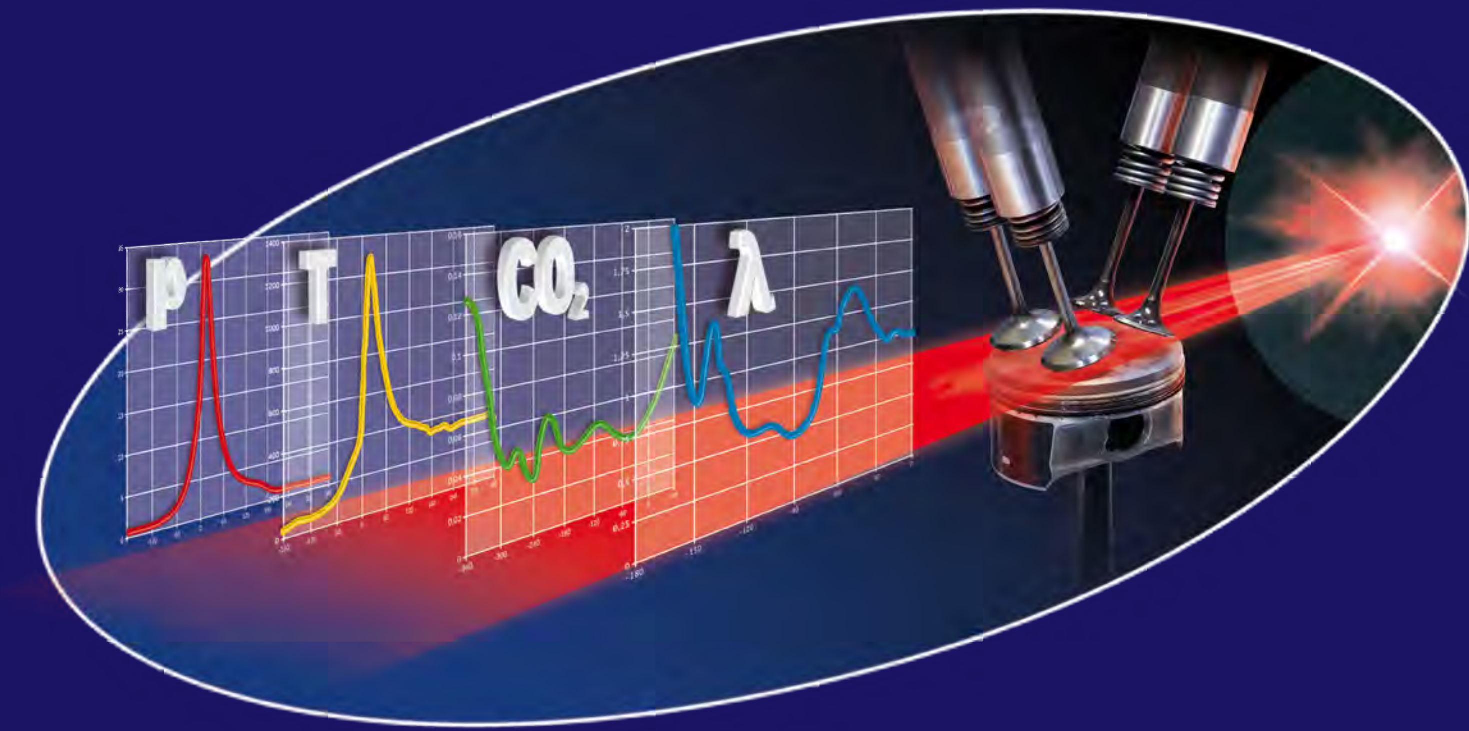



# Internal Combustion Optical Sensor (ICOS)

Optical Engine Indication

LaVision

FOCUS ON IMAGING

# In-Cylinder Optical Indication

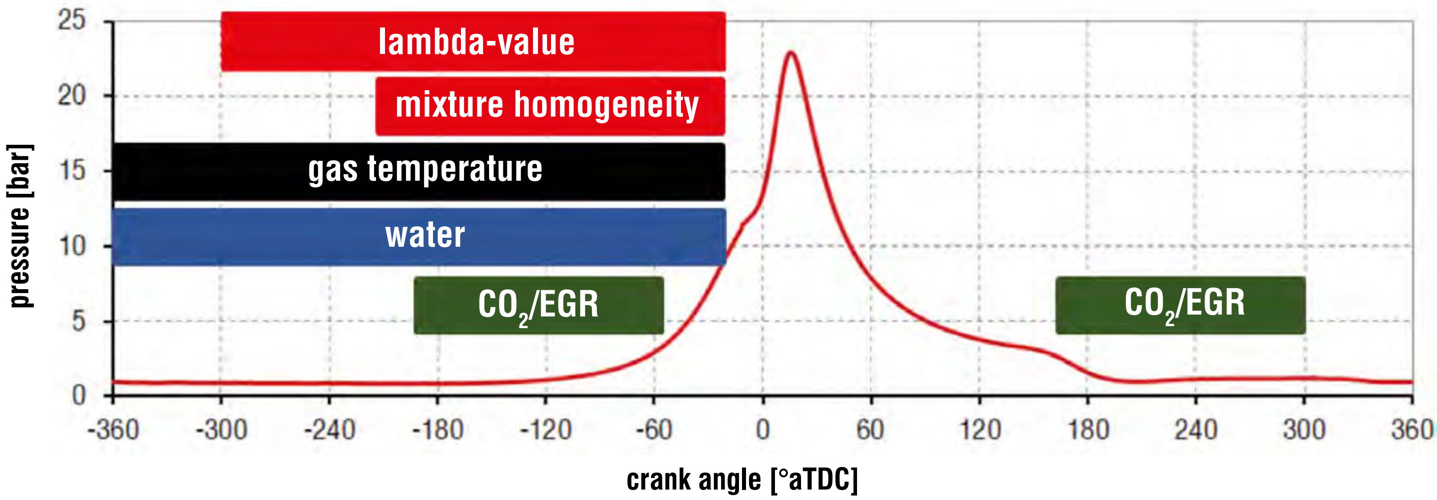
- air/fuel ratio
- exhaust gas concentration and EGR
- gas temperature
- water concentration


## Internal Combustion Optical Sensor

LaVision's **I**nternal **C**ombustion **O**ptical **S**ensors (**ICOS**) measure crank angle resolved air/fuel ratio, exhaust gas concentration or gas temperature and water concentration locally at the spark plug, glow plug or at any other in-cylinder location using optical probes. The **ICOS** systems provide highly time-resolved data of the relevant engine parameters at the tip of the probe. Single cycle parameter profiles as well as variations over many cycles are recorded.

