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Improving Combustion Process by Using a High Speed UV-Sensitive Camera

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ABSTRACT

The ever increasing demands on combustion engines with regard to exhaust emissions and fuel consumption require the use of modern analytical methods. Especially optical measurement techniques have contributed a lot to the realization of complicated engine concepts. The disadvantages of complex measurement techniques are the expenditure of time and the necessary changes of the engine.

This paper introduces a new practice oriented optical measurement technique with the aid of an example. With this technique it is possible to record the combustion process with a sampling rate of up to 200 kHz through a small drilling.

Even quick events like knocking can be recorded. The combustion luminosity is watched through a special UV-capable borescope, transmitted to an array of photoelectric transformers and finally recorded as a flame figure. We will show an SI-engine which is limited by knocking. Analyzing the optical images will show that the combustion process tends to burn to one side of the combustion chamber. It was possible to influence the combustion with flow corrections which resulted in a displacement of the knocking threshold and ultimately in a higher efficiency of the engine.

INTRODUCTION

The goal behind the usage of optical measurement techniques is the complete understanding of the combustion process. Optical measurement techniques for the combustion analysis have been used early in the engine development, but only in the research departments for the basic research. /4,6,8/. Improved computer capabilities and innovative ideas made it possible to use optical measurement techniques successfully in the development and the combustion optimization of mass production engines. /1/.

Now it was possible to record the combustion as well as knocking during near mass-production engine operation. /9/ shows a tomographic procedure which influences the combustion less than other optical measurement techniques.

Many optical probes in the head gasket reproduce a sufficiently precise figure of the combustion in that level. The disadvantage of all these measurement systems is the time consuming adaptation. Today's shorter development cycles make it more difficult to conduct intensive combustion investigations. New combustion techniques however pose greater challenges to the engineers and make it impossible to do without optical measurement techniques. Especially the new GDI-Engines require a new understanding of the combustion process /10/. But optical measurement techniques can provide solutions not only for future projects, but also for present engine problems like knocking. Furthermore, these systems can also verify new calculation models and provide the programmers with new ideas for the CFD-calculations. Optical measurement techniques are especially useful in this area because a picture or a movie of the combustion can explain much. But the adaptation of these systems should be as easy as possible and the combustion process should not be influenced. Especially for this purpose a system with a borescope and a high speed camera has been designed which records the fast processes inside a combustion engine with high time and spatial resolution. Another important feature is the UV-capability of all components because the luminosity of the combustion is characterized by the reaction of the OH-radicals. The radiation wavelength of these radicals are almost exclusively in the UV-range.

EXPERIMENTAL SETUP

Figure 1 shows the complete setup of the test equipment. The combustion luminosity is watched through the borescope and transmitted to the photoelectric transformers. After transforming the luminosity into a proportional voltage, the figure of the combustion can be displayed on the screen with a variable crank angle resolution of 0.05 °CA to 1 °CA.

