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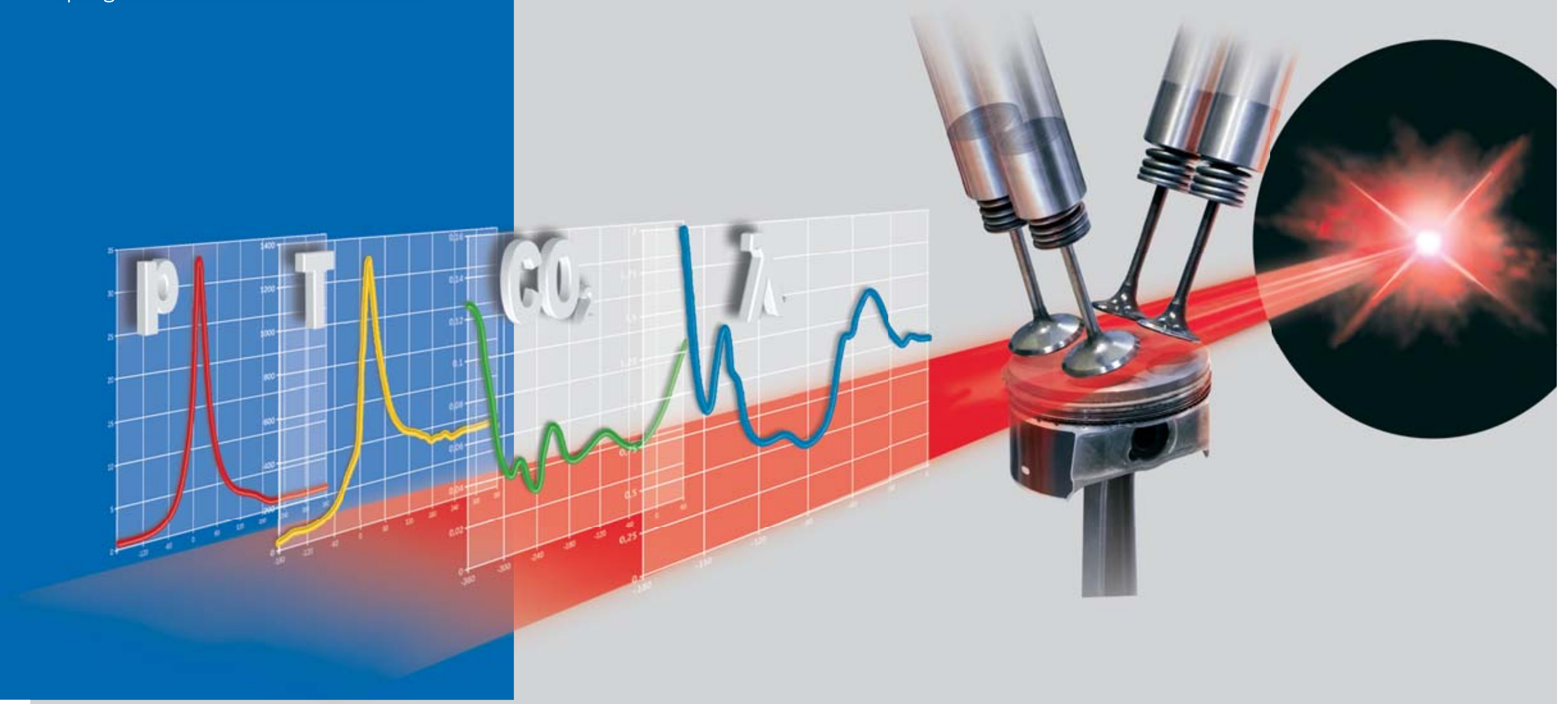
Springer Vieweg

