

Heat Release Calculation of Internal Combustion Engines by Analyzing the Flame Radiation with Crankshaft Angle Resolution

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ABSTRACT

Improving efficiency and reducing emissions are the principal challenges in developing new generations of internal combustion engines. Different strategies such as downsizing or sophisticated after-treatment of exhaust gases are pursued.

Another approach aims at optimizing the parameterization of the engine. Correct adjustments of ignition timings, waste gate position and other factors have significant influence on the combustion process. A multitude of application data is generated during the development process to predefine appropriate settings for most situations. Improvements in regards to the application effort and the quality of the settings can be achieved by measuring the combustion process and optimizing the parametrization in a closed loop. However, cylinder pressure sensors that are used during the development process are too expensive for series applications.

This paper focuses on an affordable combustion sensor based on the measurement of the electromagnetic radiation of the combustion flame.

The intensity of electromagnetic radiation by chemiluminescence is a good indicator for the status of the combustion as it is primarily dependent on the number of excited molecules. A characteristic spectral band is emitted by the OH radical, which is created in the flame front and corresponds to the number of reactants that are burned.

A research engine was equipped with an access for an optical measurement system for chemiluminescence and light emission in general. To achieve sufficient amplification and temporal bandwidth, a special detector circuitry was designed.

The measurement data was used to analyze the quality of different light emission signals and to investigate their qualification for heat release calculations.

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INTRODUCTION

When first developed, internal combustion engines were mainly controlled mechanically. The main purpose of research was to gain higher reliability, stability and power. Improvements could be achieved by the integration of more and more complex mechanical systems, but one of the biggest steps was the introduction of electronic engine control [1]. At first, the injection and ignition systems were controlled electronically and thus could be easily adjusted to different operation points of the engine. When the standards further increased and new challenges like the reduction of emissions had to be faced, more sensors were integrated to gain more accurate information about the current operation point and to be able to adjust all actuators optimally. This became especially important with new, delicate auxiliary components which were supposed to help to optimize the conditions for the combustion.

However, almost all sensors that are currently being used, such as mass air flow meters, air-fuel-ratio sensors, pressure and temperature sensors, are not able to deliver information about the status of the combustion directly. Instead, they feed models that estimate the missing information using enormous amounts of data that had to be stored during the development process. For this, commonly pressure indication systems are used, which can acquire the change of the pressure in the combustion chamber during the burning process. With these measurements, exact calculations of the heat release and other parameters that describe the combustion process are possible. To use this data in the series operation, many operation points are precalculated and the results are stored in the mentioned engine control models. For a direct series use, the pressure sensors are not affordable.

This paper builds on investigations conducted several years ago, where light emission during the combustion was examined as an alternative combustion parameter. As the sensors themselves do not

need to contain expensive parts and the evaluation electronics can be shared by several cylinders (by using and combining optical waveguides), manageable costs can be achieved. For instance, promising results for optical combustion analysis are indicated in [2] and [3]. The authors discovered significant correlations between the combustion status and optical measurements of the flame signal. They discuss problems due to the high effort to process the signals and the disturbing cross influence of black body radiation of hot parts or particles in the combustion chamber. Minimal optical access is either achieved by specialized probes applying optical waveguides, [4], integration into spark-plugs, [3, 5], or via endoscopes, [6]. For diesel combustion, similar access variants are applied in order to measure soot concentration and temperature distribution, [7, 8]. Based on the two- or more-color method, gasoline direct injection engines are also investigated, [9]. [10] describes an approach for measuring the heat release of turbulent flames by focusing on the chemiluminescence effect and thus blinding out the black body influences.

In this paper, cumulative light emissions and emission due to chemiluminescence in the cylinder of an internal combustion engine are recorded. The results are compared and their suitability for heat release calculations is examined. To measure and process the low amplitudes of the chemiluminescence effect, a special amplifying circuitry was designed.

THEORETICAL BACKGROUND

Radiative Emission in the Combustion Chamber

During combustion, chemically bound energy is converted to heat. Additionally, electromagnetic radiation is emitted. This radiation can be categorized into line, band, and continuum spectra.

