Diode-Laser-Based In-situ-CH_4-Detection for the Surveillance of Ignition Processes in Gas-fired Power-Plants

H. Pitz, T. Fernholz, C. Giesemann, V. Ebert
Institute of Physical Chemistry ,University of Heidelberg
INF 253 - 69120 Heidelberg
volker.ebert@urz.uni-heidelberg.de

Abstract: We demonstrate the first simultaneous in-situ detection of methane and water in a full-scale 1 GW_{th} gas-fired power plant with an absorption resolution in the order of 10^{-4} OD corresponding to less than 5 ppmV at 400K.

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1. Introduction

The combustion of natural gas in addition with combined-cycle processes will play an increasingly important role in the energy production due to the high conversion efficiency of the process and its very low pollutant emission and overall costs. To maintain the positive properties under all process conditions, i.e. under frequent and strong variations in total power, and to enable secure ignition - ignition failures have lead to severe power plant damages in the past- and precise active control of the multi-burner systems with up to 20 large-scale burners, it would be helpful to have a fast in-situ gas sensor, which is able to circumvent the problems associated with the local sampling character of extractive sampling probes. Species of interest for such a sensor are methane as an indicator of an ignition failure , water to perform an in-situ temperature measurement and oxygen to determine the mean fuel-to-air-ratio along the absorption path. Since the data are needed most right after the ignition of the first few burners it is unavoidable to perform a simultaneous optical temperature measurement to extract meaningful quantitative methane concentrations.

We have started with the development of such an in-situ absorption spectrometer based on near infrared diode lasers, which is able to determine simultaneously multiple species concentrations, namely CH_4, H_2O and O_2, and the temperature during the ignition cycle of a full-scale gas-fired power-plant with an inner diameter of 10 meters and a thermal gross power of 1 GW. We report about our first results regarding the optical characterization of the in-situ absorption path and about our in-situ-detection of methane and other gaseous species under ignition conditions. We can show that we are already able to detect an ignition failure and prevent dangerous process conditions.

2. Experimental details

Tunable diode lasers in the red to near infrared spectral range (630nm to 1700nm) are very promising tools for industrial in-situ species sensors [1-3]. They are inexpensive, rugged, extremely compact, can be operated at room temperature from relatively simple current sources without a need for additional cooling and offer a unique combination of spectroscopic properties like fast tunability, narrow spectral line width and high spectral brightness, which makes them near ideal candidates for in-situ sensors. For our application at a full-scale power plant we used the lasers indicated in table 1:

Table 1: Properties of NIR-Diode lasers used in our setup

Species	**Transition**	**Laser type**	**Power** mW	**Current tuning** nm/mA	**Temp. tuning** nm/K
CH_4	$2\nu_3$	DFB: 1653 nm	7	0.017	0.010
H_2O	000→211; 000→112	FP: 813 nm	35	0.007	0.067
O_2	$X^3\Sigma^-_g \rightarrow b^1\Sigma^+_g$	DFB: 760 nm	5	0.013	0.058

All lasers were coarse tuned by temperature to the transition of interest. Rapid wavelength tuning with repetition rate in the kHz range lines was initiated by current modulation to cover the rovibrationally resolved absorption. The laser beams were collimated and combined to form a single beam which was

then directed through the combustion vessel via air cooled flanges and air purged windows under Brewsters angle.

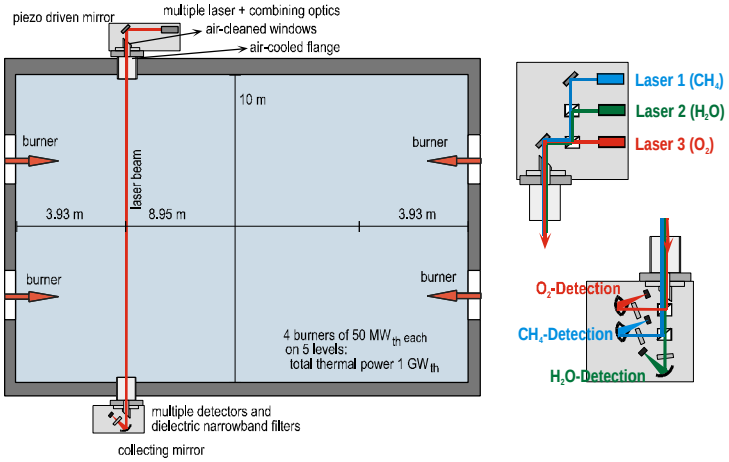

Fig. 1. Optical setup at gas-fired power plant

On the receiving side (figure1) the light was collected with a spherical mirror and separated into the individual wavelengths by dichroic beamsplitters. To further eliminate cross talk between the wavelength channels and to minimize disturbances by fluctuating thermal background emission each channel was further separated by narrow band dielectric interference filters. The absorption signals are evaluated by digitizing the dc-signals with a 12 bit ADC with 8 simultaneous sampling channels, averaging up to 200 successive absorption profiles per species and finally extracting the line area by a fast fitting routine. On of the major problems which has to be solved to be able to allow continuos combustion monitoring during the entire startup process is correction for transmission fluctuations. In order to choose the laser scan frequency to be high enough to “freeze” the disturbances during a single scan we carefully studied the amplitude and frequency behavior of the transmission of the in-situ path and of the thermal background emission which is also collected by the receiving optics. The corner frequencies for emission were 50 Hz and for transmission 1khz. Emission suppression is important since part of the transmission correction is a division of the raw scan by the reconstructed baseline. Another additional major problem which was found rather unexpected was a severe thermally induced deformation of the combustor walls during the startup phase which lead to complete misalignment of the laser beam. To compensate these wall deformations we designed and lab-tested a robust closed loop beam stabilization system (based on a position sensitive photodiode and a piezo driven mirror mount) which is insensitive to the unavoidable strong amplitude fluctuations of the pilot beam and the background emission. An In-situ test under industrial conditions is planned in the near future.

