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Heterodyne Dual Frequency Comb Laser Absorption Spectroscopy for NO and H_2O Detection in Supersonic Combustion Processes

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Abstract

The progressing climate change and its consequences commonly raises the need to reduce the environmental impact of civil aviation. A possibility for hypersonic passenger flights is the use of scramjets that are powered by hydrogen combustion. Consequently, an improvement in performance of spacecraft regarding their efficiency and flight time is an economic and social desire. While hydrogen combustion has almost zero carbon dioxide output, water vapor and NO are formed in the process. Both are believed to have a strong influence on the atmospheric chemistry [1]. Therefore, a precise experimental determination of both NO and H_2O production during the hydrogen combustion is necessary for the evaluation of environmental effects caused by hydrogen fueled vehicles. To test these models in the future in the High Enthalpy Shock Tunnel Göttingen (HEG), being one of the major European hypersonic test facilities, a novel experimental approach to study the development of gas concentrations at rapid acquisition rates is the absorption spectroscopy with quantum cascade lasers (QCLs) in the infrared regime [2].

Keywords: *hypersonic flow, hydrogen combustion, absorption spectroscopy, scramjet, HEG*

To determine H_2O and NO concentrations in hydrogen combustion processes in HEG a novel spectrometer (Iris-F1, IRsweep AG) based on the frequency comb technology is used. In contrast to conventional laser systems that emit at single wavelengths at a given time, the Nobel prize awarded technology generates an optical spectrum with many discrete equidistant lines in the frequency domain [3]. The frequency comb sources are quantum cascade lasers. The two included QCLs have slightly different repetition rates $f_{rep,1}$ and $f_{rep,2}$. When both are combined, they generate a heterodyne beating signal as radiofrequency comb spectrum with $\Delta f_{rep} = f_{rep,1} - f_{rep,2}$ (**Fig.1**, left). The repetition rates are chosen for Δf_{rep} to be on the order of 1 to 5 MHz, so that the heterodyne beating pattern can be recovered from a high-bandwidth detector. To conduct the spectrometric measurements, two beams are needed. The reference beam reaches the detector undisturbed, while the sample beam passes through the sample and interacts via absorption. The absorption attenuates the heterodyne signal and is characteristic for each gas species.

The spectrometer covers a spectral region of 1720 to 1760 1/cm. As simulated with HITRAN in **Fig. 1**, NO and H_2O lines are present allowing to study the production of these during hydrogen combustion experiments.

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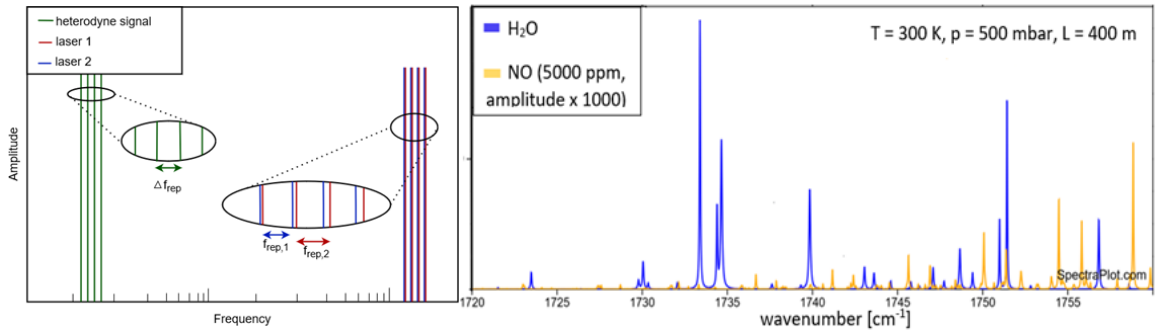

Fig 1. Frequency combs and heterodyne beating signal as RF spectrum (left). Simulated spectra of NO and H2O via Hitran (right).

The applicability of the spectroscopic technique was demonstrated and it could be applied to a test case of hydrogen combustion in HEG [4], but the measurements also showed, when analyzed in detail, the urge of more sophisticated calibration procedures for the spectrometer. Thus, part of the current work is the establishment of these procedures. The setup is presented in **Fig. 2**. A multipass absorption cell is placed inside the spectrometer's sample compartment. The so called Herriott cell consists of mirrors that reflect an incoming light beam several times to increase the path length before coupling the beam out again. In this case, the cell has a circular design with individually curved mirror segments that achieve a path length of 4 meters within a compact volume of 31 ml. After evacuating, the cell is filled either with 200 ppm NO in N_2 or with ambient air to detect the amount of water for a range of pressure between 0 and 1000 mbar which is monitored with a manometer. The spectrometer is continuously purged with N_2 to remove disturbing water molecules from ambient air. As expected, the amount of water increases with a rising pressure. The measurements for water are in good agreement with the theoretical spectra that are plotted using the HITRAN database as given in **Fig. 2**. The detection of NO came along with various challenges. A major issue were the used tubings that pulled water from the surrounding. A long evacuation time of the cell has to be attended to ensure a complete absence of water inside it. So far, the tests were conducted as long term measurements, but the spectrometer offers also a times resolved mode. This limits the acquisition time to around 33 ms, but enables time resolutions of 1-4 µs which is suitable for experiments at HEG. In a next step, a bigger Herriott cell creating a longer path length is used externally to study the weakening influence of fibers on the intensity signal. The fibers are used in the wind tunnel experiments. An outcoupling optical unit directs the sample light beam from the spectrometer into the fiber that leads towards the external setup. The same is done for the path back to the detector. After these measurements, experiments with a small shock tube employing the spectroscopy technique will be performed. The results will be reported in the paper.

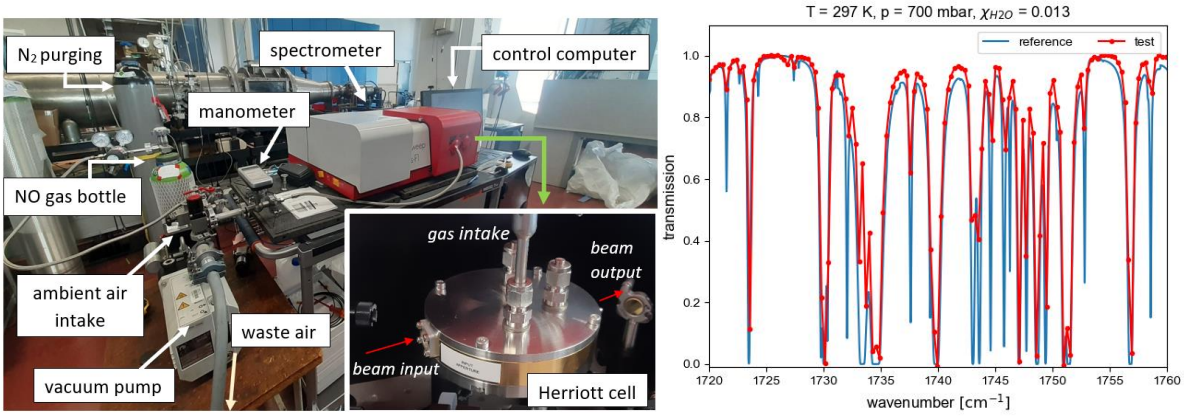

Fig 2. Experimental set-up including the Herriott cell and gas connections (left). Results from spectroscopic water measurements in comparison with reference HITRAN data (right).

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