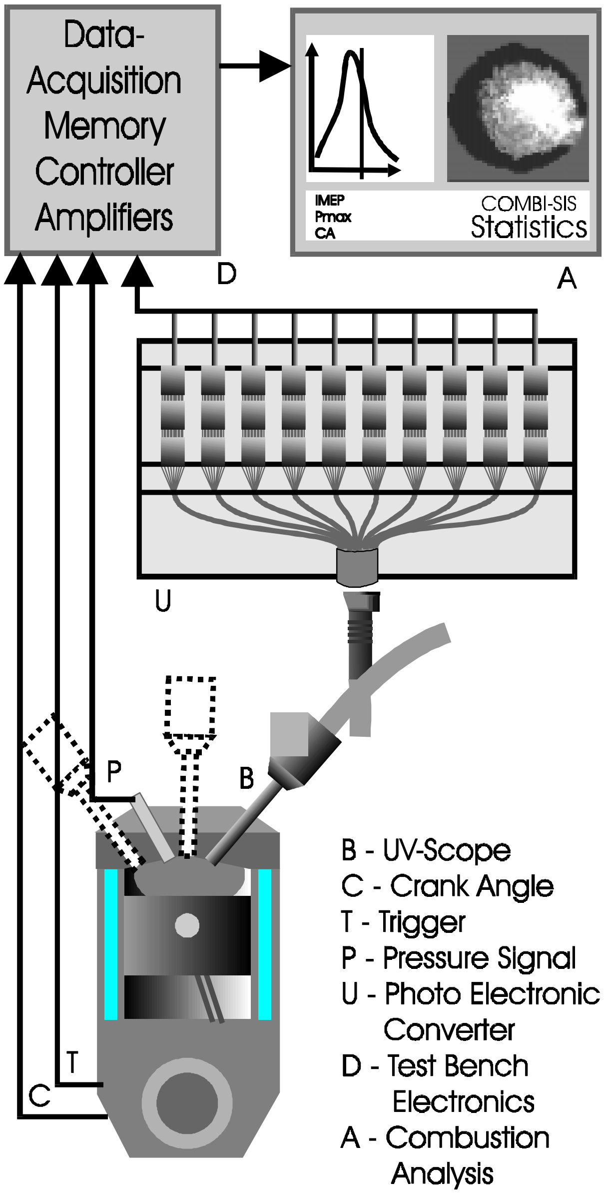

Figure 1: Flow chart of the experimental setup

Besides the pressure signal and the usual statistical values like IMEP, pmax, 50% heat release a picture of the flame development of each crank angle resolution can be shown. Moving the cursor on the left side back and forth produces a synchronous picture of the combustion on the right side of the screen which enables the user to correlate the pressure and the light phenomena.

UV-SENSITIVE COMPONENTS - As shown in /1/ the UV-Radiation is the most important radiation within the engine. In order to detect the flame front correctly, it is necessary to design all optical components like the protective glass, the borescope and the photoelectric transformer with an optimal transmission in the UV-range. The protective glass for the borescope is made of quartz glass and meets the requirements for the UV-transmission.

Borescope - An important detail within this measurement technique is the UV-capable borescope which has been developed especially for these investigations. All other available borescopes, flexible or solid, are only capable of transmitting visible light.

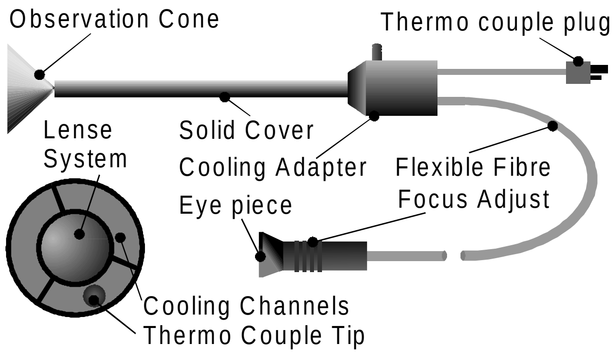

Figure 2: UV-Scope - Components and Front View

A flexible borescope (Figure 2) was used in these investigations which makes the adaptation to the camera easier. Only the part that enters the cylinder head is protected by a solid casing. This casing is also used for air-cooling to protect the sensitive lens system. It also contains a thermocouple to supervise the temperature of the borescope tip. Even smallest leakages to the engine or defects in the cooling system will result in distinct variations of the temperature. The eyepiece which contains a focussing device is standard equipment and can be fitted to every camera with a c-mount connector.

The following list shows the technical details of the used borescope.

- Spectral sensitivity: 190 - 780 nm
- Observation cone: 90°
- Diameter incl. cover: 4 mm
- Lenses diameter: 2 mm
- Optical diameter 1 mm
- Overall length: 2 m
- Solid length: 0.3 m
- Single fibers: 10,000
- Maximum temperature: 120 °C
- Depth of focus: 9 mm - 200 mm
- C-mount eyepiece for quick release