Line and band spectra are the result of chemiluminescence. According to the Bohr model, electrons are arranged at stable orbits around an atomic nucleus at discrete energy levels. Following an external energy input, an electron can reach a higher orbit, synonymous to an *excited state*. As the state is instable, eventually the electron will fall back to its stable or *ground* orbit, either via energy transfer by collision, so-called *quenching*, or by the emission of electromagnetic radiation. The discrete energy gap $E_1 - E_2$ emits a discrete line, thus the term “line spectrum”. For molecules, band spectra are observed. A full description requires quantum mechanics, taking the electron’s energetic states and its interdependencies with the vibrational and rotational bands of the radicals into consideration. Further information can be found in e.g. [11].

A high concentration of band radiation in hydrocarbon flames is found in the ultraviolet spectrum below 400 nm. According to [12], the radicals OH, CH, C_2 and HCO are dominant. The radicals are mostly emitted in the flame’s reaction zone, which makes them suitable indicators for flame propagation. In the infrared spectrum, essential contributions are provided by CO_2 , CO, and H_2O , [12]. [10] lists the influence of CO_2 radicals beginning as low as 270 nm with increasing intensities in a broadband spectrum up to 550 nm. Thus, CO_2 is a relevant source of signal cross-talk.

Hydroxyl Radical (OH)

The hydroxyl radical’s spatial and temporal proximity to the reaction zone makes it an ideal indicator. [12] determined OH chemiluminescence emission about 2.5 Crank angle degrees (CAD) prior to C_2 emission. Because of OH’s spatial proximity to the reaction zone, a qualitative correlation to the heat release rate is observed.

Figure [1] shows the simulated spectral emission of OH for a pressure of 50 bar and a temperature of 2000 K calculated with LIFBASE, [13]. A distinctive peak around 309 nm is visible, followed by less intensive bands between 280-290 nm and low emission around 350 nm. A more detailed description of OH’s chemiluminescence properties can be found in [10].

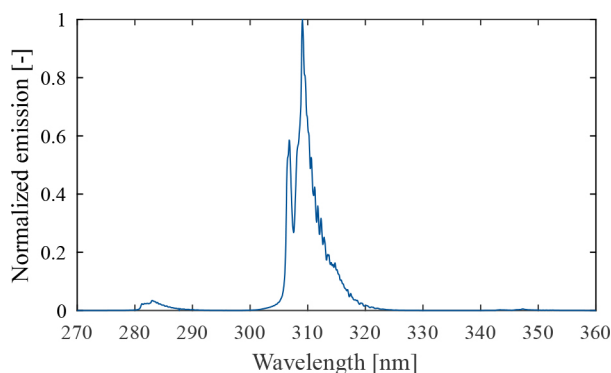


Figure 1. Simulated emission spectrum of OH at a pressure of 50 bar, temperature 2000 K, calculated with [13].

Definition of the Measurement Signal

In total, two separate spectral regions are recorded on two separate detectors. One detection channel is spectrally limited with a focus on the chemiluminescence emission of the OH radical. This spectrally limited light emission ($LEMI_{OH}$) lies in the ultraviolet part of the spectrum. Following Figure [1], the main OH signal is expected to be in the range from 305 - 325 nm. The applied detector and amplification circuitry is built in-house.

The second detection channel is spectrally unfiltered and is used as a global or *cumulated* light emission indicator ($LEMI_{Cum}$). Its spectral range towards longer wavelengths is solely limited by the detector’s semiconductor material and is characterized by a rapid decline towards 1100 nm for silicon. A maximum wavelength is given by the fact that photons need energy levels higher than the material’s band gap, that is the energy difference between the conduction and valence band, in order to be absorbed [14]. For shorter wavelengths, the limit for the commercially available detector is stated to be 400 nm.

Both channels are simultaneously logged with crankshaft angle resolution over the whole engine cycle, like cylinder pressure indication. This way, transient effects are gathered. Data acquisition in the same engine cycle eliminates the influence of cyclic variations. Detection by optical waveguides limits the spatial resolution to an integral value within the cone given by the fiber’s numerical aperture.

Methods of Detection

The available methods of detection for optical signals may be categorized with respect to spatial and spectral resolution.

