Optical Diagnostic Tools for Detection and Evaluation of Glow Ignitions

Arndt Döhler(✉) and Peter Schaffner

Advanced Engineering Gasoline Engine Technologies, Opel Automobile GmbH, Rüsselsheim am Main, Germany
Arndt.doehler@opel.com

Abstract. Downsizing as the development path chosen in recent years allows for a significant efficiency improvement of current gasoline engine concepts. However, with power densities beyond 20 bar BMEP the likelyhood of combustion irregularities is increasing.

State-of-the-art is the detection of these abnormal combustion phenomena by indication measurement technology. However, this measuring method reaches its limits when the point of origin of abnormal combustion events must be detected. The use of optical measuring systems makes it possible to generate the necessary location information.

In this study the use of optical diagnostic tools for the detection and evaluation of auto ignitions in charged direct-injection gasoline engines is evaluated. The application of "low-speed" and "high-speed" camera systems by means of combustion chamber endoscopy as well as fiber-optic measuring methods with optical access via the spark plug is presented. In addition, the use of infrared measurement technologies is discussed to enable a thermography of the combustion chamber surfaces.

It is explained how these analysis tools can be used for the detection of auto ignitions. Furthermore, the application limits of the measurement methods are discussed as well as the specific strengths of the individual methods, e.g. Low-Speed and High-Speed Video Endoscopy. Finally, an assessment is provided to explain to which extent the presented optical tools are suitable to provide the required location information.

1 Preface

Downsizing represents a technology to increase efficiency of SI engines significantly. Unfortunately, these engines are prone to abnormal combustion phenomena driven by the achieved high power densities, e.g., at high speed/high load conditions high combustion chamber surface temperatures can lead to glow ignitions. It is not known to the authors that a glow ignition like phenomenon can occur at low speed/high load too. With the thermodynamic conditions as well as the surface temperatures close to firing TDC being far below the limits for typical glow ignitions there is no obvious explanation for this phenomenon available.

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Since any kind of auto ignitions can cause severe engine failures understanding of the phenomena is crucial as a prerequisite for the development of appropriate mitigation measures.

2 Description of the Phenomenon

During the development of the 1.6 L Midsize Gasoline Engine with direct injection introduced to market for the first time in 2012, engine damages occurred under specific test conditions typical for Non-European markets.

Precondition for the occurrence of the damages was a certain combination of operational and environmental parameters: very high charge air temperatures, low engine and vehicle speeds with simultaneous driver demand for high engine loads and use of fuel with lowest octane numbers (<RON91). As a result, damages as typically known from glow ignitions occurred at the spark plug or the exhaust valves. Even total engine write-offs arose due to ring-land cracks.

It was found from the readouts of the fault memory and from the damage reports of the development engineers that the phenomenon occurred in gradations. Strongly knocking combustion cycles were detected. In addition, stationary auto ignitions with an early combustion phasing and knocking combustion occurred. Furthermore, stationary auto ignition events with a very early combustion phasing took place without knocking; see Fig. 1. A reliable detection of these auto ignitions by the knock control system was not guaranteed since the events occurred outside the knock detection window or the maximum permissible knock adjustment had already been used up.

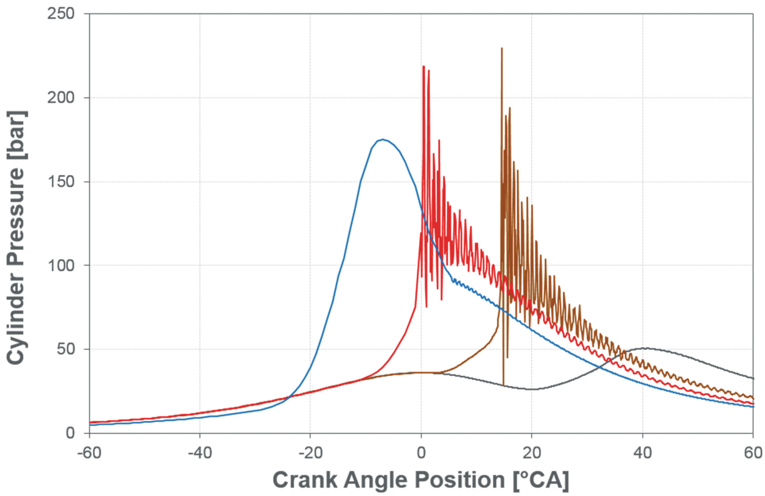

Fig. 1. Pressure traces containing auto ignitions of different intensity/combustion phasing

3 Development of Test Procedure

Reproducible tests require a test procedure which enables the development engineer to transfer the phenomenon occurring in the vehicle to the engine test stand. As described in Sect. 2, the boundary conditions have been a heavily heated engine, dynamic engine operation, high load at low speed and poor fuel quality. A qualitative description of the procedure is shown in Fig. 2. That is a ramp with decreasing speed and increasing engine load up to WOT at the same time. At this test, starting at about 1800 rpm, auto ignitions occur sporadic with increasing frequency at decreasing speed. The frequency and intensity of these auto ignitions can be varied at the test-bed by fuel quality and charge air temperature. No auto ignition occurs with fuel according to EN228.

