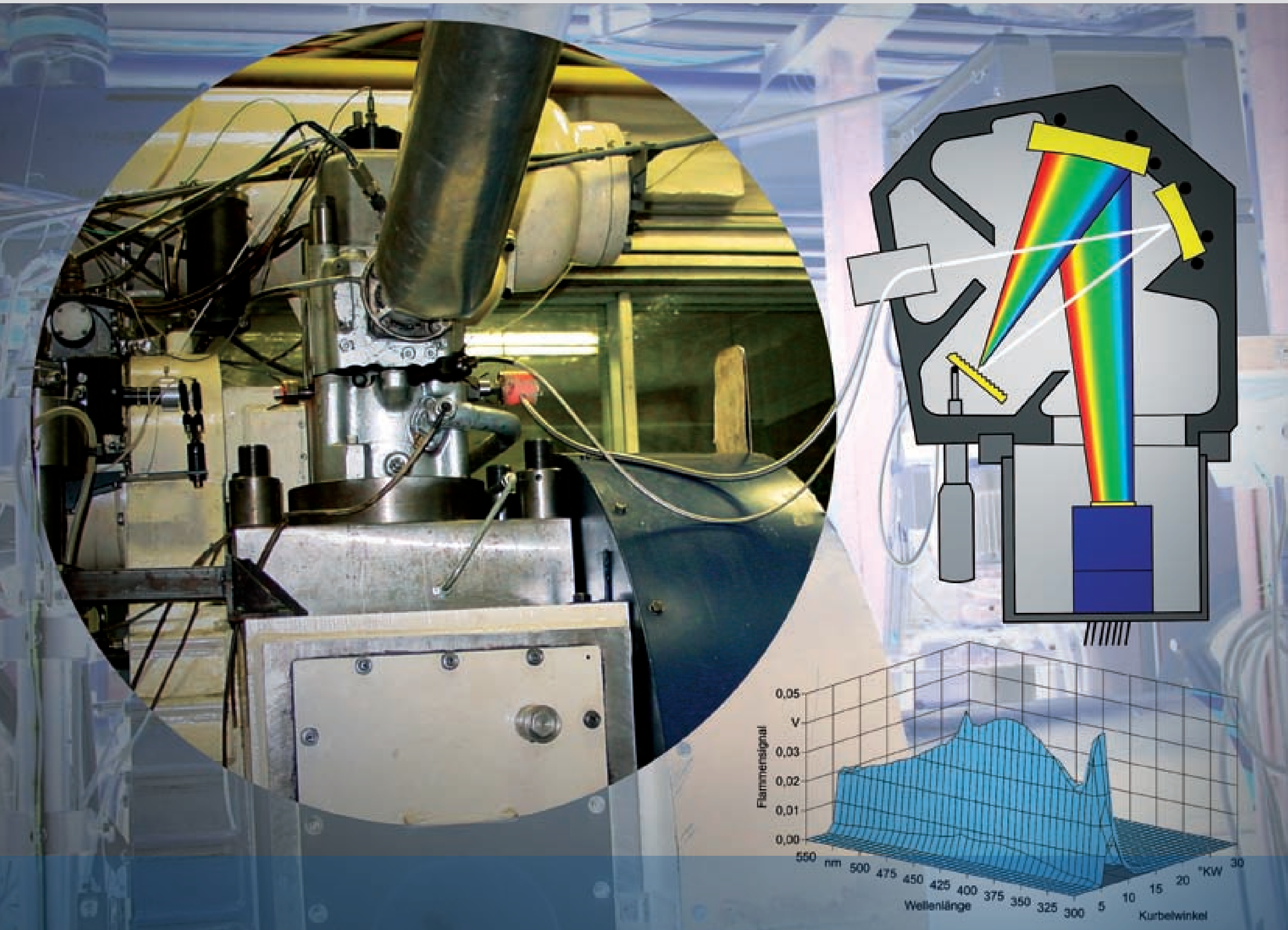

Spectroscopic Analysis of the Combustion in Diesel and Gas Engines

Optical investigations have got indispensable almost for the development of low-emission burning methods. In WTZ Roßlau gGmbH an economical and easily handable measuring device for the time-resolved spectroscopic analysis of combustion flames was developed which is usable under practical conditions to diesel and gas engines. The article describes the measuring principle and first measuring results.

1 Introduction

In the face of today's challenges for continual refinement of combustion technologies for diesel and gas engines analysis methods that help to better understand the processes within the combustion chamber become more important. Only an exact knowledge of the mechanisms of mixture formation, combustion and pollutant formation allows to influence these processes with the aim to make the combustion process as efficient as possible with minimized pollutant emissions.