The use of one photodiode integrates incoming photons and provides the least spatial resolution. It equals one detection channel with one value for read-out. Integration is carried out over the whole collection cone, described by the photodiode's numerical aperture. An array of photodiodes, each with a small numerical aperture, provides several channels in a matrix layout. A further increase of detection channels and thus spatial resolution results for example in a CCD- or CMOS-chip, as used in commercially available cameras.

Weak electromagnetic signals or signals being subject to low quantum efficiencies at the detector need to be amplified. Amplification is achieved either in the electronic output stage or by electron multiplication via secondary emission in the opto-electric detector, as applied by photomultiplier tubes. The minimization of the principle leads to so-called micro-channel plates (MCPs). MCPs either are applied as a standalone apparatus or are coupled to a CCD in one device, forming an intensified CCD.

If only a part of the detector's wavelength spectrum is of interest, its relevant part needs to be isolated. If the spectral range is in the order of a few up to hundreds of nanometers, optical bandpass-filters introduced in front of the detector are sufficient. However, they are mostly tailored to a specific measurement task. If flexibility in the transmitted wavelengths is of importance, optical spectrometers with replaceable gratings are the method of choice. In addition, their achievable spectral resolution is orders of magnitude above optical bandpass-filters.

Examples for publications utilizing optical bandpass-filters in combination with intensified CCDs are [10, 15, 16, 17], for photomultipliers [6]. [2, 3] applied photodiodes without prior spectral filtration.

DEVELOPMENT OF THE OPTICAL MEASUREMENT SYSTEM

Figure [2] gives an overall schematic illustration of the data acquisition setup. After the discussion of the optical measurement system, the remaining experimental setup is covered. Each part of the system offers potential for an improved output signal. Improvements are reached by a higher ratio between the chemiluminescence signal and the resulting voltage at the detector.

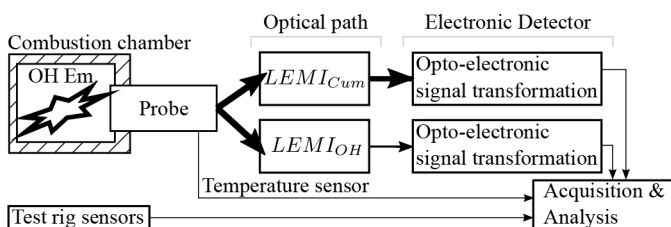


Figure 2. Schematic illustration of the data acquisition setup.

Optical Accessibility of the Combustion Chamber

To enable optical access of the combustion chamber, a prototype probe was constructed. In contrast to fully optical accessible research engines, the approach was to minimize modifications on the engine to create a versatile system, easily applicable to other combustion engines. Therefore, access via fully optical accessible engines following the Bowditch design, [18], or even the substitution of the cylinder liner with a glass ring was not feasible. The outer dimensions on the combustion chamber facing side are limited to a M10 spark plug thread.

In summary, the probe has to fulfill the following demands:

- Provide optical access to the combustion chamber and mount optical waveguides. Focus lies on a detection volume close to the spark plug.
- Gasket against combustion chamber pressure
- Resist combustion chamber's pressure, temperature and combustion residues.
- Mounting compatibility to conventional M10 spark plug thread and drill hole for versatility.

Geometry Variants

After an initial test with a central-drilled M10 screw, two probe variants were tested. Both are compatible to a M10 thread and accommodate two optical waveguides and a thermocouple.

Figure [3] shows a schematic illustration of two variants. The early version uses high-pressure fittings with a cutting ring. As the fitting insert is withdrawn from the combustion chamber, most of the side's shell is exposed to the chamber. The side-facing wall thickness is 0.5 mm. It accommodates two optical waveguides angled 25 degrees towards the longitudinal axis. The subsequent version has the same tilting angle, but is generally designed more rigidly. The spark plug thread is closed towards the chamber at the top, so that the exposed surface area is minimal. Apart from initial testing, the second version was utilized.