- **analysis of highly dynamic engine conditions**
- **crank angle and cycle resolved**
- **no engine modification required**
- **for spark ignition and compression ignition engines**

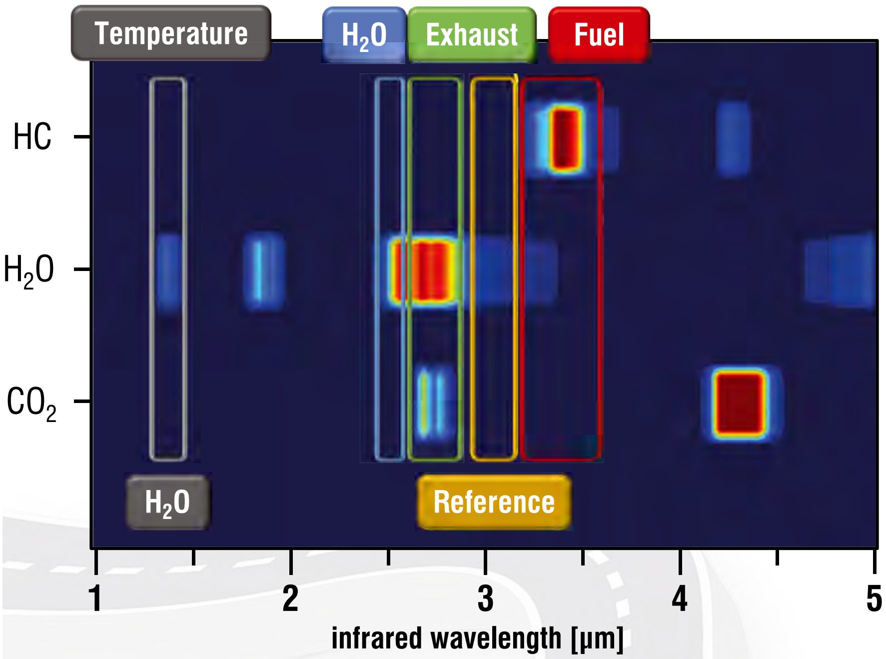
The combustion process in an internal combustion engine is typically characterized by analyzing the measured in-cylinder pressure trace. The work of the engine and the speed of the mass fraction burned can be evaluated from these pressure curves. However, the quality of the combustion is strongly influenced by the conditions and quality of the mixture preparation prior to ignition. Mixture inhomogeneity, wanted or unwanted, and ignitibility of the in-cylinder charge cannot be determined by pressure indication alone. Additional optical engine indication of the local air/fuel ratio at the spark plug position as well as $CO_2$- and water concentration measurements quantify the mixture formation and help to improve injection strategies, exhaust gas recirculation or water injection concepts. Knowledge of the gas temperature in addition to pressure is critical to operate closer to the knock-limits.




Optical engine indication synchronized with standard pressure indication allows a much more detailed characterization of the in-cylinder charge formation process.

# Measurement Principle of Optical Engine Indication

The **ICOS** measurement systems are based on infrared absorption spectroscopy of the relevant molecules like water, $CO_2$ or hydrocarbons. The in-situ absorption technique is **instantaneous** and needs **no gas extraction**. A single probe can measure multiple parameters simultaneously.




*Molecular absorption bands detected by ICOS*

Broadband light detection modules of the **ICOS** system in the mid infrared provide ultra-fast analysis of the air/fuel-ratio and $CO_2$-concentration. Gas temperature and water concentration are determined by the spectral analysis of water absorption bands in the near infrared spectrum.

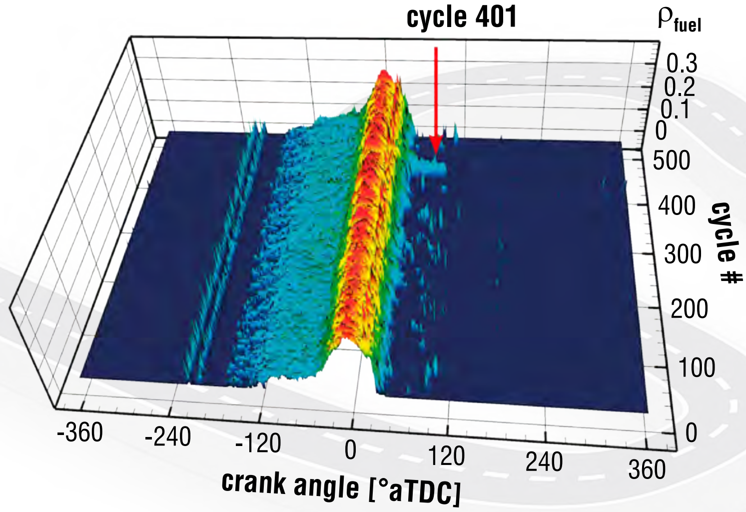
The fiber based light guiding supports different measurement geometries inside the combustion chamber.
In the spark plug configuration shown here the absorption path is realized with a small cage with a reflection mirror at its end.

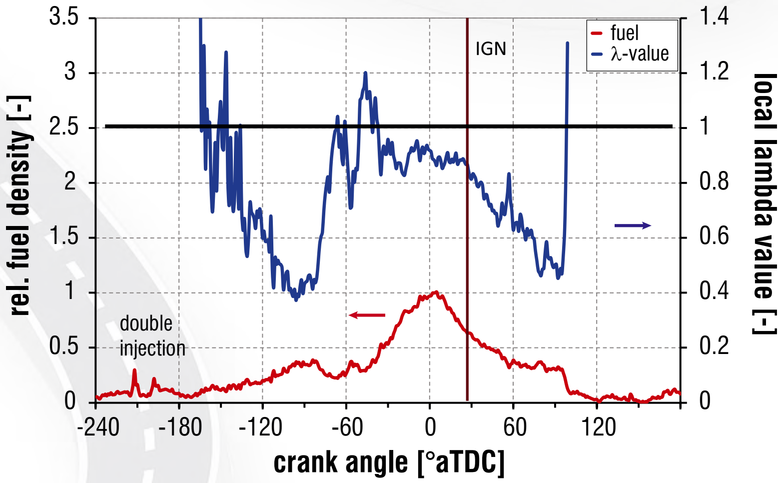
**References**
A. Grosch, V. Beushausen, O. Thiele, and R. Grzeszik, “Crank angle resolved determination of fuel concentration and air/fuel ratio in a SI-internal combustion engine using a modified optical spark plug”, SAE Technical Papers, 2007, https://doi.org/10.4271/2007-01-0644
S. Liebsch, A. Zboralski, J. Maass, M. Guenther, et al., “Cold Start Simulation and Test on DISI Engines Utilizing a Multi-Zone Vaporization Approach“, SAE Technical Papers, 2012, https://doi.org/10.4271/2012-01-0402

## Cycle-to-Cycle Variations

The **ICOS** system offers the possibility to examine hundreds of consecutive cycles with crank angle resolution to analyze e.g. the stability of in-cylinder processes before ignition. In the upper diagram fuel density profiles of a catalytic converter heating point recorded at the spark plug are shown over 500 consecutive cycles. After the dual injection (-200° and -180° CAaTDC), the fuel density rises during compression towards Top Dead Center (TDC) and decreases again due to the beginning of expansion afterwards. When ignition takes place at 30° to 40° CAaTDC, the fuel disappears. Abnormal combustion in individual cycles is resolved such as the delayed ignition in the marked cycle 401.