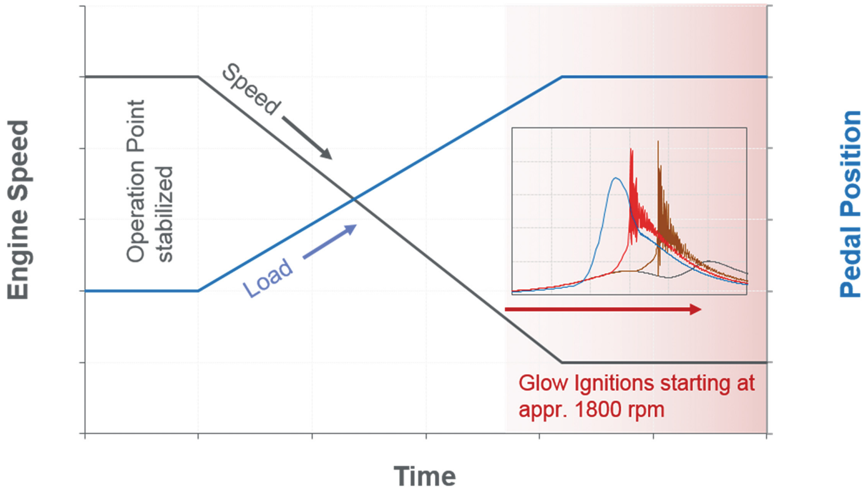

Fig. 2. Test procedure for the reproduction of auto ignitions on the engine test stand

The load/speed profile in combination with the above-mentioned boundary conditions high charge air temperature and poor fuel quality results in very late combustion phasing and enriched air-fuel mixture. At the lower end of the ramp shown in Fig. 2 an extremely retarded spark advance of approximately 20 °CA after TDC has been reached. Therefore, a long reaction time is available for self-ignition of the mixture.

4 Test Engine

Opel's 1.6 L SIDI (spark-ignited direct injection) MGE (midsize gasoline engine) used for the investigations applies a homogeneous combustion process and exhaust gas turbocharging. The engine has a capacity of 1598 ccm with a bore of 79.0 mm and a stroke of 81.5 mm. In the upper range of the scatter band for this engine concept is the compression ratio of 10.5: 1. The centrally mounted multi-hole injector is inclined by 5° and the spark plug by 21° relative to the cylinder axis. A strong in-cylinder tumble motion is generated by the inlet port. The piston has a small bowl for improved cold start performance. A magnetic injector with a 6-hole design and magnetic coil injects fuel with a maximum pressure of up to 200 bar. The pressure control of the return-less fuel system is performed at the fuel pump. Further details can be found in [1].

4.1 Optical Access

The test carrier was equipped with two optical accesses. Cylinder 4 on the output side of the engine has been chosen for installation of these accesses due to design limitations. Based on the experience within preceding projects the design of the combustion chamber windows allows for investigations of combustion peak pressures above 300 bar. Furthermore, that design shields the optical access for the endoscope as well as the access for the light dispersing stick against combustion gases to avoid glow ignitions or pre-ignitions triggered by overheating of the optical equipment, for details refer to [2]. Due to the expected high thermal stress, the cooling system has been refined to cope with a higher throughput of cooling air.

As mentioned above, the optical system consists of two optical accesses. One access is used to house the endoscope during measurement. The second bore contains the light dispersing stick. All of the optical components are still interchangeable, i.e. every combustion chamber access can be used for either lighting or recording.

Since the most favorable viewing direction for the detection of the phenomenon was the sight from the intake to the exhaust valves all following results contain only images from that access. The observation angle of the camera comprises of (see Fig. 3):

- Piston bowl,
- Spark plug,
- Injector and
- Exhaust valves.

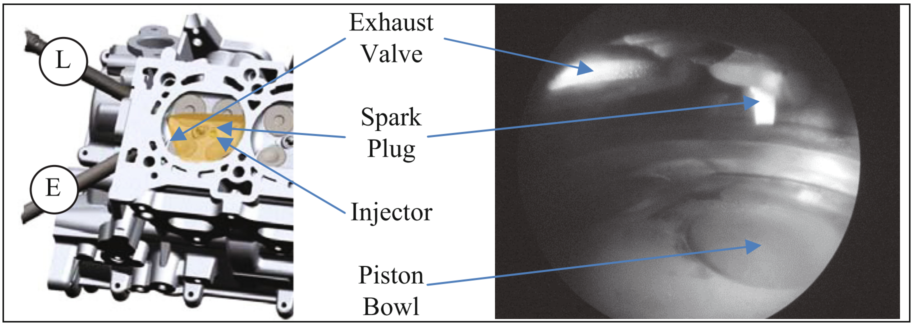

Fig. 3. Cylinder head, viewing direction on cylinder No. 4 (L = Light, E = Endoscope)