In this context, optical methods became a nearly indispensable aid when it comes to improve combustion processes. Apart from photographic recording of flame spreading, the determination of flame temperature and soot concentration during the combustion in diesel engines has been state of the art for a long time [1, 2]. Knowledge of intermediate reaction products and kinetic reaction processes beyond this can be gained by emission spectroscopy [3, 4, 5, 6, 7, 8, 9] for example. For this, radiation of excited molecules and radicals at characteristic wavelengthes in the ultraviolet and visible spectral range has to be detected. This can be relatively simple realized with modern optoelectronic components.

Objective of the work described here was to develop a measuring device for time-resolution based emission spectroscopy that can be easily operated and used under practical conditions on engines. Connections between spectral radiation emission, mixture formation and combustion process or pollutant formation were to be gained by parameter variations both on a diesel and on a gas engine.

2 Theoretical and Experimental Basics

In the following the spectral radiation emission during ignition and combustion processes in engines, the spectroscopic measuring device, the test engines, and the test run and interpretation of spectra are discussed in detail.

2.1 Spectral Radiation Emission During Ignition and Combustion Processes in Engines

Ignition and combustion processes in engines are accompanied by the emission of electromagnetic radiation in ultraviolet, visible and infrared wavelength ranges. This may be both continuous radiation and also band radiation.

Continuous radiation is emitted from thermally excited soot. The spectral-response characteristic satisfies Planck's radiation formula. The higher the temperature and soot concentration the more intensive is the radiation continuum.

In contrast to this, excited molecules and radicals being in the reaction zone of a flame only emit in limited spectral ranges characteristic for the relevant species – the band spectra. Excitation occurs by chemical reactions – that is why this is also called chemiluminiscence radiation [10, 11].

Combustion in a diesel engine is initiated by a multi-stage low-temperature ignition [12, 13]. At first a cold flame arises with formaldehyde HCHO as radiation source. During the further reaction, formaldehyde is converted into

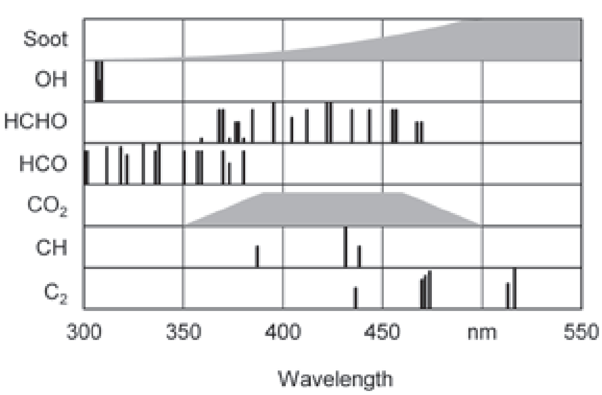

Figure 1: Emission wavelengthes of reaction species

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carbon monoxide making the blue flame. Main emitters of this flame are CH, HCO and OH radicals. The transition from the ignition to the combustion phase is characterized by oxidation of carbon monoxide into carbon dioxide. Excited carbon dioxide quasi emits a continuum in a limited spectral range. Further band spectra appear which are attributed to the C_2 radical and are considered signifiers of soot formation.

Because of the high ignition temperature of methane as main content of natural gas combustion within a gas engine occurs with typical reactions of high-temperature oxidation [12]. That is why the flame spectrum should show analogies to a soot-free high-temperature combustion of diesel fuel. CH, CO_2, HCO and OH are expected as main emitters from the natural gas flame.

Figure 1 shows characteristic emission wavelengthes and relative radiation intensities of the mentioned species that may occur in different phases of ignition and combustion [11]. Emission wavelengthes of some species overlap each other. Moreover, one has to expect pressure and temperature broadening of the band spectra due to conditions within the combustion chamber causing the spectrum to become slurred. Another major problem is the soot's continuum radiation that can superimpose the whole band spectrum.

2.2 State of the Art of Spectroscopic Measuring Technique

To detect excited molecules and radicals the flame radiation must be splitted to their spectral components and measured by high sensitive radiation sensors. Relativly simple the wavelength selection is carried out by means of band-pass filters which are selective to the emission wavelengths of different species. In [5] a measuring device is described for the detection of OH at 310 nm, CH at 431 nm and C_2 at 516 nm. As radiation sensors three photo multipliers are used. Under these measuring conditions the separation of species radiation from the soot continuum radiation is difficult. For advanced investigations [3, 4, 6, 7, 8, 9] therefore spectrometers are used for spectral splitting of the flame radiation. The detection of the spectrum is then carried out by an intensified CCD-camera. With this equipment for example 1024 spectral channels with a spectral bandwidth of 0.5 nm per channal is included [9]. Such measuring device allows a very high spectral resolution but is quite cost-intensive on the other hand and requires special knowledges of the operator.