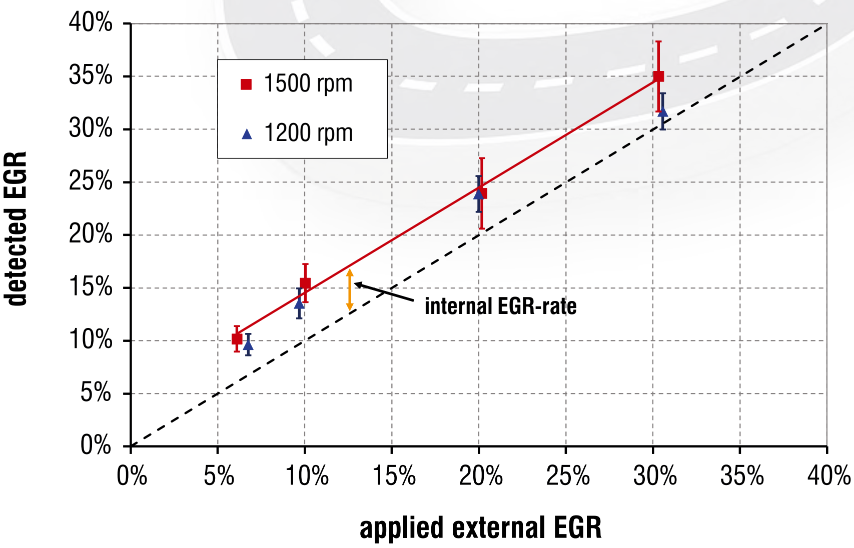
The drop in the fuel density at 100° CAaTDC marks the appearance of the flame front locally at the probe tip, significantly later than the ignition timing. For this individual cycle, the fuel density and the corresponding λ-value curve are also shown in the bottom diagram. The λ-value curve is calculated from the fuel density using a thermodynamic model.




## External and Internal EGR

The correlation between the applied external EGR rate and the measured EGR rate for two different engine speeds in a truck Diesel engine is demonstrated here. The error bars show the EGR fluctuations over 100 cycles. The offset between the measured and applied EGR-values (dashed line) is the internal EGR rate at a given condition. The results show a higher standard deviation of the EGR rate at higher engine speeds. The amount of internal EGR rate changes with engine speed and applied external EGR rate, proving the strong influence of these engine parameters on the internal flow management.

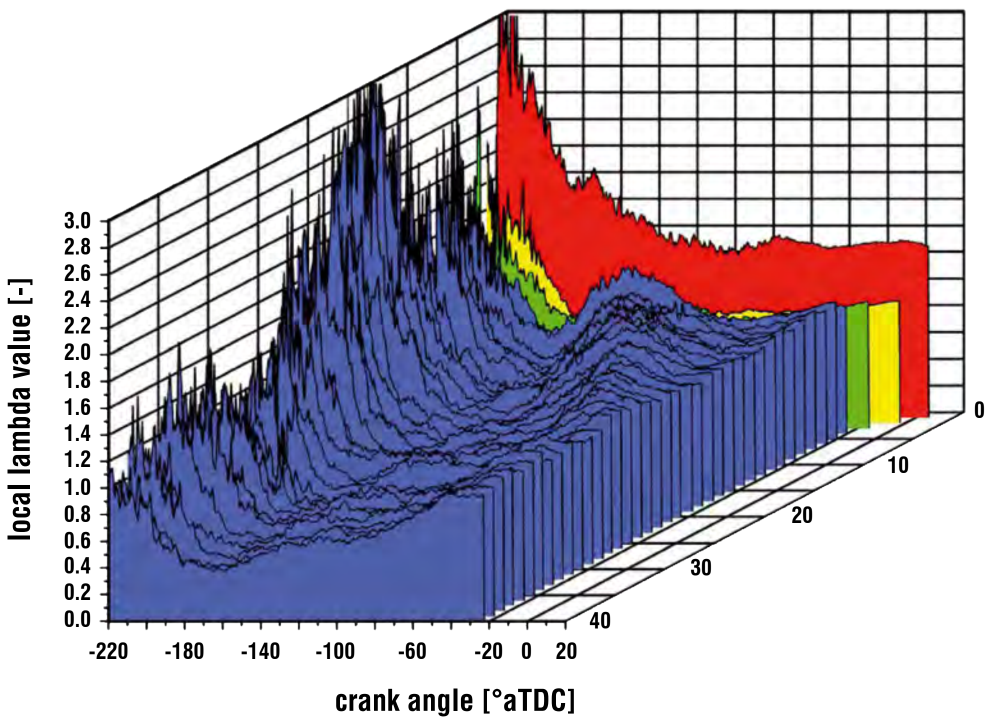



**References**

R. Vanhaelst, O. Thiele, T. Berg, B. Hahne, H.-P. Stellet, F. Wildhagen, W. Hentschel, C. Jördens, J. Czajka, K. Wislocki,"Development of an in-cylinder-optical infrared sensor for the determination of EGR and residual gas rates inside SI and diesel engines",11th Congress Engine Combustion Processes, 2013

# ▸ investigation of highly dynamic engine conditions
# ▸ verification of injection strategies and systems
# ▸ air/fuel ratio - lambda-value - transients
# ▸ external and internal EGR variation and stability

The **ICOS** system provides crank angle-resolved measurements of in-cylinder mixture formation over hundreds of single cycles for the analysis of mixture stability and combustion performance under transient engine conditions.




## Fuel Mixture Formation during Tip-In

The **ICOS** analysis of the air/fuel-ratio evaluation during a tip-in (load change) of a near production SI engine is shown on the left. The mixture prior to ignition of first cycle is lean while the second and third cycle with rich fuel mixtures.

This is the reason for high unburned hydrocarbon emissions during the first cycles before stabilizing. In the following cycles the cylinder charge develops from rich conditions (low λ-value) back to stoichiometric mixtures at the time of ignition. During the first 30 cycles a moving wave structure in the mixture formation process is detected. This is a result of changing in-cylinder flow due to different valve timings.