5 Motivation for the Application of Optical Measurement Tools

The occurrence, frequency and intensity of auto-ignitions can be clearly detected using standard measurement methods such as combustion chamber pressure indication. However, this method shows limitations in the analysis of the issue described above. It does not provide any information about the root cause and the location where self-ignition starts in the combustion chamber. A direct determination of sources typical for abnormal combustions, e.g. hot components in the combustion chamber and their respective temperatures, would be extremely helpful for a profound analysis. At this point, optical measurement tools with access to the combustion chamber are the means of choice since they enable a detailed analysis during steady state and transient engine operation.

Since the described phenomenon occurs on the multi-cylinder engine, it is necessary that optical measurement tools are applicable to the multi-cylinder engine too. The optical measurement tools should as little as possible affect the boundary conditions in the combustion chamber and the combustion process. Therefore, any modification of the combustion chamber at the test carrier due to the access bores was limited to a minor weakening of the water jacket and oil circuit. In any case, the influence of the measurement technique needs to be taken into account when interpreting the results.

For the analysis of the glow-ignition phenomenon image based measurement tools were used in the first step. Images and videos of the combustion process have been recorded by using endoscopes via optical accesses to the combustion chamber. In particular, this method provides information of the location in the combustion chamber where self-ignitions have their origin.

Another appropriate measurement tool detects the light intensity of the flame via optical lenses and fibers incorporated in the spark plug. It can be used on all cylinders which represent the greatest advantage of this technology. This tool provides statistical information about frequency and distribution of events supplementary to the determination of the location of origin of the auto ignition. Nevertheless, the use of the optical spark plug influences boundary conditions in the combustion chamber and therefore the combustion process itself by heat value and spark protrusion.

Temperatures of critical components are of particular interest once the origin of the auto ignition is known. They can be determined by measuring the radiation of the components in the infrared wavelength range. The access to the combustion chamber is realized via bores into the cylinder head too. An endoscope with transmittance for infrared radiation is mandatory.

6 Application of Image Based Tools for the Detection of Glow Ignitions

Image based combustion diagnostics allows for recording of images of the combustion chamber and combustion process at fired engine operation via an optical access in the cylinder head. A distinction must be made between so-called low-speed systems, e.g. AVL Visioscope®, and high-speed cameras. It is possible to record only one image per cycle with the low-speed system. Therefore, videos or image sequences are composed of recordings of several combustion cycles. The system is mainly suitable for the investigation of periodic processes. Greatest advantage of the low-speed endoscopy, which makes an application nevertheless meaningful, is the simple application on the engine. Easy handling due to a small camera, bright pictures and low data volume are additional benefits.

A high-speed camera, on the other hand, is capable to take continuous recordings due to its high frame rate. Its temporal resolution extends into the crank angle range. The system uses the same optical access in the cylinder head and the same endoscope as the low-speed system.

6.1 Low Speed Endoscopy

Requirements of the System and Test Conditions

Since the low-speed system allows to record only one picture per cycle, the recordings must be restricted to a constant crank angle position. Several combustion cycles are recorded at a fixed time in the cycle. The recording time is chosen in such a way that the early flame front, a few degrees crank angle after the inflammation, is recorded. In case the onset of the auto ignitions varies during the test, e.g. by changing of engine speed, several measurements at different crank angle positions are necessary. The camera system and the indication system must be synchronized in order to establish a correlation between the cylinder pressure traces and the respective images.

The early flame front is a weakly glowing event. Therefore, settings and parameters of the measurement system must be optimized with regard to light output. Parameters are the type of the camera (black & white or color), elimination of external illumination of the combustion chamber and of course exposure time. The exposure time has to be a compromise between brightness of the images and temporal resolution.

Detected Origins of Glow Ignitions with Low Speed Endoscopy

Images taken with low speed endoscopy are showing the origin of auto ignitions in the area of the exhaust valves. An example at 1556 rpm is presented in Fig. 4. The recording time of the image is 6.0 to 8.5 °CA aTDC. Auto ignition starts 9 °CA before the ignition set point at 15 °CA aTDC with the flame front staring underneath the left exhaust valve. At the time of recording, no ignition can be detected near the spark plug.

Statistical relevance is ensured by a sufficiently high number of recorded cycles containing auto ignitions. In all cases auto ignitions have their origin in the vicinity of the exhaust valves. Auto ignitions starting directly at the spark plug have not been observed. In most cases the source of the flame front is the left exhaust valve, i.e. exhaust valve #8. More rarely, two flame fronts are formed simultaneously at both exhaust valves.