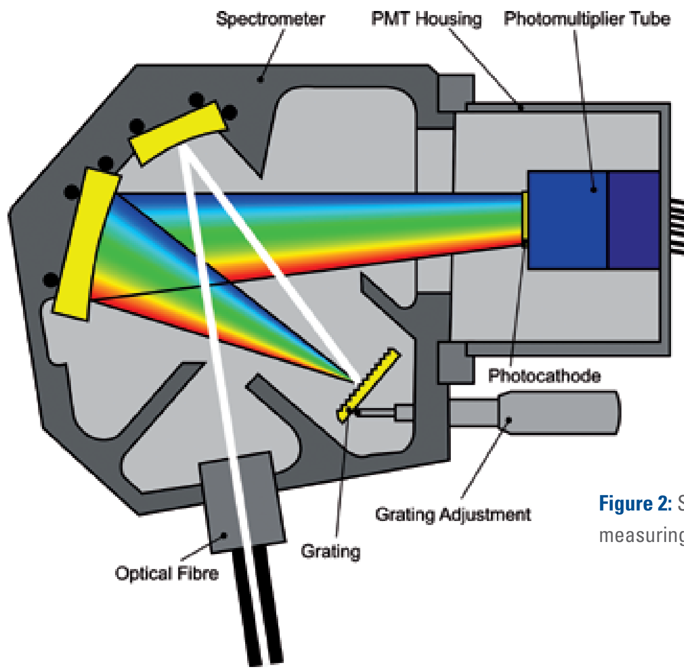

Figure 2: Spectroscopic measuring device

2.3 Spectroscopic Measuring Device of the WTZ Roßlau

For the development of the spectroscopic measuring device in the WTZ Roßlau gGmbH a compromise was sought between equipment costs, handleability and number of channels. **Figure 2** shows the construction. A commercial grating

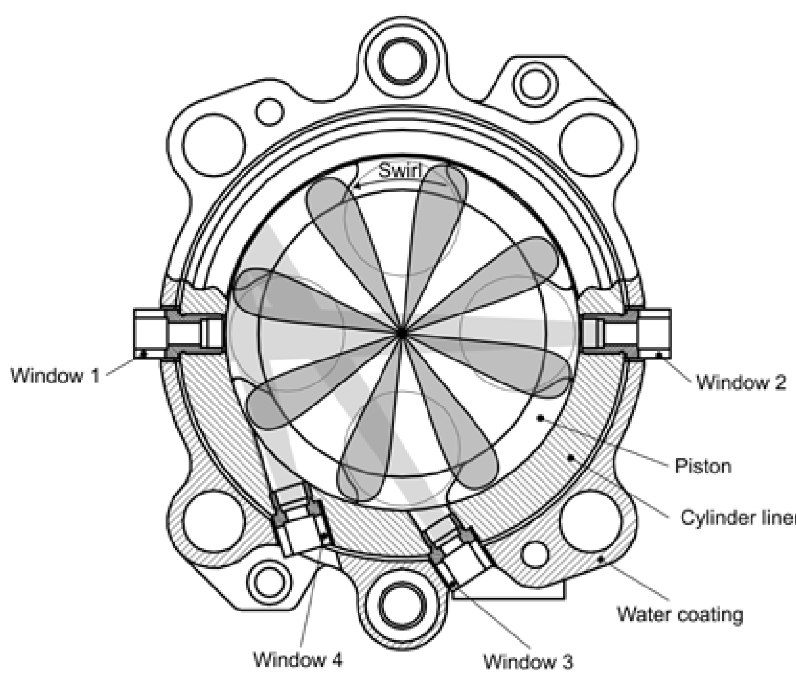

Figure 3: Arrangement of optical windows on the test engine

spectrometer was used as basic component. A quartz fiber-optical light guide is used to introduce the flame radiation from the engine. A highly sensitive 16-channel photo multiplier accommodated in a light-tight receiver housing is used as radiation detector. After appropriate signal conditioning, signal curves are recorded with a fast data acquisition system. The selected arrangement allows to capture the time history of the flame radiation during the combustion phase in 16 spectral channels parallel with a scanning rate of 20 kHz (0.5 °CA at an engine speed of 1500 rpm). The spectral band width per photo multiplier channel is 5 mm. The spectral range that can be detected simultaneously with the 16 channels is then approximately 100 nm. With the help of the grating adjustment, the detectable spectral range can be freely selected within the total usable spectral range of 250 to 600 nm.

The described measuring device is compact and easy to use. Therefore it is good suitable for the test bed. Due to the restricted number of spectral channels the spectral bandwidth per channal is greater or the simultaneously detectable spectral range is smaller than at use of a CCD camera. But the measuring results show that despite the comparatively low effort meaningful burning spectra can be get.

2.4 Test Engines

Two externally charged single-cylinder test engines with a stroke of 240 mm and a bore of 160 mm were available for experiments, with one of them operated as diesel engine and the other as natural gas spark ignition engine. The diesel engine was equipped with a common rail injection system. The spark plug of the gas engine was located centrally in the main combustion chamber. It was possible to operate both engines within a cylinder liner that allowed optical access to the combustion chamber.