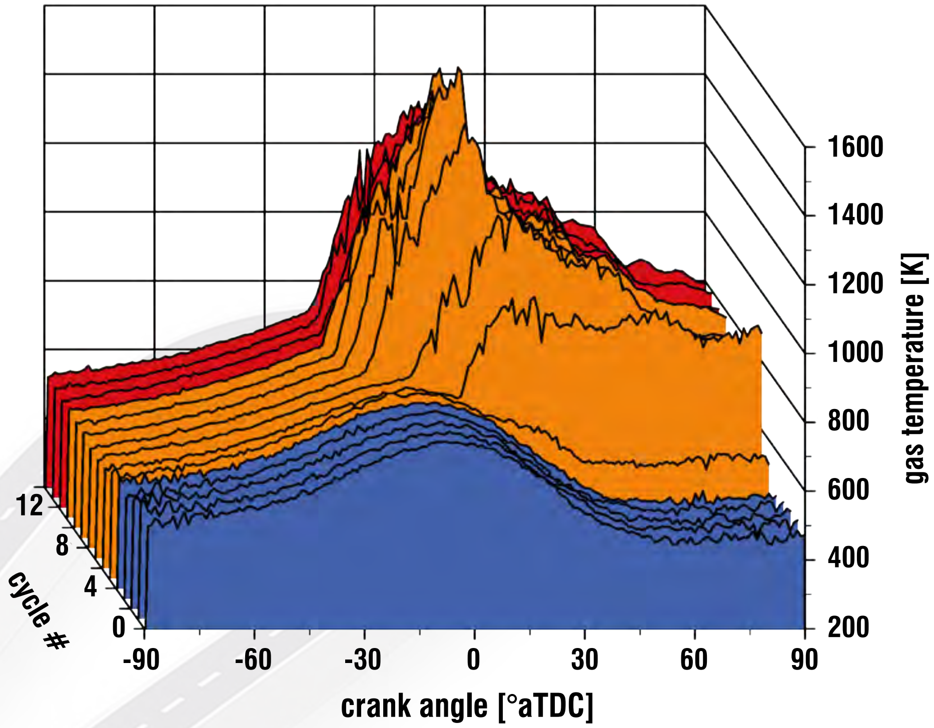
**References**

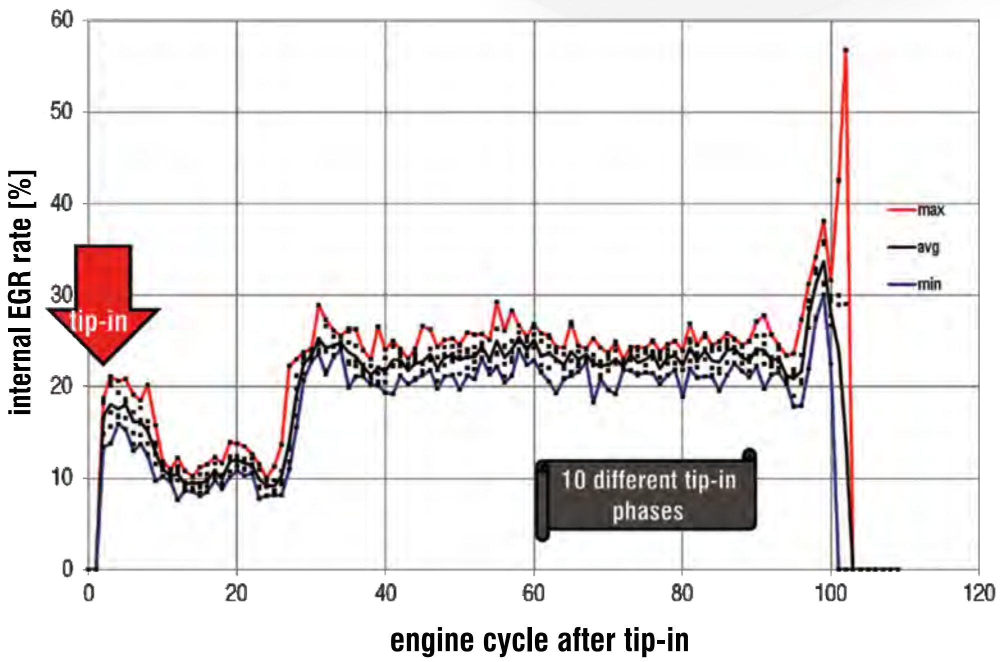
Disch, C., Pfeil, J., Kubach, H., Koch, T. et al., „Experimental Investigations of a DISI Engine in Transient Operation with Regard to Particle and Gaseous Engine-out Emissions“, SAE Int. J. Engines 9(1):262-278, 2016, https://doi.org/10.4271/2015-01-1990

# Transient Temperatures

The in-cylinder gas temperature is measured using the **ICOS-Temperature** system applying a spark plug probe. The diagram shows the transient behavior of the temperature during the tip-in (load change) operation for 15 engine cycles.

The engine is coasting over the first 5 cycles. After this the accelerator pedal is pushed down resulting in a load step and transient firing behavior over 7 cycles. The combustion process then stabilizes for the following cycles. The shown temperature profiles are averaged over 10 repeated tip-ins.