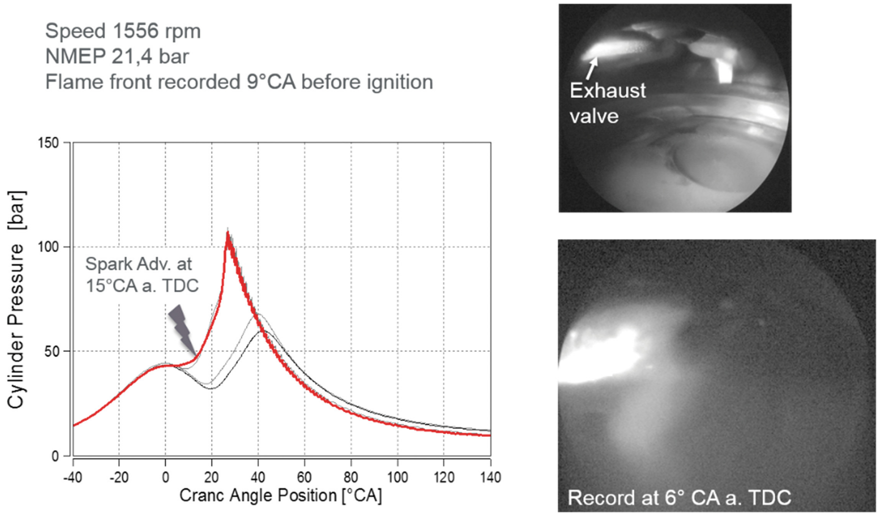

Fig. 4. Auto ignitions at the exhaust valve

6.2 High Speed Endoscopy

Requirements of the System and Test Conditions

In contrast to the frame-by-frame images taken with the low-speed system, the high-speed camera is capable to record high-resolution videos of consecutive combustion cycles. Especially the brightness of the images is a compromise between exposure time and temporal resolution. In order to achieve the highest possible temporal resolution, an electronic image intensifier can be connected to the high-speed camera. In the presented study, however, this approach was not possible due to strong vibrations driven by the high engine speeds and highly dynamic engine operation. The selected recording rate was 3000 frames per second. At an engine speed of 2000 rpm this corresponds to an exposure time of approximately 333 μs per image, respectively 4 °CA.

The measurements with the high-speed camera are time-based. There is no correlation to the crank angle position. Synchronization with the combustion chamber pressure is achieved via a synchronized start of both measuring systems. The identification of cycles with auto ignitions is based on the cylinder pressure traces. Further details about the application of the camera system to the engine are described in [2].

Glow Ignitions at the Exhaust Valve

The records of the high-speed camera confirm the results obtained with the low-speed system in more detail. The source of auto ignition is mainly located in the area below the exhaust valves. Figure 5 shows an example of an auto ignition starting underneath the left exhaust valve. The flame propagation from the left side of the combustion chamber towards the center of the combustion chamber is clearly visible.

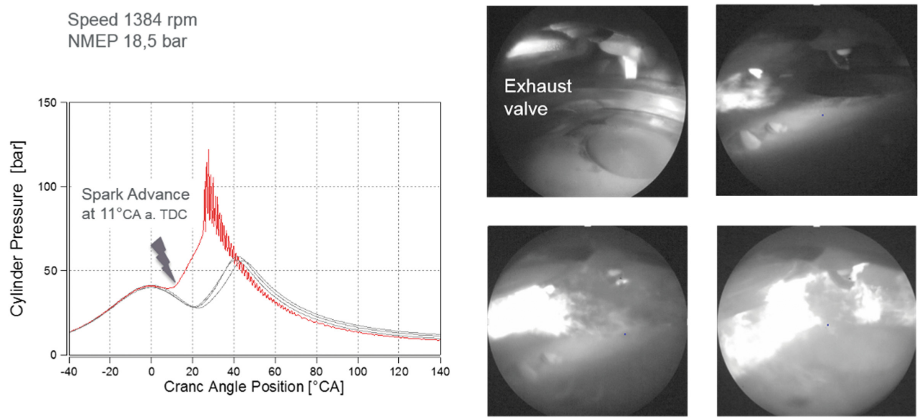

Fig. 5. High-Speed imaging of auto ignition at the exhaust valve

7 Detection of Glow-Ignitions with Fiber Optic Based Tools

Fiber optic based measurement tools have been originally designed for the evaluation of early flame kernel propagation as well as the determination of the origin of knocking combustions cycles. The system detects the self-lighting of the flame. Lenses integrated into a spark plug sensor detect light signals transmitted to photodiodes via optical fibers. The measured signal is proportional to the luminous intensity of the flame and recorded as a function of crank angle position. The location information of the detected phenomenon is derived from the known geometric alignment of the lenses.

No modifications of the cylinder head for optical accesses are necessary. Measurements are possible on all cylinders and a high number of cycles can be recorded. A minor disadvantage of the measuring system is the influence on the combustion process by replacing the original spark plug.

