EVALUATION OF OPTICAL AND SPECTROSCOPIC EXPERIMENTS OF HYDROGEN JET FIRES

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Introduction

- On accidents hydrogen in pressurized closed vessels might release and may be mixed with air to generate hot flame jets on ignition in wide ranges of fuel/oxidizer compositions.
- **Radiation of the hot species** depending on **temperature** is a main effect to influence the surroundings and contribute to strong heat transfer.
- The radiative emission of hazardous fires and gas/liquid explosions is strongly variable in **time** by jets lasting till shut down or complete release and at short scales down to milliseconds.
- As investigated in the described experiments, a fully deployed hydrogen jet (un-reacted) generates an **explosion** when ignited and transfer to a **turbulent flame jet** expanding the volume of the original jet.
- A **scanning analysis of the spectral flame radiation** must record the **flame dimensions**, be fast enough to detect pre-reactions, transient phenomena, starting explosions, enable the understanding of propagation mechanisms as well as quenching or extinguishing mechanisms.
- In contrast to pressure effects, time and spectrally resolved radiation of fires and explosions is not investigated in a sufficient way.

Background: Emission of Heat Radiation of Hydrogen Free Jets

To provide data for estimate heat radiation Q_{rad} of hydrogen flames

$$Q_{rad}(t) = \varphi(t,y)A(t)\,\varepsilon(t,T,x,c_i)\,\sigma\,T(t)^4$$

φ View factor as function of (reference) shape, distance y (see text books on heat radiation)

A Emitting area or projected area

$\sigma = 5.67 \cdot 10^{-8}\,\Omega\,m^{-2}\,\mathrm{K}^{-4}$ Stefan-Boltzmann constant

T effective emission temperature (combustion temperature)

ε Total emissivity as function of time, temperature

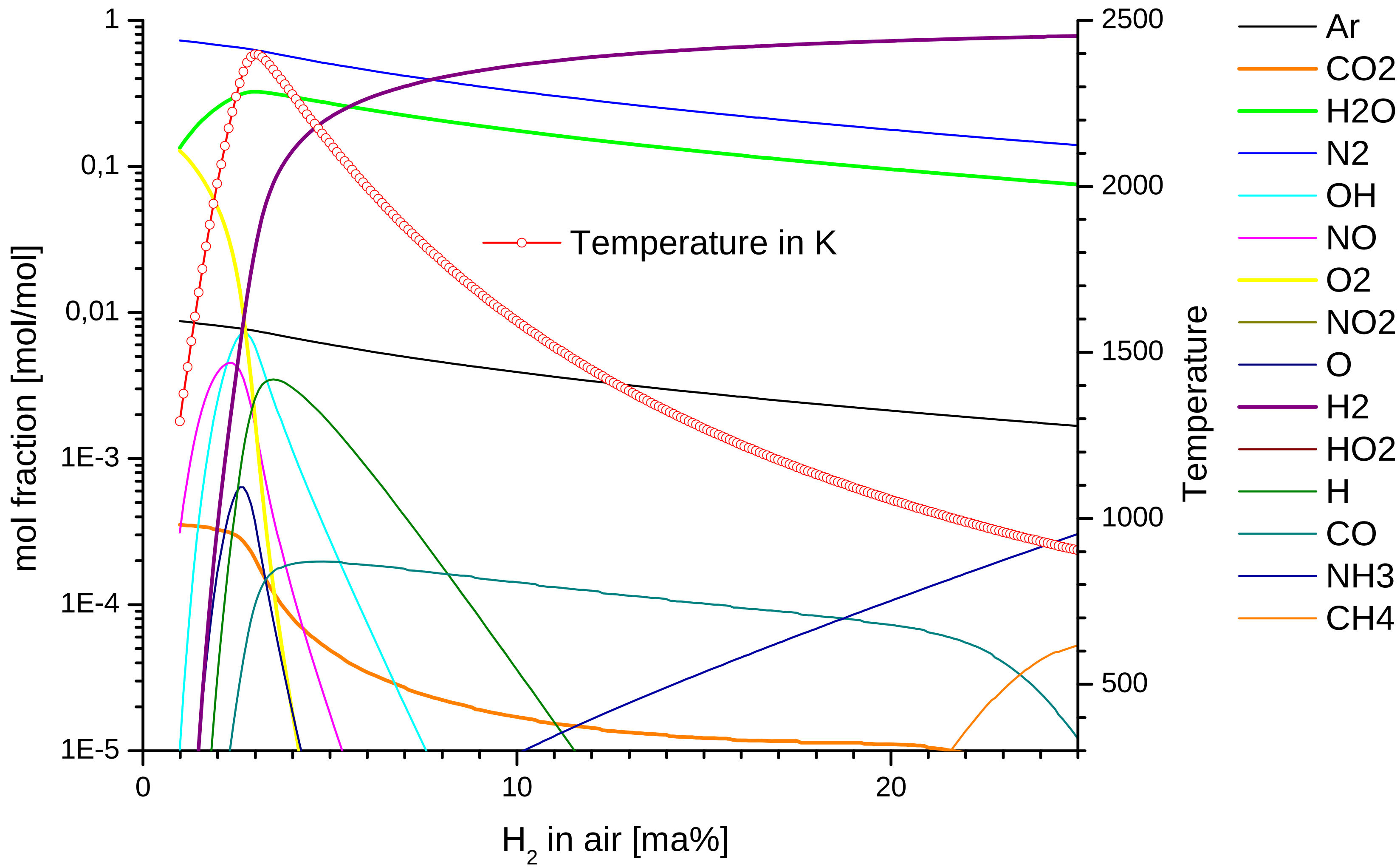
Total emissivity can derived from spectral emissivity $\varepsilon(\lambda,T)$