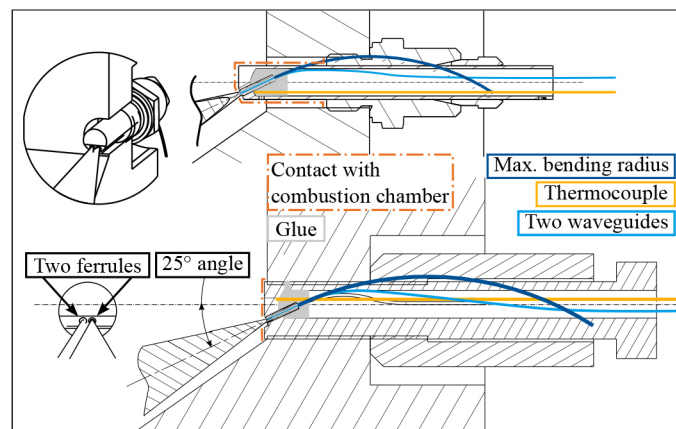


Figure 3. Top to bottom: Early and final design of the combustion chamber probe.

Definition of the Volume-of-Interest and Alignment

To record the electromagnetic radiation during the early stages of combustion, the start of combustion needs to be in the probe's optical path. In a spark-ignited gasoline engine, controlled combustion will start next to the spark plug after spark-ignition.

For the given test rig, the probe accesses the combustion chamber via the auxiliary spark plug's bore. In Figure [4], the applied optical waveguides collection angle is overlaid onto a picture of the test rig's cylinder head. If the waveguides' axes were parallel to the bore axis, the beginning combustion couldn't be recorded. The waveguides' axes are angled 25 degrees towards the bore's axis, putting the main spark plug inside the collection angle. The estimated position of the piston top in top dead center is depicted in the figure. In this alignment, the collection angle covers the volume of interest.

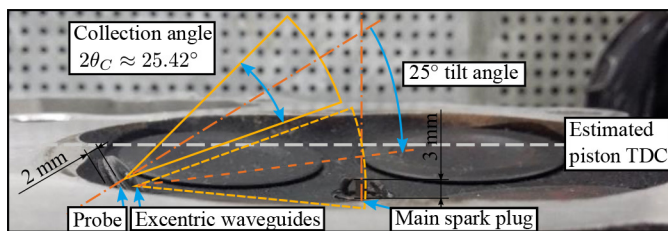


Figure 4. Early measurement probe's orientation and alignment within the cylinder head. Also shown are the waveguides' collection angles and optical axes, as well as the estimated piston position in top dead center (TDC).

Withstanding Pressure and Temperature

The probe has to withstand cyclic stresses due to pressure and temperature during fired engine operation. Because of the small size, an epoxy-based glue, Hysol TRA-BOND F123 (Henkel), was used to assemble the waveguides to the ferrules and the ferrules to the probe. The generated axial force on the optical waveguide and the surrounding ferrules is relatively low, due to their small surface area. An estimated peak pressure of 100 bar and a drill hole diameter of 1.5 mm equals 17.67 N. Split over the drill hole's shell with a height of 6.4 mm, that is an area of 30.15 mm², requires the glue to hold 0.58 N/mm². For the connection between waveguide and ferrule, the calculation leads to 1.26 N/mm². The selected glue's shear strength is stated as 20 N/mm² and is hence assumed to be sufficient.

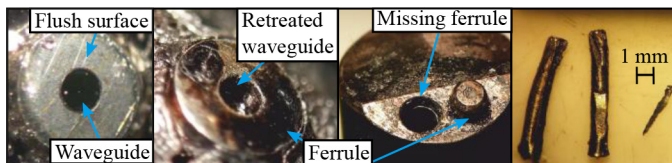


Figure 5. From left to right: Waveguide and ferrule glued into probe. Retreated waveguide after fired operation. Ripped out ferrule and waveguide after fired operation.

Temperature is believed to be the more challenging parameter. The glue's maximum operating temperature is stated as 175 °C. In two cases, the bonding between waveguide and ferrule as well as between ferrule and probe failed, see Figure [5]. In the latter case, the ferrule got loose, moved into the combustion chamber, was deformed and finally split in half. This resulted in only superficial abrasion marks along the cylinder liner and splinters nested in the top piston ring's nut.

As an alternative glue, X280 with a maximum operation temperature of 280 °C was applied. After initial tests, the bonding failed as well. Whether it was due to imperfect preparation of the surfaces or temperature cannot be reported with certainty.