7.1 Sensor Variants and Evaluation Methods

Figure 6 shows the spark plug sensor used for the investigations. It is fitted with 35 optical channels, 28 channels aligned to the circumference of the combustion chamber (knock signals), seven in parallel to the spark plug with a direct view to the piston crown (flame signals). Thus is it possible to detect the origin of auto ignitions on the circumference of the combustion chamber, the piston crown as well as on the spark plug.

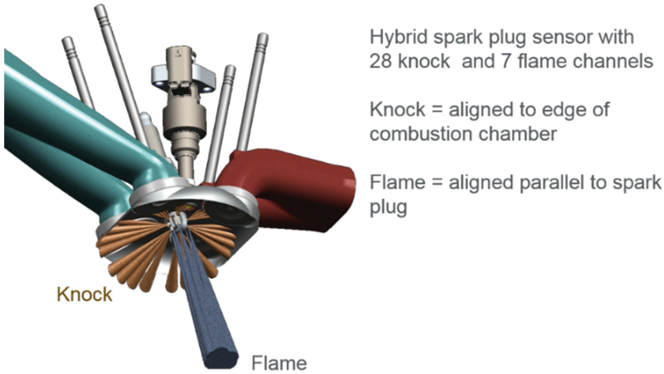

Fig. 6. Fiber optic based spark plug sensor mounted in the combustion chamber

All signal traces are high-pass filtered and plotted in a waterfall diagram as a function of the crankshaft position (see top right of Fig. 7). Here the top eight lines contain the flame signals recorded at the piston crown and the following 28 light lines show the signals coming from the combustion chamber circumference. The brightness gradients shown are used to determine the origin of the auto ignitions, i.e., the auto ignition starts at the point in the combustion chamber where the light signal trace deviates from the background noise for the first time. The known orientation of the corresponding lens provides information on the origin of the glow-igniting event.

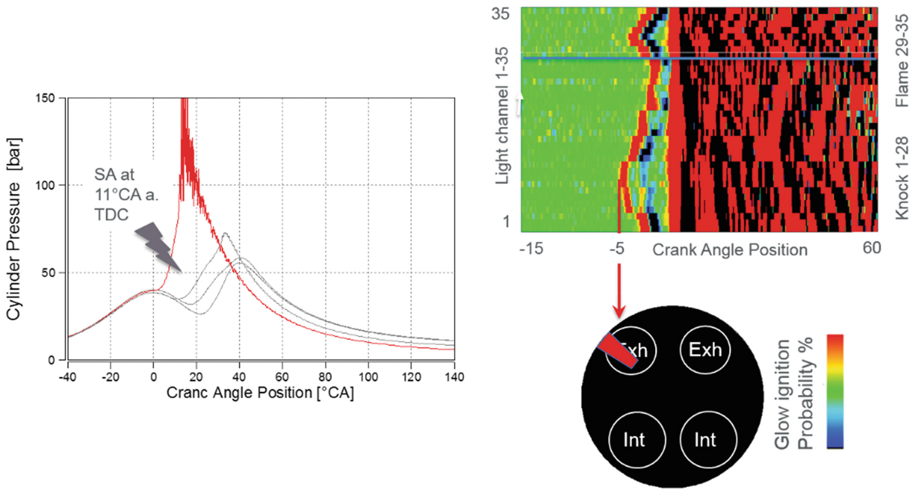

Fig. 7. Evaluation of light signals

In Fig. 7 the auto ignition is recorded for the first time 15 °CA before the ignition set point on channel 11 which correspond to a position underneath the left exhaust valve. Through the evaluation of a sufficiently high number of cycles, statistical information about the frequency and occurrence probability of auto ignition events at the corresponding positions in the combustion chamber are possible.

7.2 Detected Origin of Glow-Ignitions by Means of Fiber Bases Tools

The results obtained with image based methods could be confirmed with the fiber optic based measurement tool. On the fourth cylinder, the highest occurrence probability and frequency of auto ignitions is in the area around or underneath the left exhaust valve. On the other cylinders, auto ignitions occur as well only in the area around the exhaust valves (see Fig. 8).