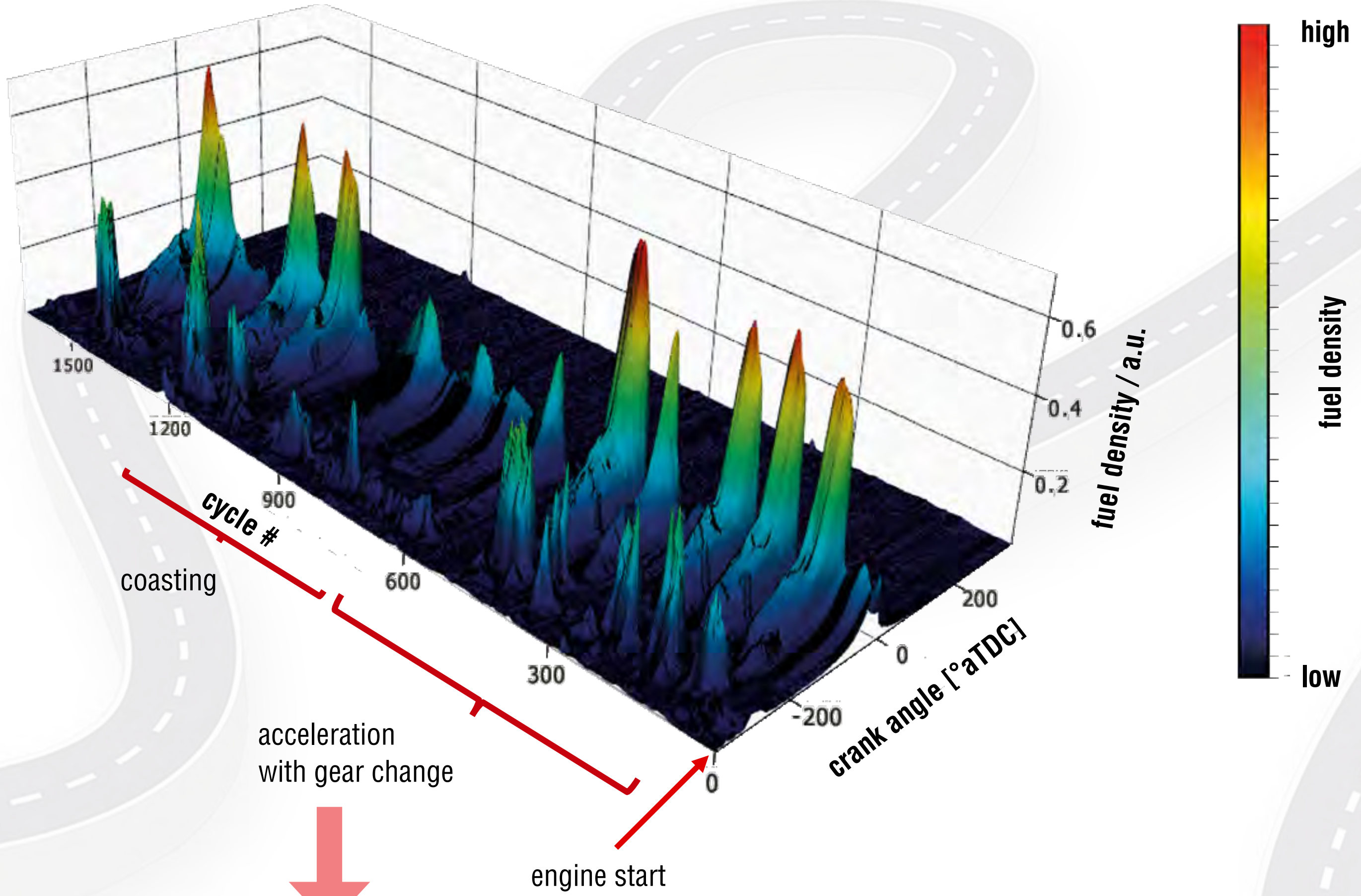



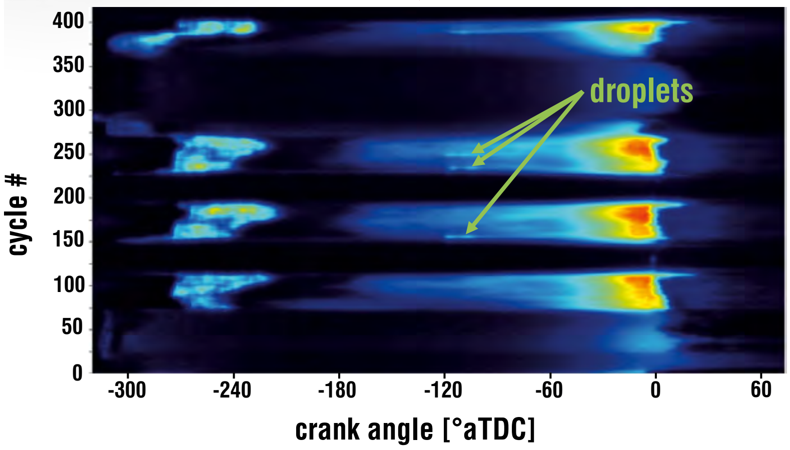

# Internal EGR

Together with the air/fuel-ratio the $CO_2$-concentration and EGR-rate are measured using the **ICOS** system under tip-in conditions. Changes of the valve timing in the first 30 accelerating cycles are changing the internal EGR-rate before a stable operation is reached again for constant engine operation.

# ▸ analysis of hundreds of consecutive cycles
# ▸ single cycle phenomena can be identified

The analysis of engine emissions under real driving conditions is necessary to meet future legislations. The **ICOS** systems measure in-cylinder parameters relevant for engine emissions in all required real driving operation modes including engine start.
Shown here is the fuel density at the spark plug location for over 1000 cycles after engine start. Measurements are carried out in the first cylinder of a six cylinder engine with variable valve timing. Real driving conditions are simulated with an engine-in-the-loop test bed setup. Different engine operation modes are related to specific fuel concentration profiles near the spark plug.



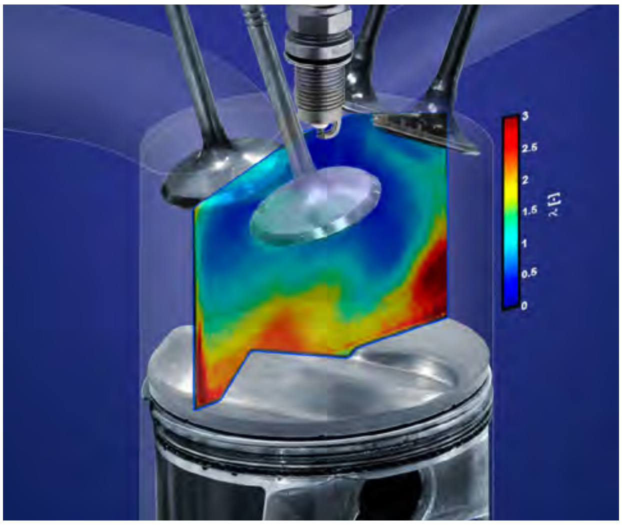




*Color coded fuel density profiles over consecutive engine cycles during acceleration.*

Single peaks in the fuel density profiles indicate droplets crossing the measurement volume near the spark plug. This unwanted effect occurs during the acceleration phase in individual cycles with negative effects on engine efficiency and emissions.

# optimization of methane and CNG engines
# mixture formation analysis
# air/fuel ratio - lambda-value

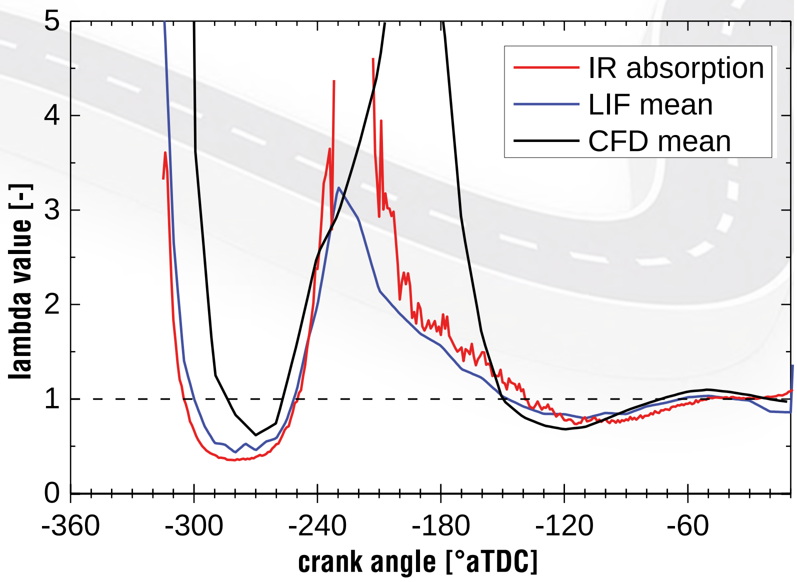
Gas engines are a potential factor in reducing overall fleet emissions. Current automotive gas engines have not reached the same maturity as their gasoline or Diesel counterparts. Mixture formation in gas engines is completely different compared to liquid fueled engines. Therefore further improvements and new concepts require special analysis tools.
The **ICOS-CNG** system measures λ-profiles in methane fueled engines as well as in compressed natural gas (CNG) engines.



*λ-value distribution measured with LIF imaging in a transparent engine.*

## Measured and Calculated λ-Profiles in a Gas Engine

For validation purposes two measurement techniques are applied in a gas engine to measure λ-values during mixture formation. While Laser Induced Fluorescence (LIF) is a 2-dimensional imaging technique only applicable in modified (transparent) engines, the **ICOS** spark plug probe measures the λ-value locally at the tip of the spark plug without any engine modifications. Both experimental results show good agreement over a wide crank angle range. Compared with these measurements the CFD calculation shows larger deviations underlining the necessity of **ICOS** data for model validation.