$$\varepsilon(T) = \frac{\int_{-\infty}^{\infty} \varepsilon(\lambda,T)\,L_S(\lambda,T)\,d\lambda}{\sigma T^4 \Omega_0}$$

$\varepsilon(\lambda,T)$ can be calculated using spectral emission modelling codes like RADCAL or ICT-BaM. Input parameter:

- ***temperature T***
- ***emitting path length x***
- ***species concentration c_i***

Adiabatic Flame Temperature and main reaction species of the combustion of Hydrogen with air for various mixture ratios (calculated by ICT-Thermodynamic Code basing on ICT-DB)



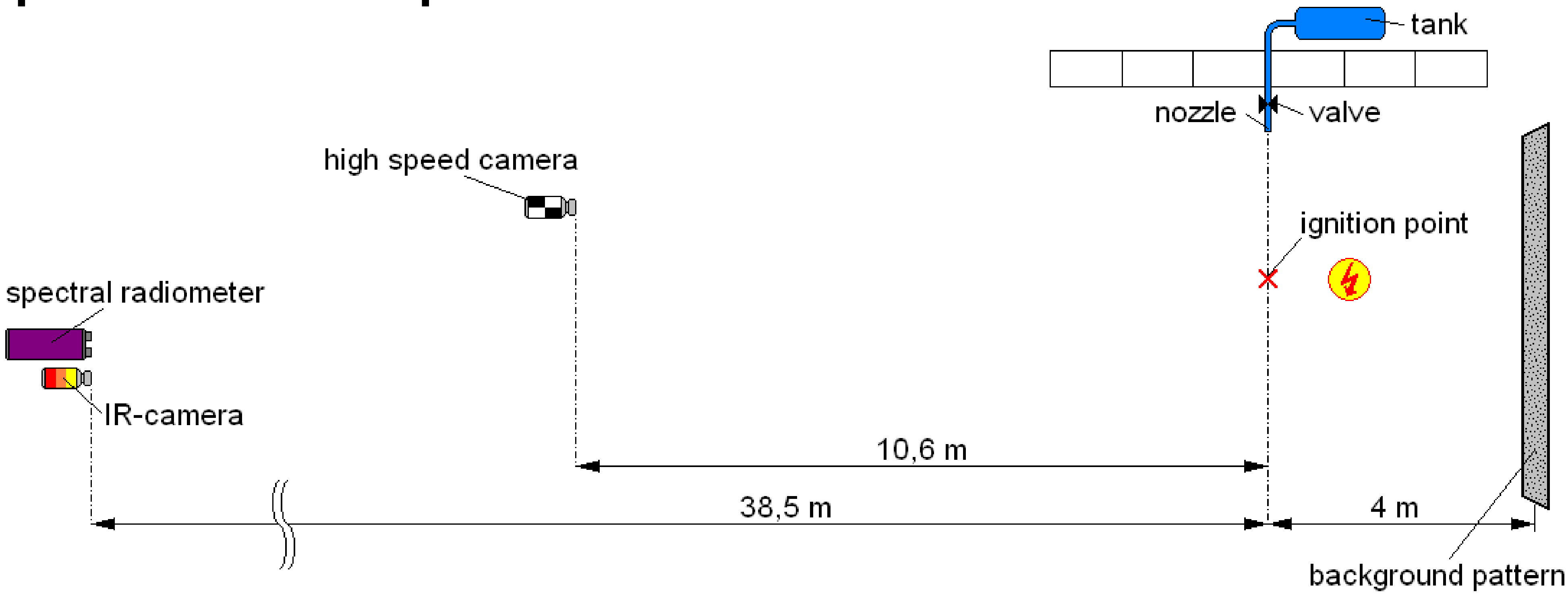
Intension