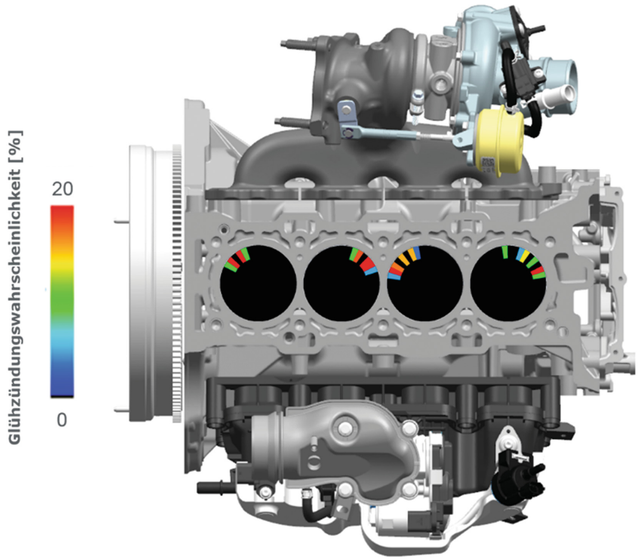

Fig. 8. Glow ignition probability at all cylinder

Auto Ignitions starting at the spark plug were not detected. This is consistent with the previous results and it seems reasonable due to the low heat value of the measuring spark plug.

8 Measurement of Critical Component Temperatures in the Combustion Chamber

All the measuring methods described above indicate the area around the exhaust valves as the point of origin of the auto ignitions. This raises inevitably the following questions regarding the temperature of the exhaust valves:

- Are exhaust valves hotter under the given operating conditions compared to WOT steady state operation?

- What is the influence of retarded ignition timing on the exhaust valve temperature due to poor fuel quality?
- What is the effect of the increased charge air temperature?
- How are the exhaust valve temperatures compared to the spark plug temperature at steady state operation and in the transient test ramp?

Measurement of component temperatures in the combustion chamber is possible by detecting the intensity of radiation of the components in the infrared spectrum between 700 and 2500 nm. The design of the optical accesses to the combustion chamber is identical to those used for the low-speed and high-speed cameras. However, the used endoscope must be permeable to infrared radiation. A specific camera is required, which can detect the heat radiation in the infrared wavelength range. The data recording system is the same as used for the low speed camera. For this reason only one record respectively temperature measurement per engine cycle is possible with this application.

Figure 9 shows exemplarily a record with open exhaust valves taken at 240 °CA aTDC. Exhaust valve temperatures can be measured at open and closed valves. In this context the temperature of the closed valves just before the intended ignition set point is relevant. The temperature level of the closed exhaust valves is close to the lower measurement limit of the infrared system. Since the lower temperature limit is mostly defined by exposure time, the chosen exposure time must be a compromise between the longest possible exposure duration and the necessary temporal resolution. Therefore, the selected exposure time is two milliseconds in the present case. The temperature measurements have been performed at 40 °CA before the ignition TDC in order to ensure a sufficient distance to the start of combustion, in particular in case of auto ignitions.

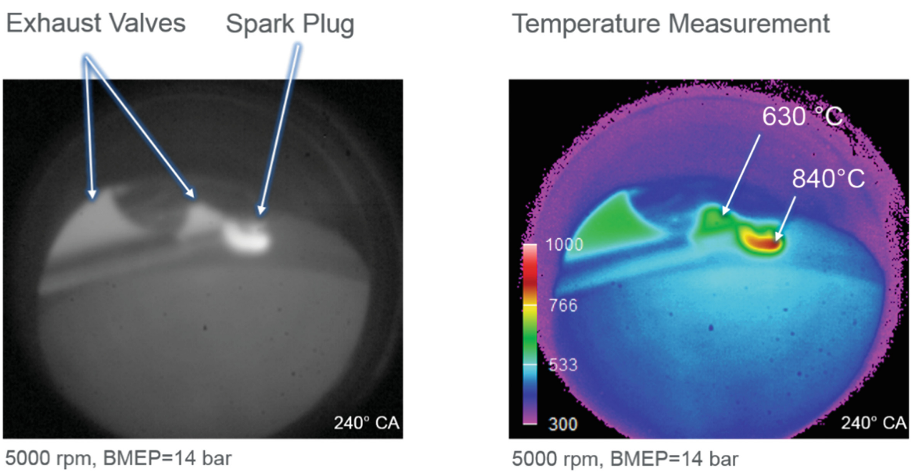

Fig. 9. Infrared record of combustion chamber at open exhaust valves

A parameter leading to an increased occurrence probability of glow ignitions is the ignition retard due to low octane fuels, high charge air temperature and transient operating conditions. Compared to steady-state operation at WOT with, e.g., RON95 pump fuel the exhaust valve temperature increases by 50 °C in case of maximum retarded ignition timing. This ignition retard increases the exhaust gas temperature by up to 240 °C (see Fig. 10, left).

