank angle degree of 50% heat-released (CA505) calculated from the pressure indication data [10]

The comparison of the gas temperature measured using the CARS method and the center of heat release evaluated from pressure indication shows the strong influence of temperature on HCCI combustion. The quantitative values demonstrate that a temperature change of less than 20K at 90 degree crankangle BTDC (which is ca. 10K at induction) is enough to shift the combustion by 8 degree crankangle.

3. Conclusions

Optical diagnostics techniques have become a powerful tool in engine research. Modern laser-based tools give insight into the engine combustion functioning chain. Nearly all steps of engine combustion from the spray formation to the stages of combustion and pollutant formation have become more transparent by the use of optical techniques. The most important features of optical tools are its high temporal and local resolution and its non-intrusive character for the investigation of complex processes. For the future it will stay important to adapt the already developed techniques to modern engine development and to come closer to realistic boundary conditions. Furthermore, there are still regions of engine combustion that are not easily accessible today like the primary spray break-up in dense spray regions, parts of the pollutant formation and exhaust gas after treatment. The development of measurements techniques for these regions and for upcoming new engine combustion concepts will keep on driving us in future.

4. Acknowledgements

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