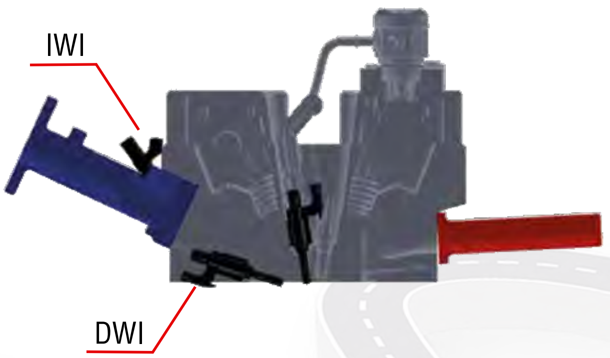



*Comparison of λ–profiles from LIF imaging, IR absorption, and CFD simulation[1].*

**References**
[1] Kranz, P., Fuhrmann, D., Goschütz, M., Kaiser, S. et al., „In-Cylinder LIF Imaging, IR-Absorption Point Measurements, and a CFD Simulation to Evaluate Mixture Formation in a CNG-Fueled Engine," SAE Int. J. Engines 11(6), 2018, https://doi.org/10.4271/2018-01-0633

# evaluation of water injection strategies

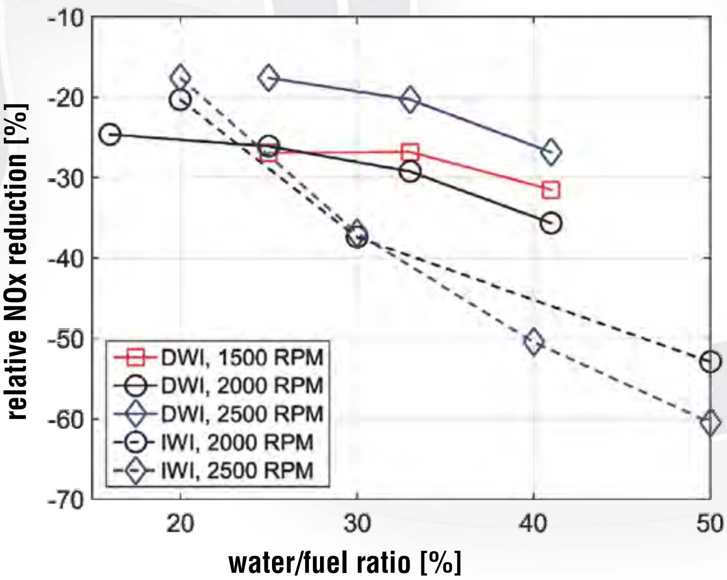
Water injection is a promising technology for further improving fuel efficiency, reducing emissions and increasing power in internal combustion engines. Especially in spark ignition engines reaching higher efficiencies is limited by knock. Charge cooling by water injection has been shown to effectively mitigate knock. In addition, water injection can lead to reduced NOx emissions. Water injection strategies include indirect intake manifold water injection, in-cylinder direct injection or fuel/water emulsion injection. To evaluate the different injection strategies, the knowledge of in-cylinder gas temperature and water concentration is invaluable.



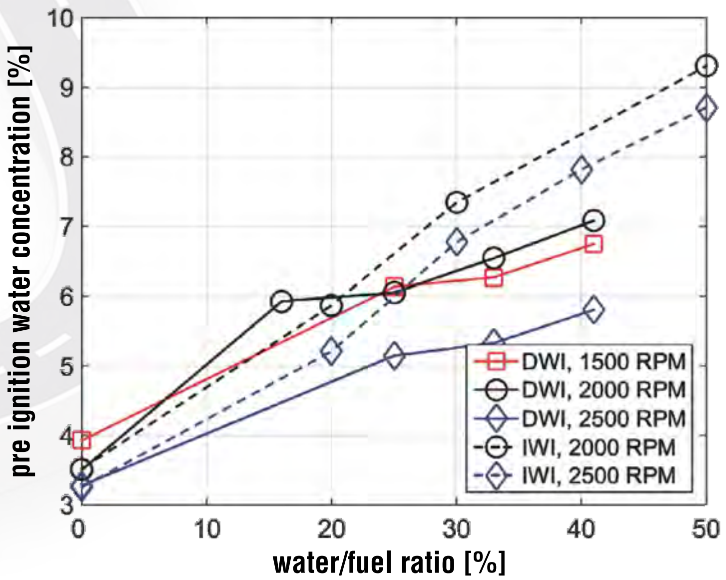

*Cylinder head showing positions of Indirect Water Injector (IWI) and Direct Water Injector (DWI).*

## Comparison of Direct and Indirect Water Injection

Different water injection strategies are carried out in a single cylinder engine[2]. The indirect water injection (IWI) in the intake manifold shows a higher efficiency in NOx reduction in comparison to direct water injection (DWI) in the cylinder (see left figure below). One important factor for NOx reduction is the cooling effect of vaporizing water and its presence as inert gas right before ignition. The in-cylinder water concentration for both injection strategies is measured with **ICOS**, shown in the figure below (right). For IWI, the expected linear relationship between injected water (water / fuel ratio) and measured in-cylinder water concentration, can be observed. In comparison the measured pre-ignition water concentrations for DWI are significantly lower. Typical spray-wall interaction mechanisms, i.e. wall impingement and/or entrainment in the wall oil film, are the most likely cause. The reduced water content in the reactive zone is the reason for the less effective NOx reduction for DWI.




*$NO_x$ reduction due to water injection[2].*




*Pre-ignition water concentration for DWI and IWI for injected water / fuel ratio[2].*