Figure 3 shows the location of optical windows in the cylinder liner and of the injection jets for diesel operation. Whereas the windows 1 and 2 detect radiation from the diametrical (central) combustion chamber area, also tangential or wall areas of the combustion chamber can be observed through the windows 3 and 4. The fiber-optical light guide used to transmit the flame radiation to the spectroscopic measuring device was directly coupled to the relevant window.

2.5 Test Run and Interpretation of Spectra

As shown by earlier studies [14], combustion in diesel engines within the engine's normal power range occurs with a lot of soot formation. The continuously emitted soot spectrum would fully superimpose the considerably less intense molecule band spectrum and render its detection impossible. That is why the injected amount of fuel for the spectroscopic analysis was reduced so that conditions arise within the combustion chamber as they are typical for pre- and post-injection in common rail operation. For all experiments on the diesel engine the injection duration was 2 °CA at a motor speed of 756 rpm. In contrast to this, it was possible to execute analyses for gas operation over the engine's full power range as the combustion occurs without noteworthy soot formation. The spectra shown here became taken at load point 25 kW, 1000 rpm.

Flame signals in the 16 spectral channels were recorded at increments of 1 °CA. To obtain representative signal curves averaging was made over 200 cycles for each crank angle degree. To record a full spectrum from 300 to 550 nm three separate measurements with different grating adjustments were necessary. By means of a evaluation software developed himself the measurements from the separate channels were combined for an overall spectrum. Basis for this was the calibration of the spectrometer at a tungsten ribbon lamp. The flame signals represented in the spectra are proportional to the radiation intensities emitted from the combustion flame.

Figure 4 shows typical combustion spectra for diesel and gas operation obtained with the developed measuring device. A