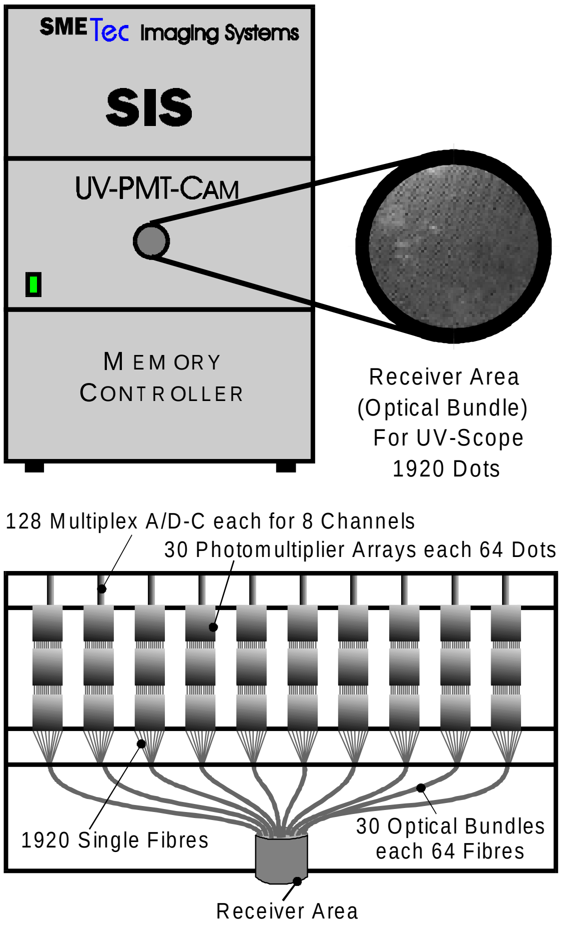

Figure 3: Camera system

UV-Camera - The borescope is attached to the UV-camera as seen in figure 3. In a usual CCD-camera the picture would be transmitted to a photosensitive area of the CCD-chip. In the depicted UV-camera the picture is focussed onto an area of about 25 mm in the front of the camera. This area consists of 1920 single fibers packed tightly into a circle. The 10000 dots of the borescope are therefore reduced to 1920 dots which are transmitted to 30 photomultipliers (PMT) with 64 photosensitive areas each. So each fiber corresponds to one photomultiplier. A photomultiplier produces a voltage proportional to the light which hits the sensitive area. This function is similar to that of CCDs or photodiodes. The differences however are the spectral response in the UV-range and the higher sensitivity. Even the smallest amounts of photons produce a detectable voltage which makes a very short exposure times possible. During measuring each voltage is transmitted to an analog-digital converter which converts the voltage to a digital signal with up to 200 kHz. The converted data is then stored in memory. After reading, the software converts the data into a picture of the flame.

Because the described camera can only detect emissions the system offers the possibility to record a picture of the combustion chamber with a CCD-camera too. This picture can then be overlaid with the flame pictures which enables the user to detect the flame luminosity and correlate it to the internals of the combustion chamber.

The PMT-UV-CAM can record many successive pictures with a high frequency which is only restricted by the used analog-digital converter. In this case 200 kHz.

The results of one measurement are shown in figure 1 in correlation with the combustion pressure. The higher the intensity the brighter the flame representation on the screen. Dark areas represent areas, which has not been reached by the flame yet or where the flame is already terminated.

The results in figure 10 and 11 show flame developments where the inner area is darker then the outer area. The reason for that is that the main reaction happens in the outer area and after the flame front, only some other gaseous components illuminate with less intensity.

In order to measure every area of the combustion chamber and get a detailed analysis of the combustion it is advantageous to make more measurements with different borescope positions. Figure 1 - dotted lines.

The following table shows the technical details of the UV-Camera

Spectral Response	200 nm - 650 nm
Number of Dots	1920
Acquisition Frequency	200 kHz
Resolution	10 bit
Memory	32 000 frames

The diagram in figure 4 shows the spectral response of the PMTs. Figure 5 shows the main spectral components of a HC combustion in comparison to the PMT response of figure 4. It is obvious that both ranges fit. For the investigations described in this paper only the spectral range of the first reaction (OH-Radicals in the flame front) is important whereas the long wave radiation of the soot combustion, which is not detected by the PMTs, is insignificant. Therefore no extra filters are necessary to investigate the flame front development.