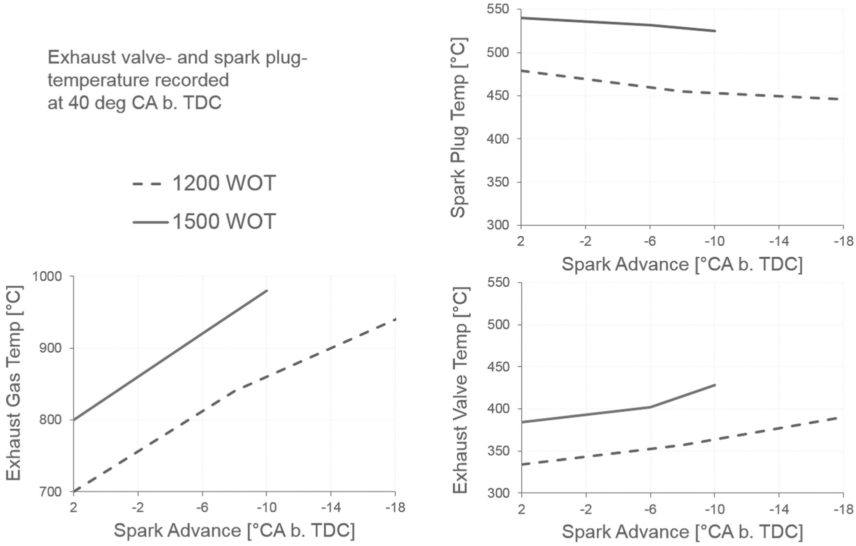

Fig. 10. Exhaust valve and spark plug temperature at WOT steady state operation

The temperature of the spark plug mass electrode remains rather stable. At most the temperature is slightly decreasing when retarding the ignition timing and combustion

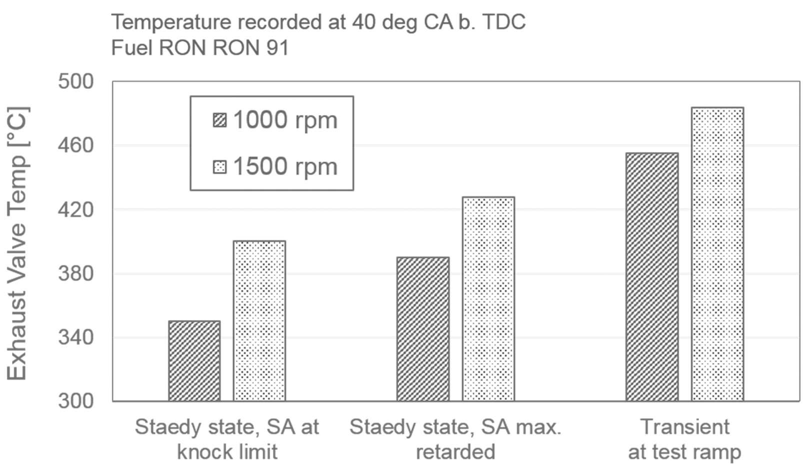

Fig. 11. Exhaust valve temperature at test ramp

phasing. However, the spark plug is always hotter than the exhaust valves with a difference of about 150 °C at regular ignition timing. At maximum retarded ignition set point that difference is reduced to 60 °C (see Fig. 10, right).

During transient operation of the test ramp the outlet valves are again 50° to 60 °C hotter compared to steady state operation at maximum retarded combustion phasing. That means the exhaust valve temperature during the test ramp is approximately 100° to 120 °C hotter compared to steady state WOT operation with optimized parameter settings Fig. 11. It means that the described combination of parameters leads to temperature conditions in the combustion chamber which are not reached during steady-state WOT operation. A further rise of exhaust valve temperature during the test ramp is driven by the temperature storage capacity of the exhaust valves.

At steady state operation, the temperature at the spark plug mass electrode is always significantly higher than the temperature of the closed exhaust valves. During retarded combustion phasing, this is the case too. During the test ramp conditions can be reversed and the exhaust valves are hotter than the spark plug (Fig. 12). The inertia of the spark plug electrode against temperature changes is significantly lower than that of the much larger exhaust valves. Therefore, the spark plug temperature changes relatively quickly during transient operation.

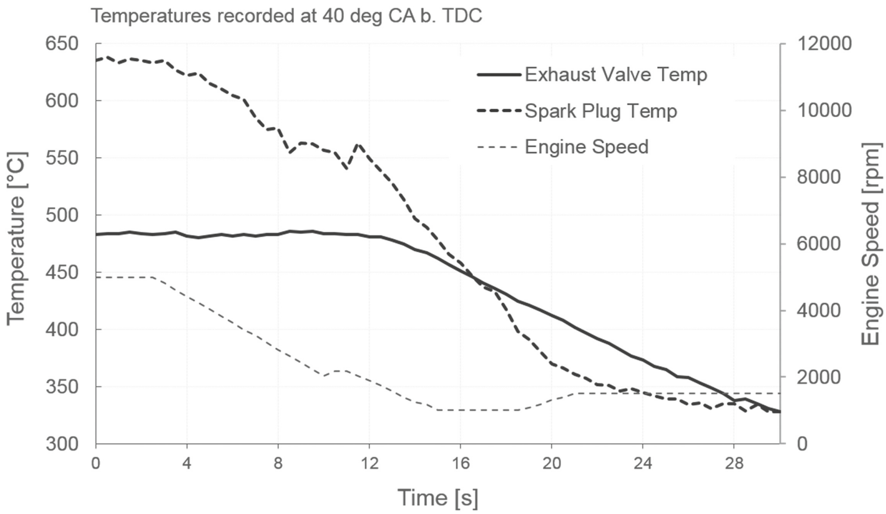

Fig. 12. Exhaust valve- and spark plug temperature at test ramp

The comparatively large and hot exhaust valves cause a much higher heat input into the combustion chamber than the small spark plug. Therefore, it is understandable that the auto ignitions originate from the circumference of the combustion chamber underneath the exhaust valves and not from the vicinity of the spark plugs.

