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Temporally-resolved spark-induced emission spectroscopy for optical in-cylinder ignition diagnostics

Temporally-resolved spark-induced emission spectroscopy was developed as an optical diagnostics method to monitor ignition of homogenous methane-air mixtures at engine relevant pressure levels in a quiescent constant volume cell. Hydroxyl (OH) emissions at 308 nm, NH emissions at 336 nm and cyanogen (CN) band emissions at 388.3 nm were investigated. Spectral fingerprints of different gas composition were identified to relate plasma emissions to combustion relevant parameters such as the local air-fuel ratio. The temporal-resolved method provides valuable information about the coupling of the electrical discharge characteristics to the measured spectra. Transferring the method to an optical spark plug allows minimally invasive in-cylinder ignition diagnostics.

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Introduction

Hydrogen enrichment of methane enhances the ignitability, the flame kernel formation and growth in spark-ignited internal combustion engines. Earlier engine studies demonstrated the benefits and drawbacks of hydrogen enrichment to compressed natural gas on inflammation, combustion duration and emissions [1,2]. Plasma emissions during the ignition process are a fingerprint of the local gas composition; temporally-resolved spark-induced emission spectroscopy helps to understand the underlying processes of flame formation under engine relevant conditions. Using an optical spark plug as indicated in Figure 1 would allow to do minimal-invasive in-cylinder ignition diagnostics on engine test benches.


Figure 1: M10 optical spark plug with two fibers dedicated to spark-induced breakdown spectroscopy

Experimental test rigs and methods

Spark-induced breakdown spectroscopy (SIBS) is a technique to analyze the availability of different species during ignition [3]. The impact of fuel composition, pressure, temperature and cross-sensitivity on the spectral characteristics are investigated in an optically accessible ignition cell at quiescent conditions and compared with simulated spectra.

Experiments were conducted in a small constant volume chamber at an elevated pressure level of 10 bars and compared to pure air and methane emissions. A lens-coupled spectrometer (f=150 mm) was linked to a high speed image intensifier and a high speed camera to monitor the plasma emissions during the electrical discharge at a rate of 100 kHz along the spark plug gap of 1 mm as shown in Figure 2.

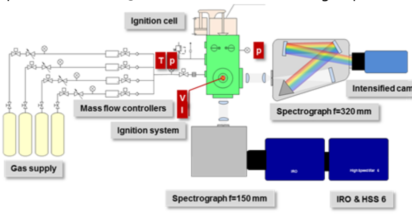

Figure 2: Setup on the ignition cell for spark-induced emission spectroscopy

Spectral emissions were captured from the near UV range up to 400 nm. Additionally, a second, higher resolution, long-integrating, classical spark-induced emission spectroscopy setup (f=320 mm) was used as a reference. Current and high voltage probes on the secondary side of the coil ignition system completed the measurement setup to determine power and energy input.

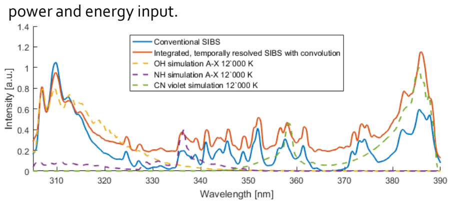

Figure 3: Comparison of a conventional SIBS spectra, an integrated, temporally resolved and convoluted SIBS spectra and simulated OH, NH and CN emissions of a reactive methane-air mixture (λ=1) at 10 bar.

Results and Conclusions

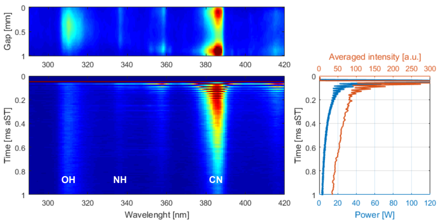

Figure 4: 1-D conventional SIBS (upper left) and temporally-resolved SIBS (lower left). Temporally averaged intensity levels agree well with measured electrical power (right)

SIBS spectra contribute to the understanding of the transitional phase from the plasma channel to the early flame kernel from a chemical perspective. A proper decomposition of metal emissions originating from electrode wear and intermediate reactants from air and fuel is crucial to identify combustion relevant parameters. The application of a temporally-based method provides valuable information about the coupling of the electrical discharge characteristics to the measured spectra.

Cyanogen (CN) band emissions at 388.3 nm and NH emissions at 336 nm were found to strongly correlate with electrical power, but hydroxyl (OH*) emission at 308 nm did not as indicated in Figure 4. Comparison of conventional 1-D spectra with integrated, temporally resolved and convoluted spectra revealed a good agreement in terms of spectral characteristics and resolved species.

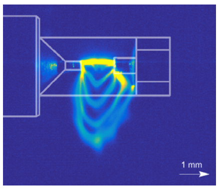

Figure 5: Multi-exposure of a deflected plasma channel during an ignition event

Moreover, the results assist in specifying an optimal camera gating for the conventional approach and the experimental setup can be used to provide calibration maps for engine applications. Taking into account the deflection of the plasma channel due to generally turbulent in-cylinder flow fields [4] as shown in Figure 5, short gate widths shortly after breakdown are of main importance to achieve high signal quality to transfer the method to an optical spark plug.

Optical ignition diagnostics

Significant advances in engine development are currently limited by a poor understanding of the details of ignition and flame development at the early stage of combustion due to the limited optical accessibility of real engines. However, the formation and development of the flame at the early stage of combustion greatly influence the later flame propagation and thus the combustion process and stability.

The spectroscopic data of the ignition event enhances the understanding of the transition from the plasma to the early flame kernel and allows to further refine and validate CFD models of the ignition process. Temporal resolved spark-induced emission spectroscopy enables a detailed analysis of the transient behavior of the plasma channel.

Integrating this method into an optical spark plug provides insight into the ignition process and can reveal important information on a cycle to cycle basis.

References

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