To measure the probes temperature, a PT-100 thermocouple was integrated. Like on a spark plug, a conventional copper gasket was used for the sealing of the combustion chamber.

Operation Strategy

The current temperature was monitored with a thermocouple placed on the outside of the probe's front area close to the combustion chamber. At a maximum of 150 °C, the transition from fired to motored operation was undertaken to account for a temperature gradient from the surface to the thermocouple.

In Figure [6], probe temperature in motored and fired operation is plotted over operation time. For the earlier design stage, the probe's temperature gradually rises to around 90 °C. After the transition to motored operation, a steep temperature gradient with a maximum temperature of 212 °C after only 35 s is observed. With the final design stage, the temperature gradient diminishes after a very similar start. In comparison with the earlier version's 21 s, the break-off temperature of 150 °C is reached after 85 s of motored operation. One reason for this behavior might be the shorter protrusion length of the final design inside the combustion chamber. Combined with improved wall thickness, leading to improved heat conduction, as well as a connection to the spark plug thread starting at the very top, the surface area exposed to the combustion chamber is significantly smaller. The operating condition was fixed at 2500 rpm with a variable start-of-ignition (SOI) between 680 and 695 CAD.

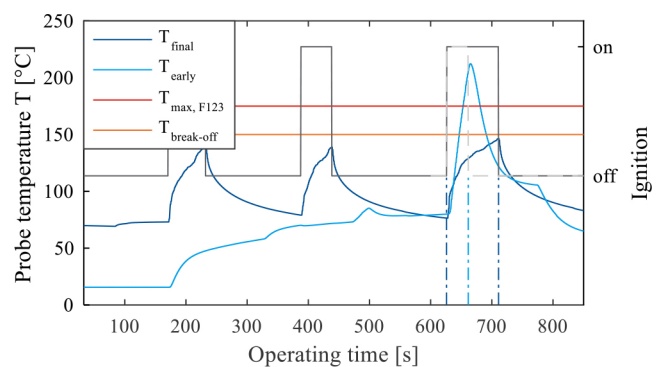


Figure 6. Temperature progress for both probes in fired and motored operation. $n = 2500$ rpm, SOI = 680-695 CAD.

In order to stay within the temperature limits, measurements were recorded intermittently. If the break-off temperature is reached, operation is switched from fired to motored until the recorded temperature drops down to 90 °C.

Radial Alignment

As the outer mounting ring of the probe is free to move and thus offers no feedback of the actual radial position of the probe relative to the volume-of-interest, proper alignment needs to be checked in another way.

With the volume-of-interest being next to the spark plug, the spark's arc-over can be used as a reference. While the probe is mounted, the recorded optical signal is checked with an oscilloscope. That way the radial position can be optimized for the highest signal output. Figure [7] shows the measured signal amplitudes for both optical channels. Due to the overall higher amplification of channel one, the amplitude is higher as for channel two. The ignition coil's current is measured and allocates the light emission temporally to the arc-over. Following a dwell time of 4.5 ms, the spark duration under ambient conditions is roughly 3.15 ms.

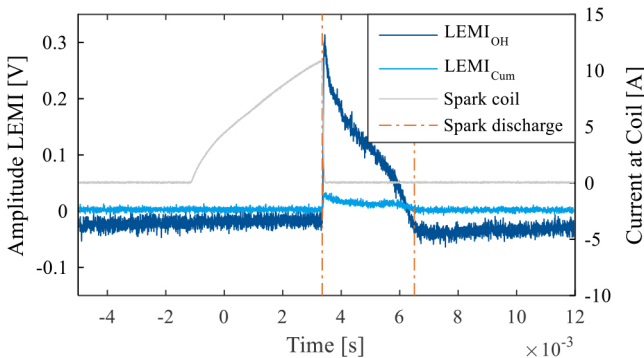


Figure 7. Measured optical signal amplitudes after correct radial alignment of the probe. According to the light signal, spark duration is roughly 3.15 ms.

Optical Signal Transfer

Optical Waveguides

Figure [8] shows the working principle of an optical waveguide or fiber. Incident light from within the combustion chamber is collected and transferred towards the remaining optical path. If the light enters at an angle of less than θ_C towards the optical axis, it is within the collection angle. In that case, the signal is subject to total internal reflection and routed via the fiber.