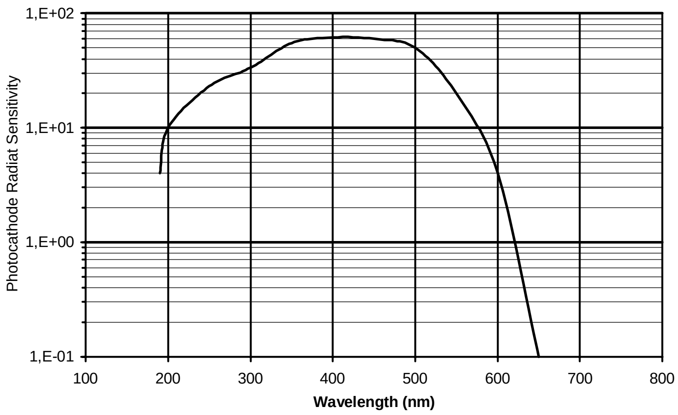

Figure 4: Spectral response of PMTs

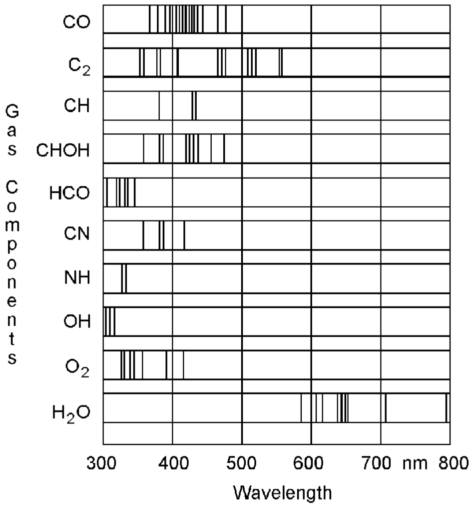

Figure 5: Spectral bands of HC-Combustion in SI-Engines

ENGINE SETUP - A mass production engine was used for these investigations. Figure 6 shows a sectional view of the engine and the arrangement of the experimental setup in the cylinder head. For the investigation of knocking the borescope was integrated into a spark plug adapter (figure 7). It is not necessary to add any holes when the spark plug adapter is used. In this spark plug adapter the electrode is slightly displaced which makes space for the borescope. A tumble shield was attached to the intake port to influence the intake flow. The adjustment range (0° to 15°) is marked.

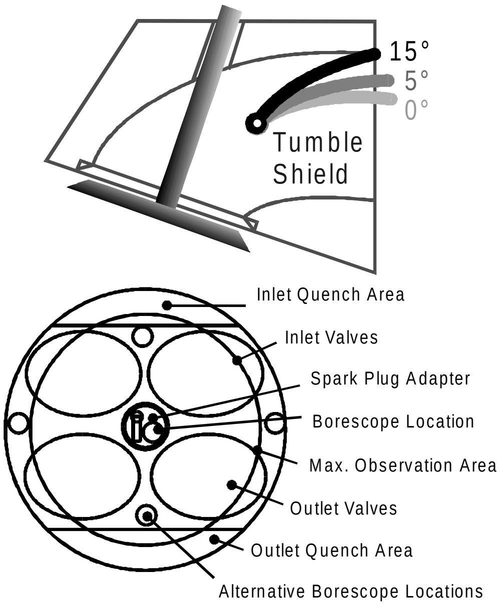

Figure 6: Cylinder head arrangement

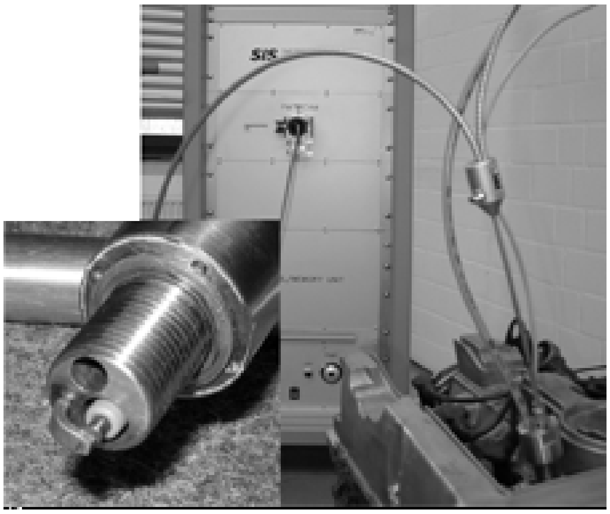

Figure 7: Spark plug adapter and test bench view

The following table displays the engine type and parameter of the experiment.

Cylinder	4
Type	Row
Valves per Cylinder	4
Displacement	1998 cm
Compression	11,5
Load	Fulload
Throttle angle	90
Speed	2000 rpm
Air/Fuel ratio (Lambda)	1,0
Intake air temperature	30° C
Oil temperature	90° C
Ignition time	Knock Limit (max. eff.)
Sampling rate	0,2 °CA

Variations - It will be shown how a slight adjustment of the intake flow has an influence on the combustion of the engine. The intake flow adjustments were realized by a tumble shield in the intake pipe. This arrangement had no effect on the negative pressure level which guaranteed the comparability of the experiments.

RESULTS

The results will show that small variations of engine parameters have a great influence on the combustion.

ENGINE BEHAVIOR - To guarantee the clarity of the experiments only two different measuring points will be compared. The following table displays those points.