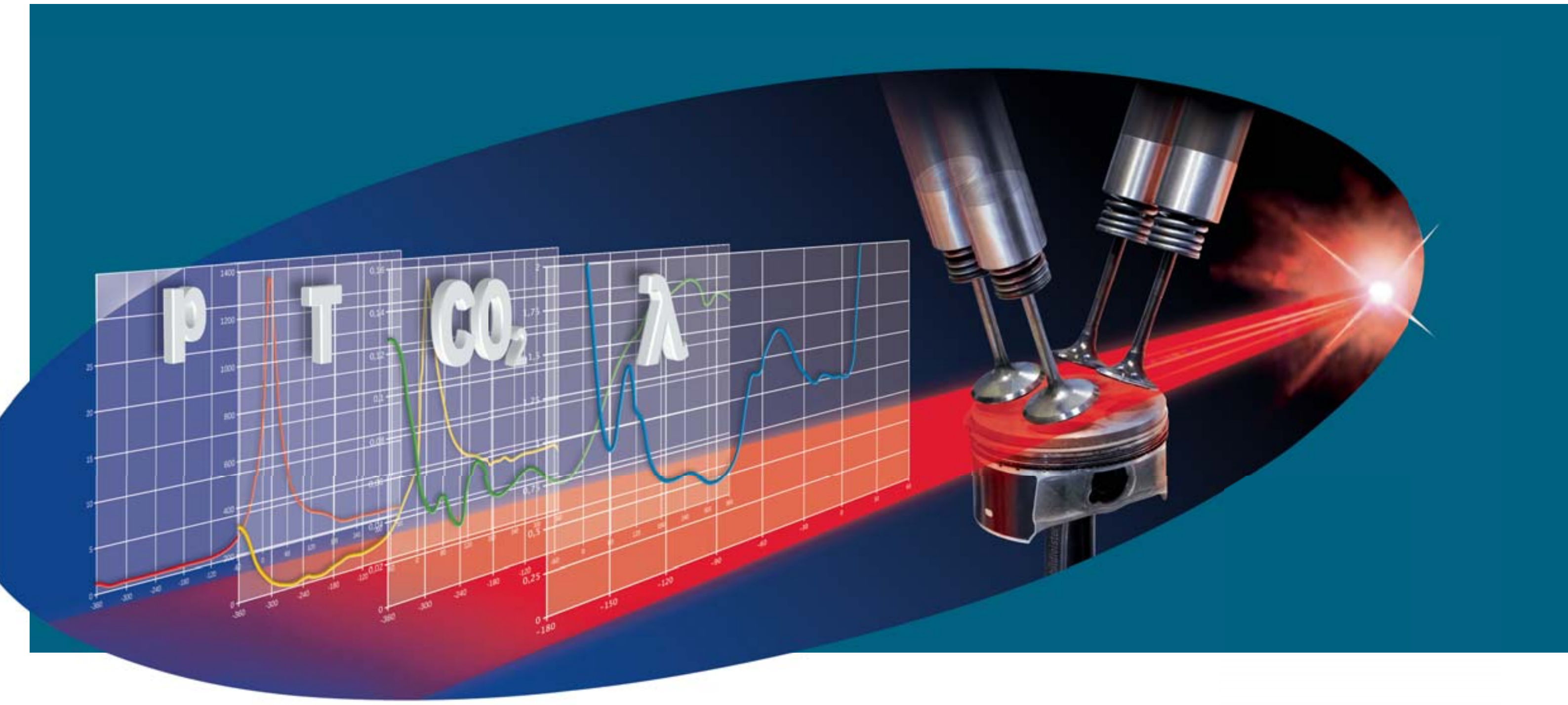
MTZ WORLDWIDE

06 June 2013 | Volume 74

Offprint
from MTZ 06.2013
Springer Vieweg
Springer Fachmedien Wiesbaden GmbH



MEASUREMENT OF IN-CYLINDER MIXTURE FORMATION BY OPTICAL INDICATION



NEW MEASURING METHOD

Modern engine concepts are based on complex mixture formation and combustion processes with direct injection, exhaust gas recirculation and downsizing. Their successful optimisation as well as specific conditions such as cold start behaviour requires an extension of pressure indication by the addition of engine-relevant indication quantities.