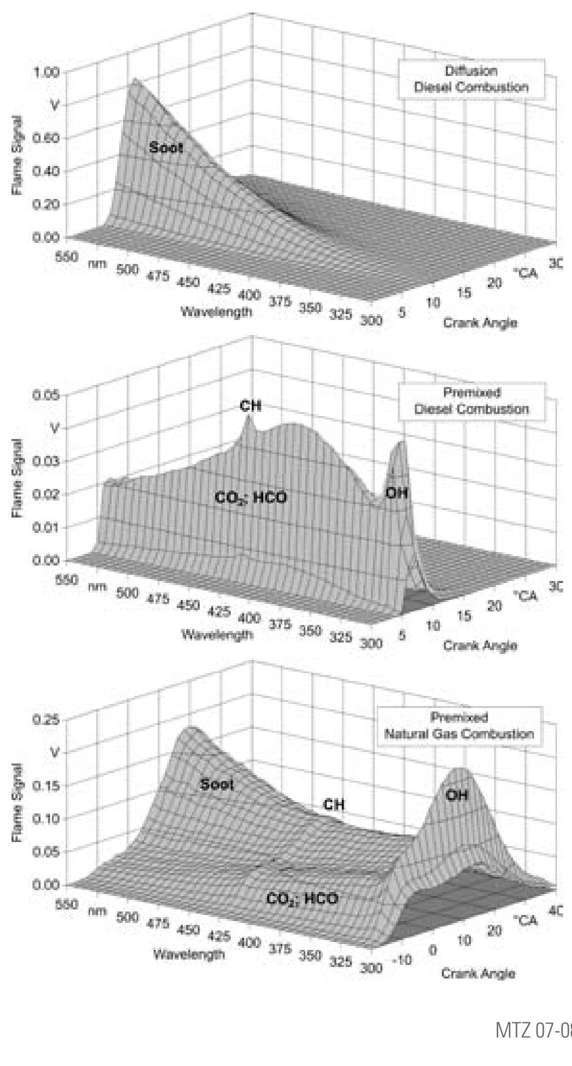

Figure 4: Typical combustion spectra

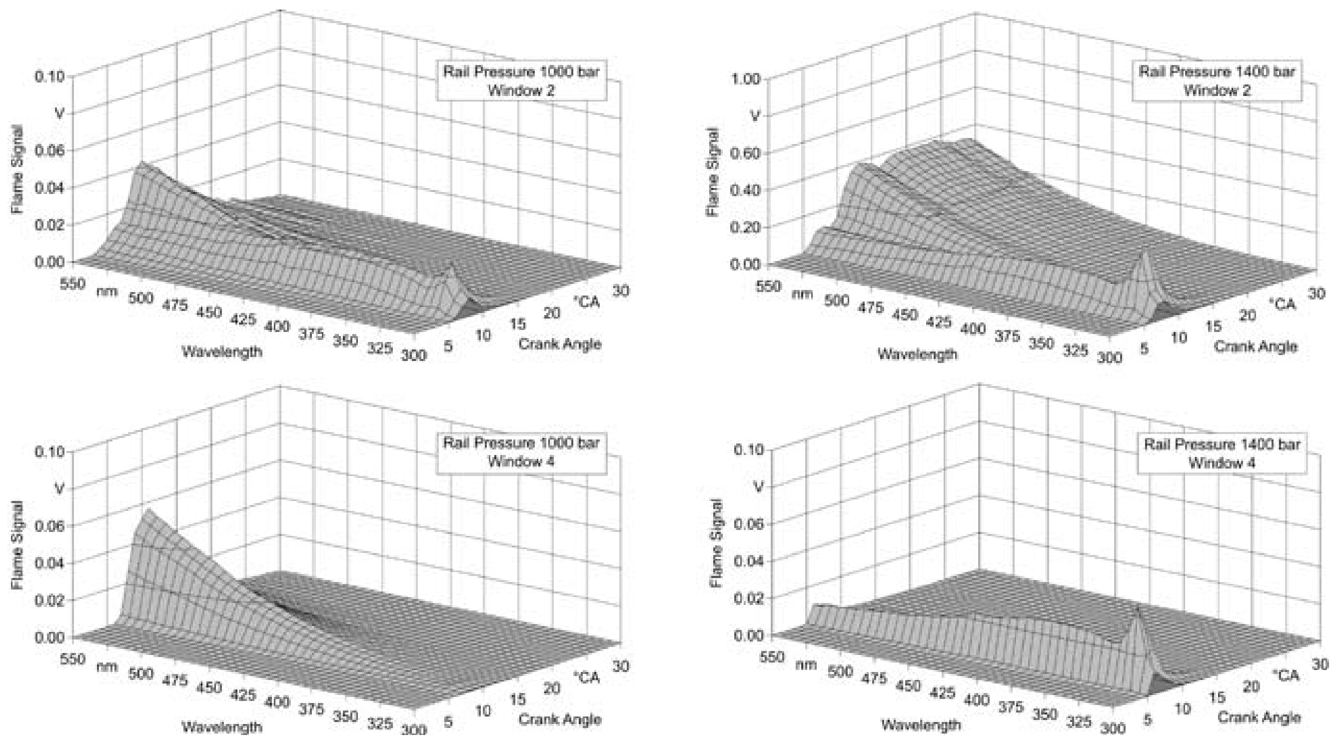

Figure 5: Variation of rail pressure

mainly diffusive diesel combustion shows the soot continuum with a continuously increasing radiation intensity towards larger wavelengthes. In this case, the molecule band radiation is fully covered by soot radiation. This course of combustion is typical for the core area of the injection jet and very low rail pressures.

With a higher rail pressure or in the edge zones of the injection jet, the combustion spectrum of a premixed diesel combustion can be observed. Over a background radiation that decreases towards larger wavelengthes the OH bands at 310 nm and the CH bands at 430 nm can be seen. The background radiation with a radiation maximum around 400 nm consists of emission bands of the species CO_2 and HCO, which lie close to each other and form a quasi continuum. In this case, there is no soot radiation at all. All species mentioned here are typical for the hot combustion zone of a premixed flame. The scaling of the flame signal axis shows that the radiation intensity of the molecule band radiation is approximately 20 times less intense than that of soot radiation.

The lower portion of Figure 4 shows a typical spectrum of a natural gas combustion. During the whole combustion time, an intense OH and a weaker CH band can be seen. In the first combustion phase, a background radiation similar to the premixed diesel combustion occurs, which has to be attributed to the species CO_2 and HCO. In the main combustion phase, however, a weak soot continuum can be demonstrated, which was not expected because of the premixing of gas and air outside the engine. But the soot concentration is by a factor 300 smaller