	BASIC	VARIATION
Tumble Shield	0°	5°
Speed	2000 rpm	2000 rpm
LOAD	Full	Full
IMEP (bar)	12,6	12,1
Ignition	18	16 (CA BTDC)

An adjustment of the tumble shield in the intake pipe to the position 5° (33%) has already a distinct influence on the combustion and reduces the full load significantly. The knocking limit is reduced by 2 degrees which in turn reduces the power limit of the engine. This intentional worsening corresponds to a usual development state in the engine design to realize laid out goals in consumption, power or emission. In this case the engine was already optimized so the combustion had to be worsened to show parameter variations and their influence on the combustion.

Combustion behavior - Now that the effects of the variations on the combustion are known, the results must be interpreted. A normal flame development without knocking will be shown from the ignition to the end of the combustion. Finally we will show knocking combustion cycles. Especially the different knocking locations will be discussed. But at first, we will explain the signal courses of the combustion.

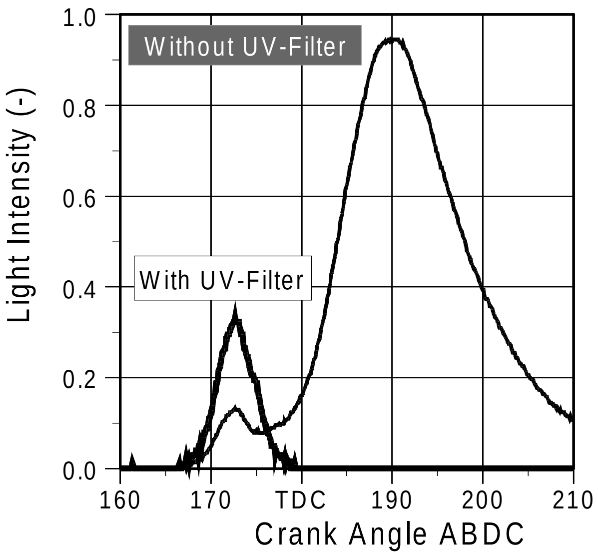

Figure 8: Light signals with different spectral response

Figure 8 shows the course of one flame signal from the 1920 dots. The signals have been recorded with one photomultiplier at a not specified location in the cylinder. The spectral range of the flame was recorded in the entire spectrum from 200 nm to 650 nm. Obviously the signal course resembles the course of a pressure curve. The first signal rise representing the reaction of the hydrocarbons into energy is noticeable. The main part of the course displays the radiation of CO which radiates from 380 nm to 480 nm. To measure only the radiation of the main chemical reaction, it is advantageous to add an UV-filter. The result is shown with the thicker line. One can see that the main reaction happens within 10° CA is classified by the OH-radicals. The advantage is a better detection of the flame front, however the intensity diminishes and the signal has to be amplified.