The sensor system presented in the following supplements the established pressure indication system by adding the optically measured in-cylinder characteristic quantities of fuel density, residual gas content and mixture temperature, as well as the λ value and cycle-resolved EGR rate derived from these. The optical indication system, which carries out its measurements in real time, measures these combustion chamber quantities with high temporal resolution both locally in the combustion chamber and spatially averaged over the entire cylinder cross-section of series-production engines [1]. This comprehensive characterisation of mixture formation and combustion makes it possible to meet the stricter requirements of new exhaust and CO_2 standards for gasoline, gas and diesel engines.

OPTICAL INDICATION

Pressure indication cannot fundamentally provide any direct information on the quality of mixture formation with regard to ignitability (λ value), residual gas content (internal EGR rate) or the gas temperature in the cylinder before combustion. These quantities can be measured only with the aid of optical indication methods. The combustion chamber sensors presented here enable these measurements to be made in situ, i.e. directly in the combustion chamber of series-production engines without any need to extract gas for sampling. In contrast to pressure indication, optical indication measures quantities locally at predetermined locations in the combustion chamber, such as at the spark plug or glow plug, although the measured section can also be extended over the entire cylinder diameter. The crank angle-resolved fuel and CO_2 concentration

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MEASUREMENT OF IN-CYLINDER MIXTURE FORMATION BY OPTICAL INDICATION

The company LaVision has developed an optical indication process that can be used to determine lambda, residual gas and temperature curves in the combustion chamber with high temporal resolution. The sensor system is able to provide crank angle-resolved, real-time measurements of the complete process of in-cylinder mixture formation over hundreds of single cycles.

curves can be recorded simultaneously with the same sensor probe. From the measured CO_2 concentrations in the cylinder, cycle-resolved internal EGR rates can be determined, and the simultaneous operation of several probes can also represent the uniform distribution of exhaust gas recirculation over different cylinders.

The gas temperature is measured directly using the identical probes, or it can be determined indirectly by measuring the gas density, for example the CO_2 curve, with the aid of thermodynamic assumptions, as is also the case for the cylinder pressure. Thus, the CO_2 sensor signal alone can provide a multi-parameter indication (residual gas, EGR rate, pressure and temperature).

MEASURING PRINCIPLE AND SENSOR PROBE CONFIGURATIONS

In-cylinder gas analysis for optical engine indication is based on the infrared (IR) absorption of hydrocarbons as evidence of fuel and on the IR absorption of carbon dioxide or water. All three relevant gas components absorb the incoming IR light on different wavelengths and their presence can therefore be proven selectively. To implement the absorption measuring principle, the sensor probe has a short absorption section at the combustion chamber end that is exposed to IR light. Each gas component attenuates the strength of the incoming light along the measuring section, and the level of absorption is directly proportional to the gas density. If the engine conditions at valve closure are known, the measured gas densities are converted into gas concentrations or λ values [2].

As shown in ❶, the optical sensor probe can be integrated into a spark plug with an M12 or M14 thread or into a glow plug. Alternatively, in the form of an M5 screw-in probe, it can be installed in the combustion chamber at any point at which the protruding sensor head does not impair the movement of the piston. If the entire cylinder diameter is selected as the measured section, the cross-cylinder sensor heads are mounted flush with the cylinder wall. The concentration curves (temperature curves) which are recorded at 30 kHz (23 kHz) are transferred by the sensor electronics to a crank angle scale and, therefore, allow a direct comparison with other indicated characteristic quantities such as cylinder pressure. ❷ gives an overview of the most important sensor speci-