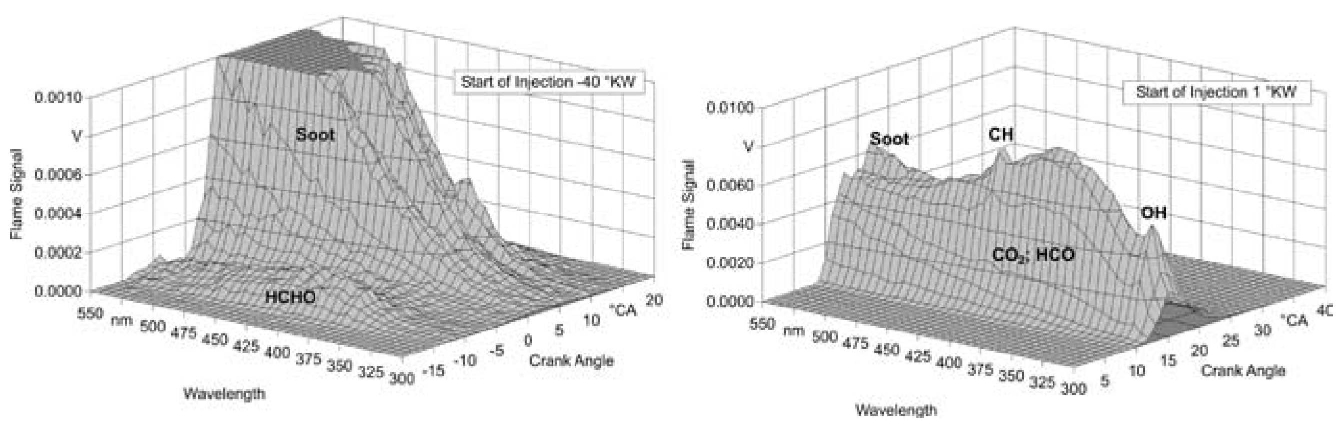

Figure 6: Early and late injection

than in the diesel engine. With comprehensive parameter variation both on the diesel and also on the gas engine, further correlations between spectral radiation emission and combustion course could be attained. Some main results are described below.

3 Studies on the Diesel Engine

A common rail injection system offers the possibility to choose the rail pressure over the full characteristic range freely. The investigation results in [14] showed that there is an optimal rail pressure in the part-load range. If this pressure is exceeded, the particulate emission in the exhaust gas will increase again. **Figure 5** shows the result of a spectroscopic analysis for the optimal rail pressure of 1000 bar and for an increased rail pressure of 1400 bar, with the injected amount of fuel kept constant. In the diametrical combustion chamber area (window 2), one can see at first the spectrum of a premixed combustion for both rail pressures. This may be the edge zone of the monitored injection jet, see Figure 3.

With progressing combustion, due to swirling, also the core zone of the injection jet enters the combustion chamber sector covered by the window 2. This core jet mainly burns diffusively and shows the typical soot continuum. With the optimal rail pressure, only less soot is formed that burns away quickly. In contrast to this, at higher rail pressures, a strong soot continuum over wide crank angular ranges can be seen. At optimal rail pressure a weak soot continuum can be detected close to the walls of the combustion chamber (window 4). With increased rail pressure the spectrum of a premixed combustion can be seen in this combustion chamber sector. The measuring results support the conclusion that, at excessive rail pressures, a large portion of fuel is reflected from the walls to the center of the combustion chamber where zones with a lot of soot build up that can not be oxidized. In contrast to this, there is a diametrically uniform distribution of fuel within the combustion chamber at optimal rail pressure. This results in a good air entrainment by the combustion flame and thus in slight soot formation. Whereas the injection started at -5 °CA for these tests, the following describes the combustion course for very early and very late injection.

Figure 6 shows the relevant combustion spectra. When the injection starts at -40 °CA, after an ignition lag of 25 °CA, a very weak flame radiation within the spectral range between 340 nm and 500 nm occurs, which can be attributed to formaldehyde HCHO. Once the HCHO radiation has decayed a weak soot continuum is emitted. OH radiation could not be detected in any combustion phase. Evidently the cold flame can be monitored under these conditions as it is clearly offset from the subsequent diffusive combustion. When the injection start is shifted to 1 °CA the spectrum of an almost fully premixed combustion with low soot formation can be seen. These findings coincide with results in [14], which showed that a mixture homogenizing is obtained and particulate emission in the exhaust gas decreases at a very late injection due to the large ignition lag.

Figure 7 shows a comparison between flame signals at selected wavelengthes and the thermodynamic combustion rate. With a rail pressure of 1400 bar, almost the whole energy generation occurs in the first premixed combustion phase and the combustion rate shows a good correlation with the OH radiation at 310 nm. In contrast to this, the intense radiation signal at 500 nm in the late combustion phase has to be attributed to soot that does no longer contribute to energy generation. Like the combustion spectrum, also the combustion rate shows a two-stage combustion course at an injection start at -40 °CA. The 500 nm flame signal is at first dominated by formaldehyde and later by soot radiation. Energy generation occurs both in the cold flame phase and also during subsequent diffusive combustion.