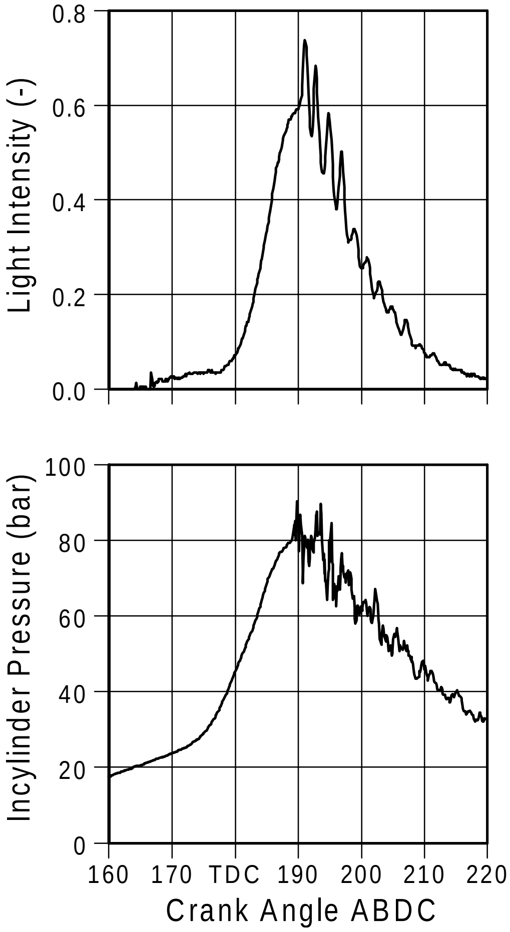

Figure 9: Signal course of a knocking combustion

Figure 9 shows a flame signal of a knocking combustion. This signal shows the correlation between pressure and light emission. Shortly after the first pressure maximum the signal is overlapped by a higher frequency, the self resonance of the engine. This knocking results from the reaction of residual gas which has not been included by the flame. This reaction triggers a detonation which stimulates the gas to resonate. This high frequency resonance is known from the combustion pressure. The wavefront which runs through the cylinder triggers local pressure peaks visible also in the light signal. The radiation is proportional to the pressure and the temperature. There is however a difference in the quality of the light and the pressure signals because the pressure signal is overlapped by distortions due to structure borne sound which is transmitted by the pressure sensor. Therefore the light signal displays less distortions.

Following the results of the investigation will be compared.

Figure 10 shows a conventional flame development recorded with UV-filter and no reduction in power (tumble shield 0°). Two images from a cycle have been chosen to depict the characteristic properties of the combustion seen in the static figure. The pictures are averaged of 50 cycles. Since a borescope is not always able to watch the entire combustion chamber, the averaged figures have been calculated from different view angles of the borescope. Ignition timing for these cycles was the knock limit of the basic version which means no knocking in any cycle. Image A.) shows the combustion 15° after ignition. 30% of the observation area have been engulfed by the flame.

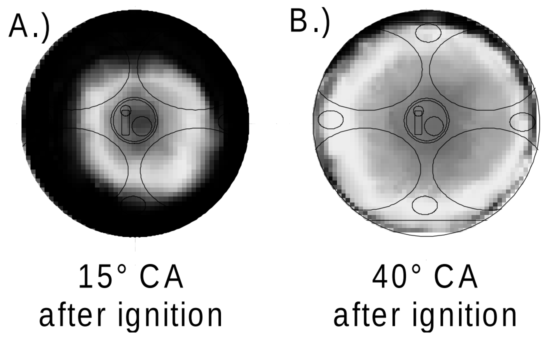

Figure 10: Flame development (tumble shield 0°)

The reaction of the hydrocarbons near the spark plug is almost complete which can be seen by the darker regions. The lighter regions in the outer regions of the flame show the reaction front of the flame and indicate an even combustion. The flame burns very evenly out of the observation range, which is shown in B.). Only the immediate region near the outlet valve shows an earlier burning.

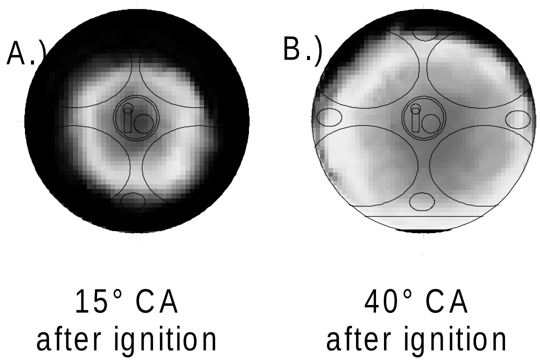

Figure 11. Flame development (tumble shield 5°)

The changes of the flame development with a different adjustment of the tumble shield (5°) is shown in figure 11. The engine was again operating at the knock limit to prevent damages. The difference of the flame 20° after ignition is not very pronounced. However, at the end of the combustion, the flame shows a distinct tendency towards the outlet valve. This tendency results from the higher energy level near the outlet valve and from a stronger inlet tumble.

<u>Knocking combustion</u> -. To detect the pressure front more clearly no UV-Filters have been used during the knocking investigations. Figure 12 shows the combustion behavior at a tumble shield position of 5 and an ignition point of 20° BTDC. The combustion resembles the combustion of figure 11 and shows the tendency towards the outlet valve. The bright area (left inlet side) in the figure is not reached by the flame.