**References**

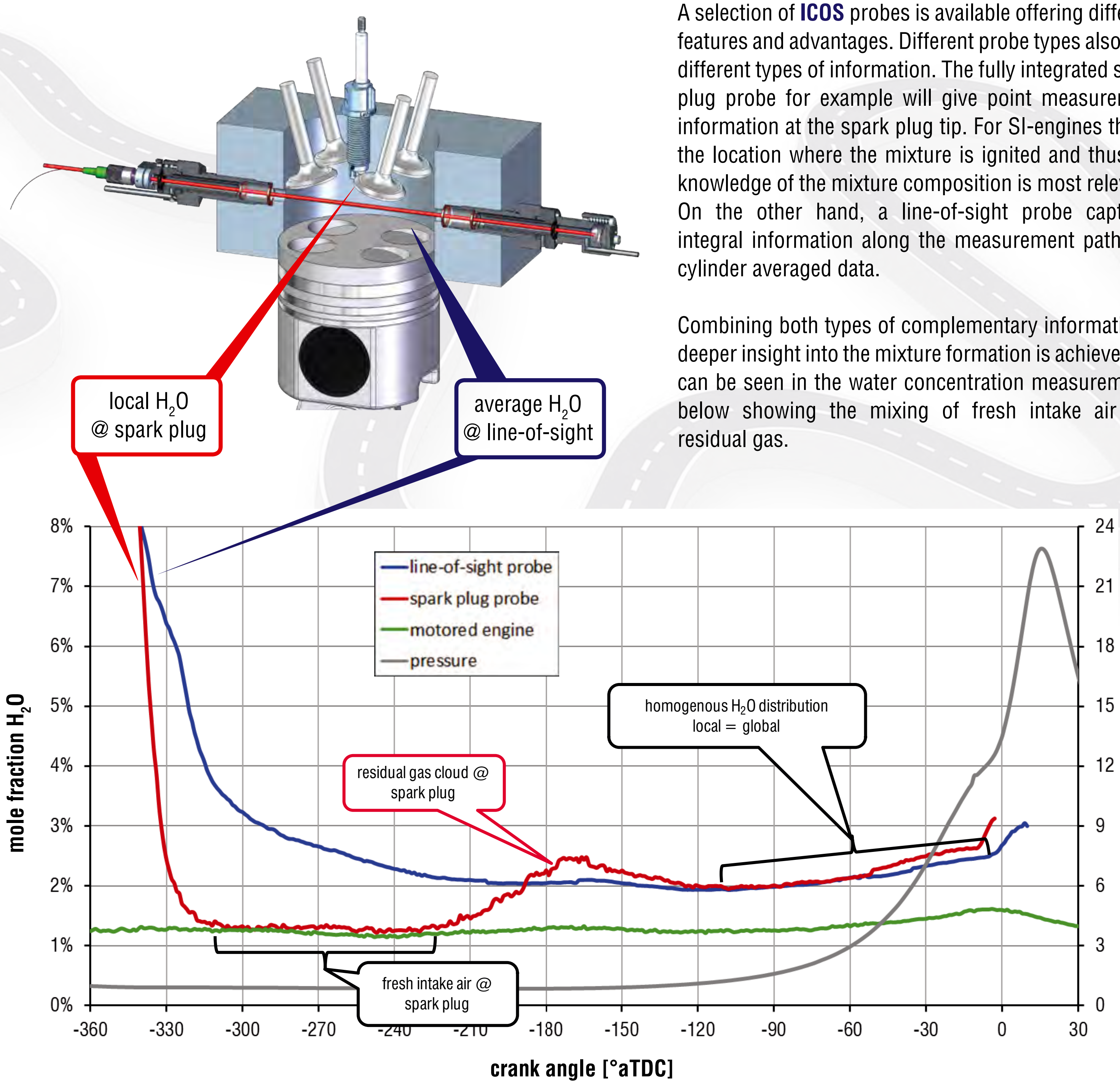
[2] M. Kauf, M. Gern and S. Seefeldt, "Evaluation of Water Injection Strategies for $NO_x$ Reduction and Charge Cooling in SI Engines", JSAE 20199014, SAE 2019-01-2164, 2019

# in-cylinder probes for local indication
# line-of-sight probes for cross-cylinder averaged information

## Comparison of Local and Global Water Concentration Measurements

A selection of **ICOS** probes is available offering different features and advantages. Different probe types also give different types of information. The fully integrated spark plug probe for example will give point measurement information at the spark plug tip. For SI-engines this is the location where the mixture is ignited and thus the knowledge of the mixture composition is most relevant. On the other hand, a line-of-sight probe captures integral information along the measurement path, i.e. cylinder averaged data.

Combining both types of complementary information a deeper insight into the mixture formation is achieved, as can be seen in the water concentration measurements below showing the mixing of fresh intake air and residual gas.



- integrated spark plug probes
- non-firing probes for flexible choice of location
- integral line-of-sight probes
- large variety of adapters to suit different engines

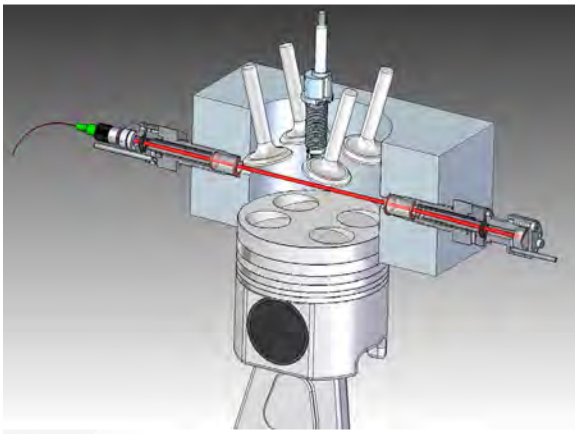
## Spark Plug and M5 Probes

Firing and non-firing sensor probes are available for the **ICOS** systems. The in-cylinder probes can be installed in nearly any engine with almost no modification required. This is applicable for research test engines as well as near production engines without optical access. For example, the spark plug probe directly replaces the standard spark plug in SI engines while maintaining full firing capability.

A single probe can measure air/fuel ratio and exhaust gas simultaneously. Multiple probes can be installed to measure in different cylinders simultaneously.

All in-cylinder probes have a small mirror at the tip of the light absorption path and reflecting back the light to the receiver. Measuring over several hours or days using the same mirror is realistic under standard engine operating conditions. The mirrors are exchangeable and supplied as a set of spare parts. Exchanging a mirror only takes a few minutes.

## Integral Line-of-Sight Probes



For certain investigations it is more relevant to obtain global measurement data from inside the engine to compare with 1D-simulation results. LaVision offers customized line-of-sight probe solutions to measure spatially averaged parameters. The picture shows a schematic installation of a line-of-sight probe in an engine for cross-cylinder temperature measurements. The long absorption path of this configuration also results in a favorable signal to noise ratio without interfering with the combustion chamber geometry and gas flow.

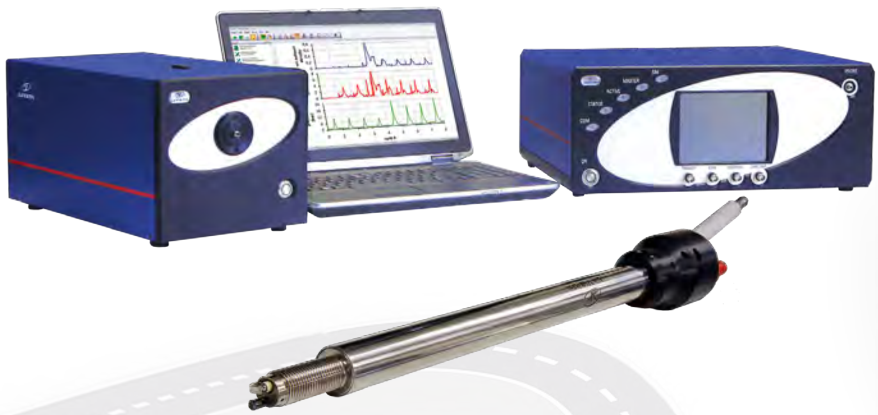
| ICOS probe | Line-of-sight | M5 | Spark plug |
|---|---|---|---|
| **Engine type** | Gasoline, CNG<br>Diesel | Gasoline, CNG<br>Diesel | Gasoline, CNG |
| **High IMEP (>0.7 MPa)[1]** | ✓ | - | - |
| **Max. operating peak-pressure** | 30 MPa | 20 MPa | 20 MPa |
| **Lambda**<br>**EGR**<br>**Temperature**<br>**Water** | ★★★<br>★★★<br>★★★<br>★★★ | ★★★<br>★★★<br>★<br>★★★ | ★★★<br>★★★<br>★<br>★★★ |
| **Measurement location** | averaged across cylinder | local near wall | local at spark plug |
| **Nominal thread size M14**<br>**M12**<br>**M10**<br>**M8**<br>**M5** | ✓<br>✓<br>✓<br>✓[2]<br>- | ✓[3]<br>✓[3]<br>✓[3]<br>✓[3]<br>✓ | ✓<br>✓<br>-<br>-<br>- |
| **Impact to engine** | 2 holes | 1 hole M5 or glow-plug adapter | replaces spark plug |
| **Easy adaption to engine** | ★ | ★★ | ★★★ |
| **High load conditions** | ★★★ | ★★[4] | ★ |

[1] usage of M5 and spark plug probes is limited to lower/mid IMEP conditions. Typical limit for water cooled passenger car engines shown in brackets.