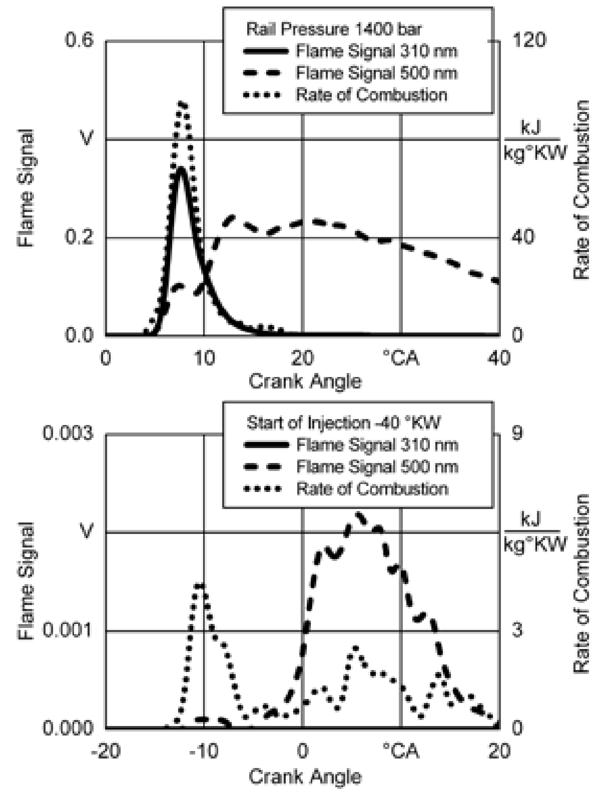

Figure 7: Flame signal and combustion rate in the diesel engine

4 Studies on the Gas Engine

Combustion in a gas engine is characterized by premixing of fuel gas and air as well as spark ignition. As a result the flame front spreads out concentrically through the combustion chamber starting from the spark plug.

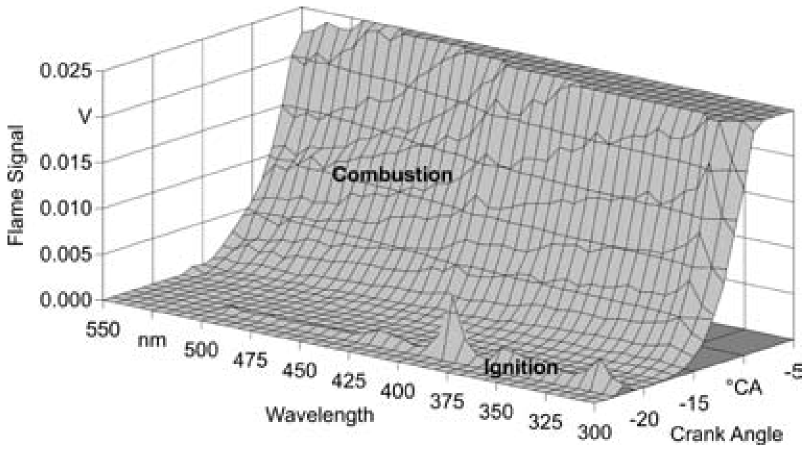

Figure 8: Ignition spectrum

Figure 8 shows a typical ignition spectrum with subsequent combustion. There are considerable differences between ignition and combustion spectrum (see also Figure 4 bottom). The ignition spectrum shows extremely low intensities and features a significant band structure in the wavelength range between 300 and 500 nm. Apart from the OH band at 310 nm, weak HCO bands between 330 and 370 nm can be seen. Further bands at 380 nm and 420 nm cannot be identified clearly. The species CH and CO_2 could not be detected in the ignition spectrum; they only appear in the combustion spectrum.

The air ratio is an important variable for controlling the combustion process within gas engines. **Figure 9** shows the influence of this parameter on the combustion spectrum. At an air ratio of 1.74 a distinctive soot formation occurs in the central combustion chamber area (window 2). During the expansion of the flame front, this soot is oxidized to a great extent so that only molecule radiation can be detected close to the combustion chamber walls (window 4). By an increase of the air ratio to 1.79 soot formation can be almost fully suppressed and only molecule radiation occurs in the whole combustion chamber. At the same time, the combustion temperature decreases considerably and the nitrogen oxide emission decreases by a factor 10. The flame front velocity can be calculated from the time offset of combustion start between combustion chamber center and wall. Values between 160 m/s at high load and small air ratio and 18 m/s at part load or higher air ratio were calculated.

For gas operation, **Figure 10** shows a good correlation between flame radiation at 310 nm and thermodynamic combustion rate. All the studies on the gas engine could demonstrate that the OH radiation is a by far more sensitive indicator for the start phase of combustion than the thermodynamic measurement. Always OH radiation occurs before the thermodynamically calculated start of combustion. Evidently the combustion zone is not large enough in this phase to cause a significant change of the ther-