❶ Types of sensor probes: probe in spark plug, M5 probe in glow plug, M5 probe

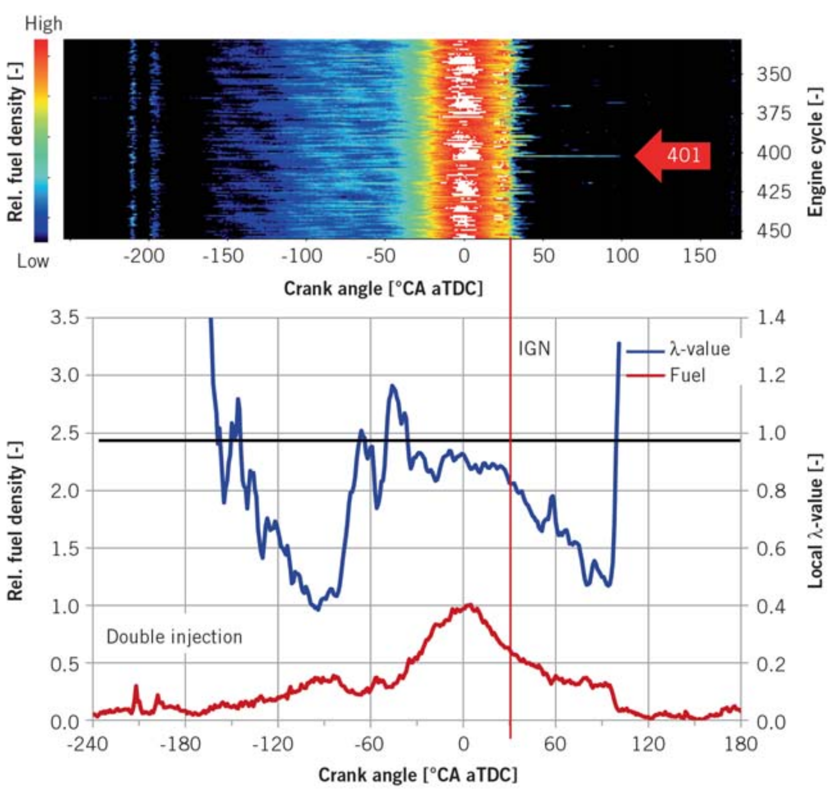
INDICATED QUANTITY	FUEL	RESIDUAL GAS (CO_2, H_2O)	GAS TEMPERATURE
Data rate	30 kHz	30 kHz	23 kHz
Data acquisition	Crank angle-resolved multiple cycles		
Accuracy	< 2 %	< 2 %	± 20 K at 3 vol. % H_2O
Derived quantity	λ value	Internal EGR	–
Sensor probes	M12/M14 spark plug, M5 glow plug adapter, M5 indication bore hole, transmission probe		
Applications	Mixture preparation, stability of the combustion process		
	: Direct injection : Cold start : Load changes : Ignition behaviour	: Cycle-resolved EGR rate : Equal distribution over cylinder : Valve timing	: Validation : Supercharging, EGR : HCCI

❷ Overview of systems

fications as well as typical application cases for the corresponding indication quantity.

FUEL DENSITY CURVE AND LOCAL LAMBDA VALUE

When a cold engine is started, the variation of the fuel density and the local λ value at the spark plug is very high. Crank angle-resolved measurement at the point of ignition can allow conclusions to be drawn about the ignitability of the mixture in the starting engine, and therefore enables the injection and ignition strategies to be optimised. Fast load changes result in non-steady-state conditions for charging and gas flow in the combustion chamber. Flexible selection of the installation location for the sensor probe in M5 indication bore holes, spark plugs or glow plugs makes it possible to record the curve of the mixture formation at selected measuring points.

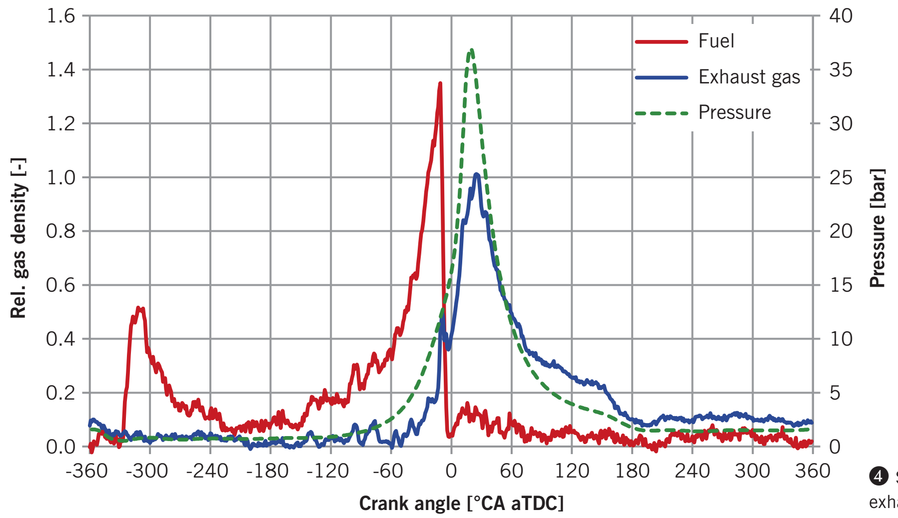


❸ Non steady-state fuel density curve of a catalytic converter heating point and the derived λ values at the spark plug for engine cycle #401