[2] at reduced signal

[3] with appropriate adapter

[4] a cooled version is available for higher heat loads



## ICOS System

The ignition quality of in-cylinder charge cannot be determined by pressure indication alone. The optical engine indication of fuel density and local air/fuel-ratio at the spark plug position using the **ICOS** system reveals a quantification of the ignitibility of the mixture at the exact ignition position. Additionally, concepts of Exhaust Gas Recirculation (EGR) can be verified by measuring the $CO_2$-concentration with the system inside or outside the engine.

- air/fuel-ratio – lambda-value
- $CO_2$-concentration and EGR-ratio

## ICOS-Temperature System

The knowledge of the gas temperature and water concentration during the mixture formation is becoming increasingly interesting for the development of state-of-the-art combustion processes. Especially the impact of recirculated exhaust gas or additional water injection strategies to the mixture formation is analyzed using the **ICOS-Temperature** system.

- gas temperature
- water concentration


## ICOS-CNG System

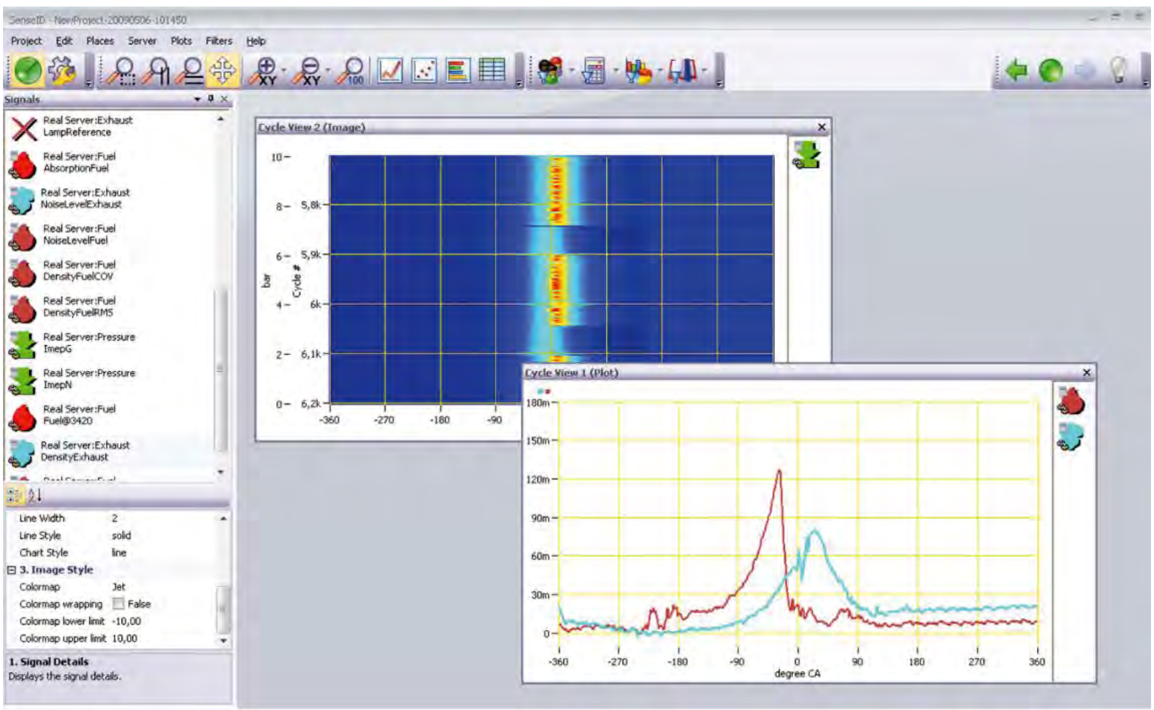
The concentration of methane or compressed natural gas (CNG) is measured highly time-resolved with the **ICOS-CNG** system recording the air/fuel-ratio (lambda-value) evolution to evaluate gas injection strategies.

- methane and CNG gas engines
- air/fuel-ratio – lambda-value

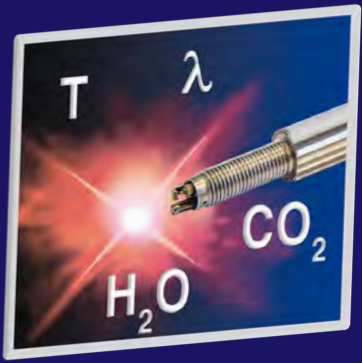
| System | ICOS | ICOS - CNG | ICOS-Temperature |
|---|---|---|---|
| Indicated quantities | Fuel density, air/fuel ratio<br>$CO_2$-concentration, EGR-rate | Fuel density, air/fuel ratio<br>(CNG, methane) | Gas temperature,<br>$H_2O$-concentration |
| Acquisition rate | 30 kHz<br>(33.3 µs response time) | | 23 kHz<br>(43.5 µs response time) |
| Measurement error | Fuel density: < 2%<br>$CO_2$-concentration: < 0.2 vol% | CNG-concentration: < 5% | Gas temperature: < 20 K<br>$H_2O$-concentration: < 0.2 vol% |
| Applications | Mixture preparation<br>Combustion stability | | |
| | Direct injection<br>Cold start<br>Load changes<br>Ignition behavior<br>Internal & external EGR<br>Multiple cylinder EGR distribution | Gas engines<br>CNG / methane fuel<br>Dual fuel | Validation<br>Downsizing<br>EGR<br>Water injection<br>HCCI |

## ICOS Software

The SenseID software is developed for data acquisition and operation of the LaVision **ICOS** measurement systems. SenseID is optimized for measurements on internal combustion engine test beds. Measurement data are continuously output on the online data display and synchronized to the engine's rotary encoder signals, allowing recordings of hundreds of consecutive engine cycles.



# Automotive Measurement Products

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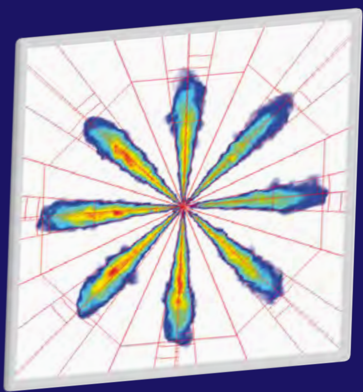

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