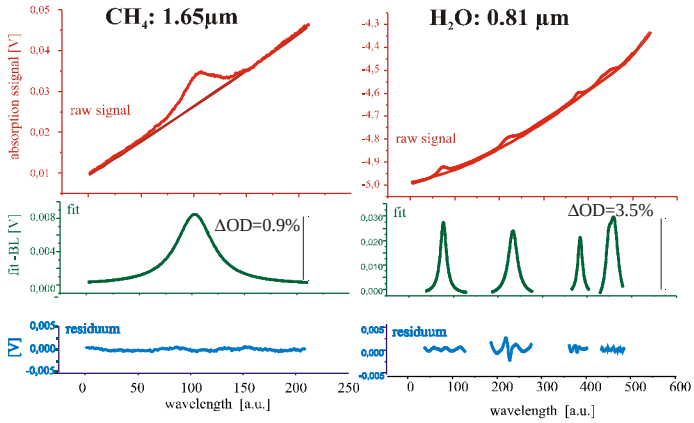

Fig. 2. In-situ signals of methane and water at the 1 GW$_{th}$- gas-fired power plant

3. Results

First results gained with the described setup at the full scale device during startup conditions are shown in figure 2. The depicted raw in-situ signals with peak absorptions below 1% for the R5-line methane and up to 3.5% for the line group of water were captured simultaneously and could be fitted with good

accuracy to Lorentzian line shapes. Despite strong background emission and severe transmission fluctuations down to 5% transmission we estimate from the residuum of the fit an absorption resolution for the spectrometer in the order of 10^{-4} OD, which is equivalent to an improvement in signal to noise by the transmission correction of more than three orders of magnitude. The time resolution achievable depends obviously on averaging rate, with a 200 fold average a time resolution of two seconds could be achieved. A typical time evolution of the methane absorption signal during a startup event is shown in figure 3.

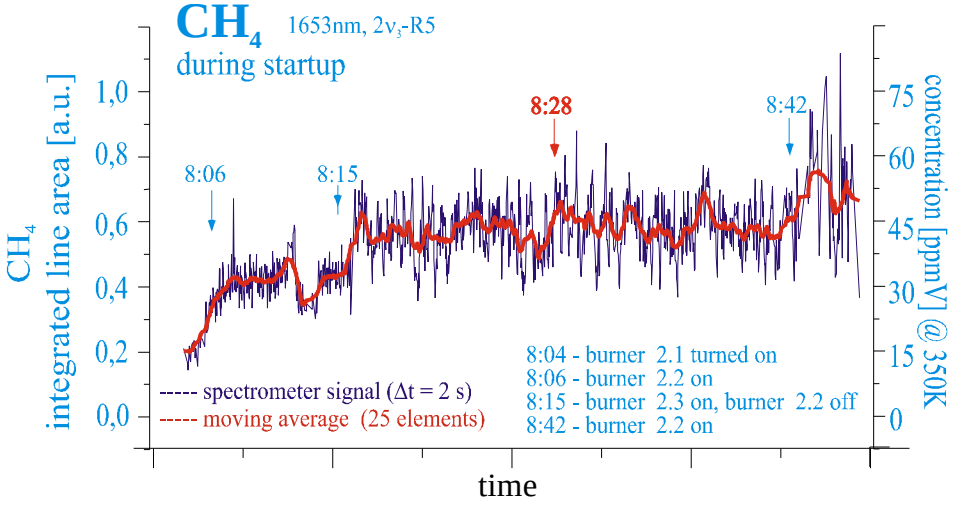

Fig. 3. Time evolution of the in-situ methane signal

Arrows indicate special events during the startup procedure like the ignition of an additional burner. As shown it is already possible to detect a weak increase in the signal during some ignition events, which has to be concentration rise since it cannot be explained by the increase in temperature.

To convert the absorption signal in concentration units it is necessary to perform a temperature correction which will be done in the near future. As a first preliminary step we used the shape of the methane line and HITRAN calculations to estimate the temperature of the gas to roughly 400K and compared this temperature with the result of the line strength ratio of the water peaks which lead to a temperature of at least 700K. This surprising discrepancy seems to indicate that the temperature of the water and the methane molecules differs by some hundred degrees. If this discrepancy is caused by incomplete mixing and resulting temperature gradients or by other causes will be investigated during the following measurement campaigns by redundant temperature measurements with different educt and product molecules. Using the temperature estimated from the methane line shape to convert the absorption signal to a concentration we end up with an average methane concentration during startup of 50 ppmV which is in good agreement with the expected values under standard process conditions. From this we conclude that we are able to detect clearly any ignition failure with the in-situ spectrometer since the concentration would then rise to far more than 100ppmV.

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[3] Ebert, V., Fitzer, J. ,Gerstenberg, I., Pleban, K.-U., Pitz, H., Wolfrum, J., Jochem, M., Martin, J., "Simultaneous Laser-based In-Situ-Detection of Oxygen and Water in a Waste Incinerator for Active Combustion Control Purposes", 27th Symposium (Int.) on Combustion, The Combustion Institute, Pittsburgh, pp. 1301-1308 (1998)