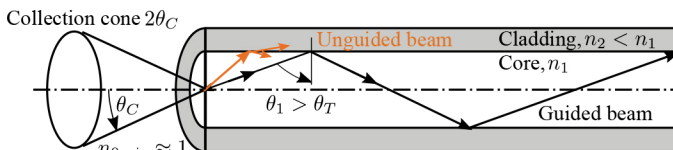


Figure 8. Schematic illustration of the working principle of an optical fiber, following [19].

For angles greater than the critical angle $\theta_{crit} = 90^\circ$, Snell's law is no longer fulfilled. θ_T is calculated according to the equation (1) for θ_{crit} :

$$\theta_T = \arcsin\left(\frac{n_2}{n_1}\right) \quad (1)$$

For angles $\theta_1 > \theta_T$, the light ray is totally reflected with no diffraction, the boundary layer between core and cladding acts as an ideal mirror. In comparison, for signal transfer by diffractive elements like lenses or real mirrors, losses occur on every transmitted or incident surface by absorption respectively by reflection. This makes the technique ideally suited for light transportation over long distances, [20]. The selected multi-mode fibers provide a numerical aperture $NA_{fiber} = 0.22$, which equals a collection angle of 25.42 degrees, [19]:

$$\sin\theta_C = \sqrt{n_1^2 - n_2^2} = NA \quad (2)$$

High collection angles simplify the coupling, as light parallel to the optical axis up to the angle is transmitted, leading to a multitude of modes. Various modes lead to pulse dispersion and result in different path lengths. Because of the experiment's path length of about two meters the effect is negligible compared to the increased light collection efficiency.

The fibers' flexibility makes a rigid connection of the detector to the volume-of-interest unnecessary. In this way, the detector was decoupled from the engine's vibrations. The decoupling reduces stress on the components and displacement of the optical components.

The probe operates with one fiber per optical channel. For future measurement tasks, an adapted number of fibers or the application of fiber bundles are implementable. Fibers with an active core diameter of 365 μm are used in the experimental setup, as they provide adequate size and collection angle while maintaining a reasonable bending radius for the probe's installation space. Despite the given long-term minimal bending radius of 40 mm, no signal decrease due to a smaller radius could be detected.

Optical Path Design

The measurement signal is collected from the combustion chamber with optical fibers and transmitted to the remainder of the optical path. For the laboratory setup, the remaining optical path towards the opto-electronic signal conversion is built out of standard equipment. Figure [9] shows a schematic illustration of the setup. At the end of the FC-PC-terminated fiber, the transmitted light is outcoupled into a cone with a half-angle of 12.7 degrees.

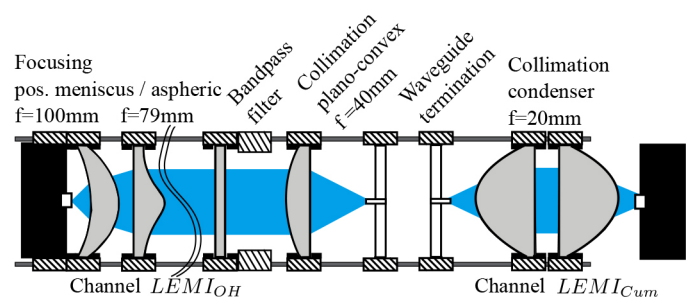


Figure 9. Schematic setup for both optical channels. The elements are positioned out of proportion.

Channel one collects $LEMI_{OH}$. An anti-reflection coated plano-convex lens collimates the divergent beam. With a numerical aperture of $NA_{collimation} = 0.28 > NA_{fiber} = 0.22$, collection of the whole light cone is ensured. The collimated beam gives flexibility on the axial arrangement of the following components. The setup is designed to integrate either a commercial image intensifier for debugging purposes or an optical bandpass filter. Finally, two lenses focus the collimated beam onto the photodiode's active area. To push the focus diameter below 1 mm, a combination of an aspheric plano-convex and a negative meniscus lens is used. Both lenses are made from synthetic fused silica to enable adequate transmission in the ultraviolet spectrum.