❸ shows the fuel density curve of a catalytic converter heating point recorded at the spark plug. These curves are colour-coded in the upper section of the image, with each line representing a cycle and each pixel representing one degree of crank angle. After the dual injection, the fuel density rises during compression to TDC. The uneven behaviour for each cycle is a result of the charge motion. Afterwards, the fuel density decreases again due to the beginning of expansion. When ignition takes place at 30 to 40 °CA ATDC, the fuel disappears from the measuring section. The uneven break-away edge in the fuel signal shows the strong variation of ignition from cycle to cycle. The marked cycle 401 is noticeable for its very delayed ignition, shown by a decrease in the fuel density at 100 °CA ATDC significantly after the ignition point. For this individual cycle, the fuel density and the corresponding λ value curve are also shown in ③ (bottom). If the fresh air quantity is known at the point in time of valve closure, the λ value curve can be calculated from the fuel density curve on the basis of a thermodynamic model, with calibration taking place at a known operating point [3].

SIMULTANEOUS FUEL AND RESIDUAL GAS MEASUREMENT

In downsized engines, secure ignition of the mixture is becoming increasingly difficult due to higher exhaust gas recirculation rates. The time-resolved simultaneous measurement of residual gas and fuel directly at the spark plug therefore allows targeted conclusions to be drawn with regard to ignitability [4].



❹ Simultaneous indication of fuel density, exhaust density and pressure in a gasoline engine

The example in ❹ shows a single cycle with simultaneous indication of the fuel density and residual gas density using a sensor probe integrated into a spark plug and measurement of the pressure curve at the same time through a separate indication bore hole. The measurement of the residual gas density in the cylinder allows the EGR rate, which is composed of the external and internal EGR rate, to be derived from a comparison of the curve before and after combustion.

CO_2, EGR RATES AND DERIVED QUANTITIES

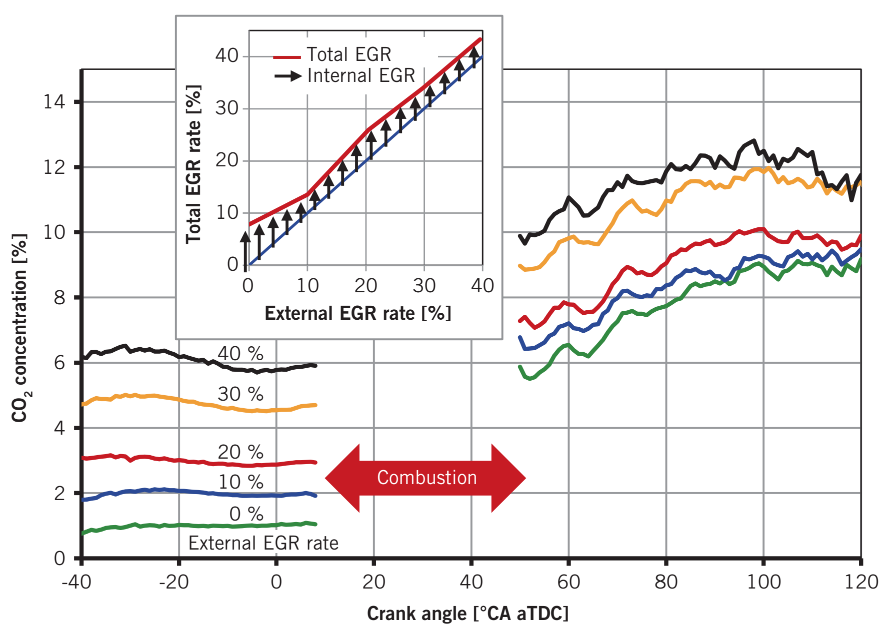
A uniform distribution of the EGR rate, an even residual gas mass in all cylinders combined with low cyclic fluctuations are the basic prerequisites for a series-production combustion process while ensuring compliance with exhaust emissions standards and low fuel consumption. In a similar way to the determination of the λ value, measured residual gas density curves can be converted into CO_2 concentration curves. This is shown in ❺ for a diesel engine with a different external EGR rate. The initial CO_2 concentration level before ignition is made up of the external EGR and the internally recirculated residual gas. The grading of the CO_2 concentration curves is based on the increasing external EGR. Even without external EGR, a residual gas quantity that is recirculated internally is still measurable (internal EGR).