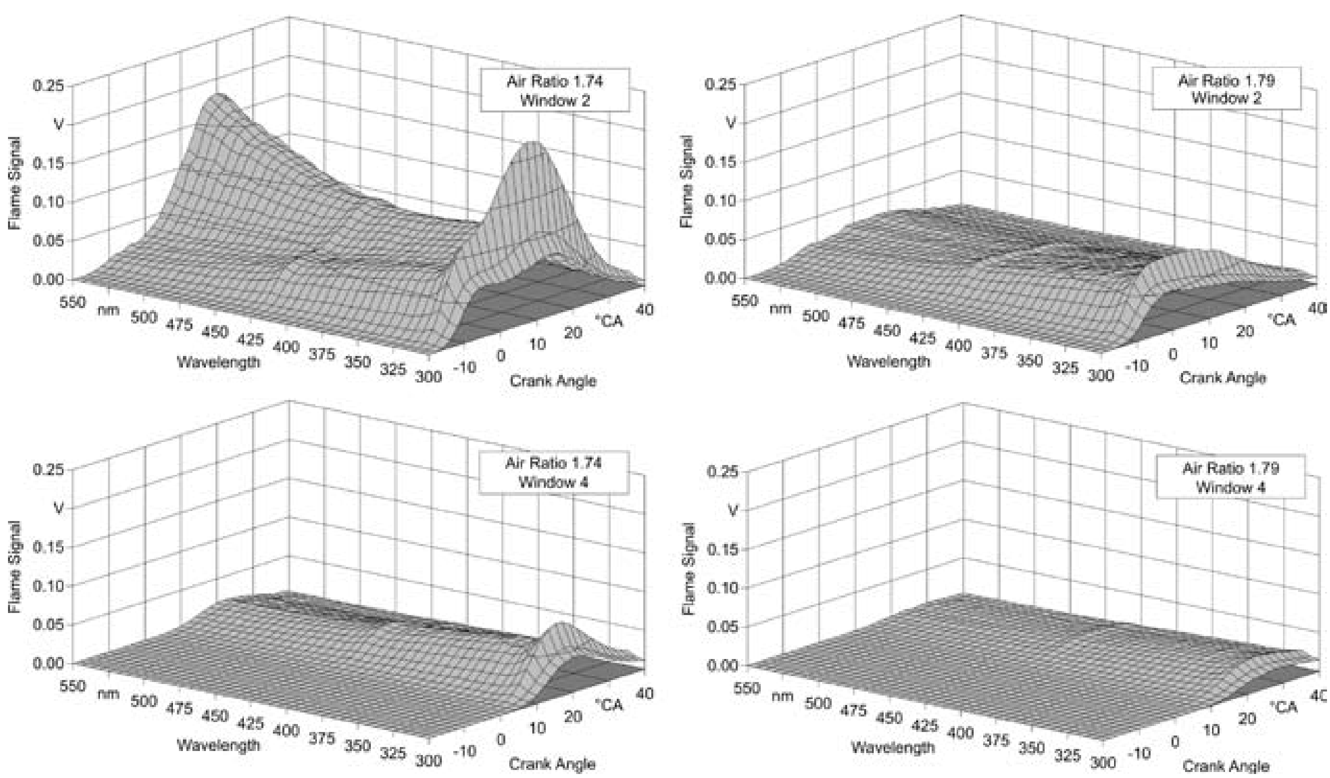

Figure 9: Variation of air ratio

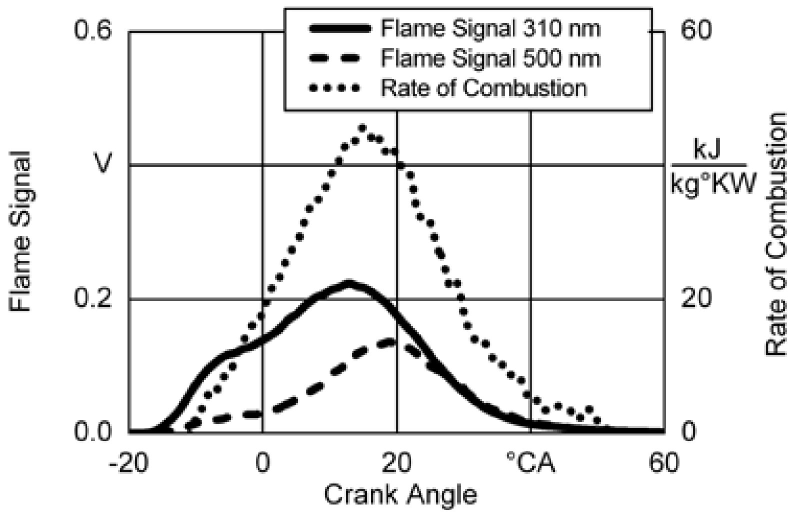

Figure 10: Flame signal and combustion rate in the gas engine

modynamic condition in the whole combustion chamber.

5 Summary

An economical and easily handable measuring device for spectroscopic analysis of combustion flames in engines was developed within the scope of a research project by WTZ Roßlau gGmbH. It allows to detect the radiation in ultraviolet and visible wavelength ranges over the time with highest sensitivity in 16 parallel spectral channels.

The suitability of the measuring method was demonstrated by measurements on a common-rail diesel engine and on a natural gas spark ignition engine (1-cylinder research engines). In doing so, connections between the spectral characteristic of the combustion flame and the local and time dependend processes of mixture formation, combustion and pollutant formation could be established. Future applications are expected in the clarification regarding reaction mechanisms of combustion and pollutant formation, which are again the basis for modeling such processes.

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