9 Simulation

Opel uses an in-house simulation model to assess the tendency to knock for a specific combustion chambers design during the development process. With further progress of the development, this model is repeatedly validated and calibrated taking into account the results of other simulation tools (e.g. GT-Power) and results from engine measurements (e.g. engines equipped with temperature measuring systems).

In addition, the knock model has been validated with the location and temperature information derived from optical measurements. The goal was to evaluate the critical area of the combustion chamber around the exhaust valves in terms of knock probability due to residual gas content as well as mixture and temperature distribution in the relevant load and speed ranges.

Figure 13 shows the probability of knocking combustion events at a given location within the combustion chamber. It can be derived from Fig. 13 shown below, that the probability for knocking cycles and auto ignitions is significantly increased in the area underneath the exhaust valves. This simulation result correlates well with the experiment; see Figs. 8 and 13.

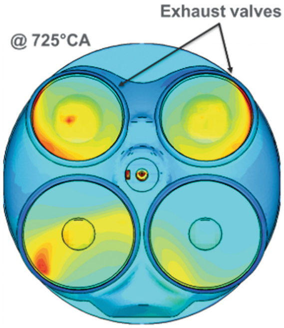

Fig. 13. Knock probability at cylinder No. 1

10 Discussion of Results

The phenomenon of auto ignitions in the low speed range described in detail in Sect. 1 can be a problem especially in "hot" markets. Charged engines with direct fuel injection and thus relatively high compression ratio - in the present case with a compression ratio of 10.5: 1 - have been introduced in these markets in recent years. Therefore, no validated development procedure tailored to the specific issue of low-speed auto ignitions was available. The test procedure described in Sect. 2 reproduces the customer behavior under standardized, repeatable test conditions. This reproducibility is a fundamental prerequisite for the comparison of the used measurement methods and the results achieved with them. In the future, the developed test procedure enables an early validation of the product under development as part of the standard development process.

As described in Sects. 6 to 8, all measurement methods deliver similar results. The optical results in the visible range of the spectrum enable in any case the allocation of the point of origin of the auto ignitions to an area below the outlet valves. This result is supported by the surface temperatures of the exhaust valves determined by means of infrared measurement technology. With temperatures of about 400 °C the exhaust valves represent by far the hottest parts in the vicinity of the combustion chamber roof. These results lead to the conclusion that the exhaust valves are the most likely source of ignition.

However, these temperatures are still significantly lower than the component temperatures that typically lead to glow ignitions at high engine speeds. The question arises whether the described phenomena is a glow-ignition in the most traditional sense or not. An additional temperature increase through the “hot” outlet valves leads to a thermodynamically critical state of charge. The “hot” exhaust valves provide enough locally limited activation energy to ignite the cylinder charge. This inflammation process is promoted by the high retention time of the charge in a thermodynamically critical state.

11 Summary

It can be derived from the above that numerous measurement methods are available to conduct investigations of abnormal combustion phenomena. Advantages and disadvantages of these tools are shown in Fig. 14.

Measurement System	Time Information	Location Information	Temperature Information	Application and Handling Effort	Measurement and Evaluation Effort
Low-Speed Camera (visible spectrum)	-	+	-	O	O
Low-Speed Camera (Near Infrared)	-	+	+	O / -	O
High-Speed Camera	+	+	-	-	-
Optical Spark Plug	+	O	+ / O	+	+

Fig. 14. Comparison of available measuring tools

The use of an infrared measurement system is essential if the determination of temperature information is in focus. Optical spark plugs and low-speed infrared cameras are available for this specific task. Beneficial is the simple handling of the optical spark plug on a multi-cylinder engine. However, temperature information can be obtained only in a very small viewing area when using this measuring system. In case a temperature distribution over larger areas of the combustion chamber surface needs to be determined, an infrared camera is the tool of choice.

The great strength of high-speed cameras lies in the measurement of highly dynamic processes. However, these high-speed investigations are limited to the visible spectral range due to the necessary short exposure times. At the same time, the localization of phenomena is easily possible due to the large field of view. In contrast, the considerable handling and evaluation effort needs to be considered. Minimal application effort in conjunction with acceptable local resolution is the strength of the optical spark plug, which can be applied to any cylinder without modifications.

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