The EGR rate is determined from the ratio of the residual gas concentration before and after combustion. If the externally set EGR rate is compared with the measured total EGR rate, the difference is the cycle-resolved internal EGR rate, ⑤ (top), which can be directly measured only with this in-situ indication of the residual gas.

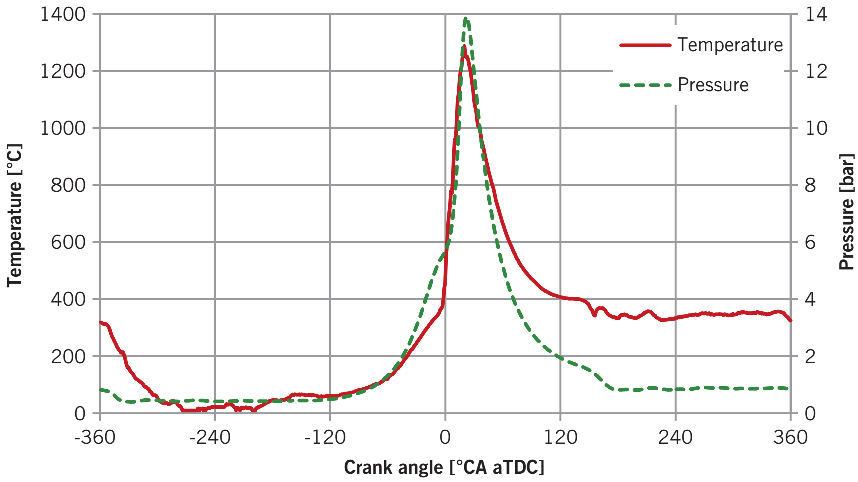
Measurement of the residual gas density or CO_2 density makes it possible to derive further crank angle-resolved and cycle-resolved characteristic quantities [5]. The corresponding pressure and temperature curve can therefore be determined from the CO_2 density signal. While a thermodynamic analysis furthermore allows conclusions to be drawn on the main points of combustion, the change in the CO_2 concentration provides information on the energy conversion.

CURVE OF MIXTURE TEMPERATURE

The temperature sensor allows direct measurement of the temperature curve during mixture formation and combustion. The curves of the temperature close to the cylinder wall can be measured with the reflection sensors shown in ①. Temperatures averaged globally over the



❺ Crank angle-resolved CO_2 curve and difference between external and total EGR rate



❻ Gas temperature curve of a gasoline engine, measured close to the spark gap

cylinder cross-section are measured with an arrangement of transmission sensors. ❻ shows the temperature curve together with the indicated pressure in a gasoline engine. Temperature indication can be used to observe the influences of, for example, exhaust gas recirculation on the gas temperature during the compression phase in real time, thus making it possible to clearly classify the ensuing effects on the combustion process and ignition behaviour.

SUMMARY AND CONCLUSION

Optical engine indication extends the established process of pressure indication by the addition of the in-cylinder characteristic quantities of fuel density, residual gas content and charge temperature as well as the derived local lambda value and the cycle-resolved internal EGR rate. As an innovative development tool, this sensor system is therefore able to provide crank angle-resolved, real-time measurement of the complete process of in-cylinder mixture formation over hundreds of single cycles. This measuring tool for development engineers enables in-cylinder conditions and relationships to be recognised more quickly, thus reducing the number of optimisation steps and shortening test stand time.

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