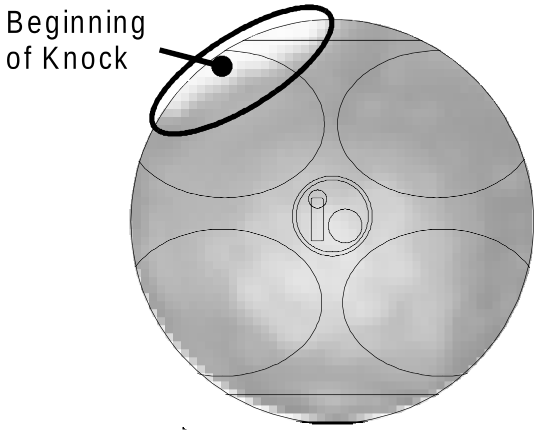

Figure 12: Beginning of knocking combustion with variation of the inlet flow (tumble shield 5°)

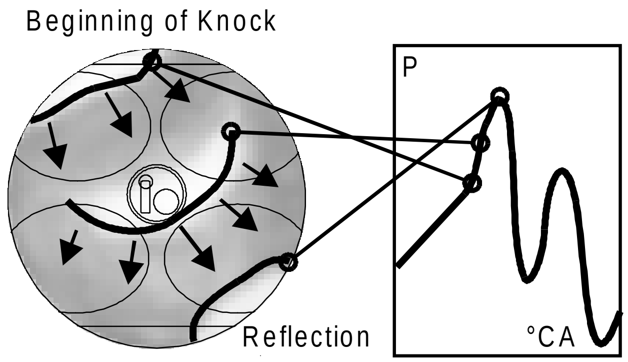

Figure 13: Spreading out of pressure waves after initial knocking

The gain of the PMT-UV-Camera was set lower for this investigation to detect the intense knocking. Otherwise the bright knocking would have resulted in overexposure. The beginning of the knocking can be seen in the left side of the figure 4 °CA later than in the right side of the figure. One can clearly see the bright area near the quench zone of the inlet side which represents the quick reaction of the residual gas. This quick reaction stimulates the resonances in the combustion chamber. The resonance can be seen in figure 13. The left side shows the initial pressure wave, directed from the point of origin to the outlet area. The wave has spread out into the whole combustion chamber and is reflected at the outlet side which leads to overlapping waves creating a complex wave structure inside the combustion chamber.

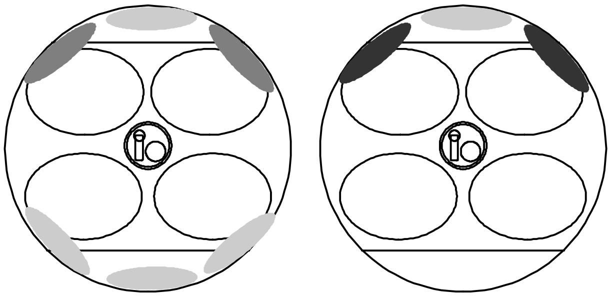

Figure 14: Statistical distribution of places of origin of knocking

The final figure 14 shows the distribution of the places of origin of knocking in the combustion chamber for both engine variations at 4° CA after knock limit. With a tumble shield position 5° the origins are concentrated near the inlet area which represents the bad burning performance in this area. The mixture in this area has the longest time for a self ignition whereas the mixture in the other side burns so quickly that there is not enough time for a self ignition. In the basis version with a tumble shield position 0° the places of origin of knocking are distributed near the quench areas but there is also a tendency towards the outlet area. Because of the higher energy level in the outlet area due to the valves the time is shorter which explains the knock origins. The places of origin are marked in different colors. The darker the color, the higher the probability for knocking. The basis version shows knocking besides the quench areas, but the probability is higher near the inlet area. The version with the tumble shield position 5° shows knocking besides the quench areas too. The reason that the knocking does not start directly in the quench areas is the fact that the mixture is cooled down because of the quench effects. The highest energy level is therefore besides the quench areas.

CONCLUSION

It was shown that changing engine parameters have a distinct influence on the combustion. The results can be detected by the usual measurement values for example IMEP. The causes for the changed results however can be detected by the use of optical measurement techniques specially designed for the combustion analysis.

A symmetrical flame development is the requirement for an optimized combustion. If in addition the flame exhibits a quick propagation it is possible to shift the knocking limit and increase the efficiency of the engine.

The optical measuring of the combustion should however be performed with easily adaptable measurement techniques. Only then it is possible to react to the needs of the engineers.

To stay informed on the current progress of development it is advisable to support every engine development with optical measurement techniques. Every step of development should be accompanied by optical measurement techniques to be able to make a better assessment of the current stage.

The results of the investigations show that a symmetrical flame development results in a better knocking behavior of the engine. The goal of an engine optimization should be an even combustion. Since the combustion tends to burn more quickly in the direction of the outlet area, it may be advantageous to direct the basic flow of the mixture more towards the inlet area.

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