- Investigation of a realistic hydrogen free jet regarding to emitted radiation
  - Temperature
  - Concentration
  - Emitting area / volume
- Experiments were performed under the framework of **HySafe** in parallel to HYPER-experiments performed by HSL, Buxton
- Fraunhofer ICT used their equipment to visualise the jet fires by
  - fast video techniques
  - IR-cameras
  - fast scanning spectroscopy in the NIR/IR spectral region

Also refer:

- M. Royle (paper 200) for experimental set-up
- A. Kessler (paper 204) for imaging technologies

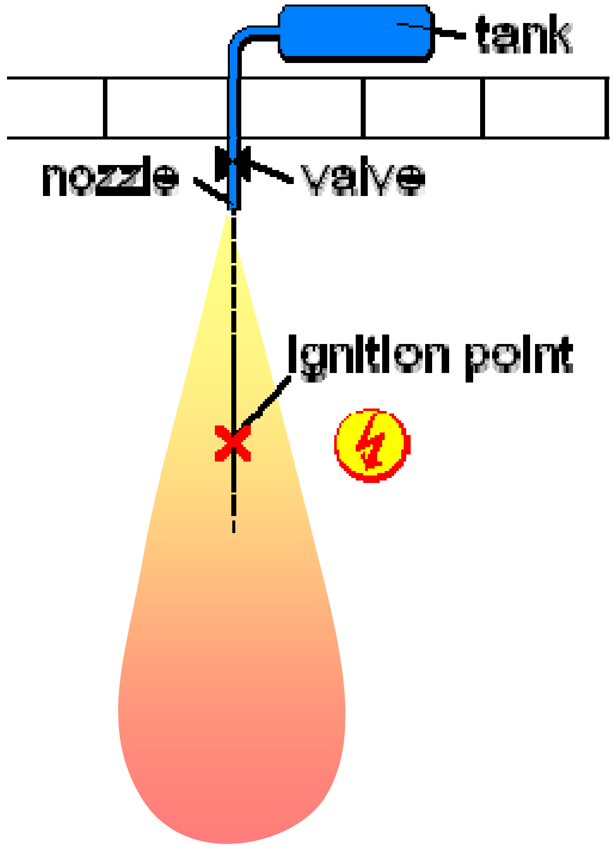
Experimental Set-up



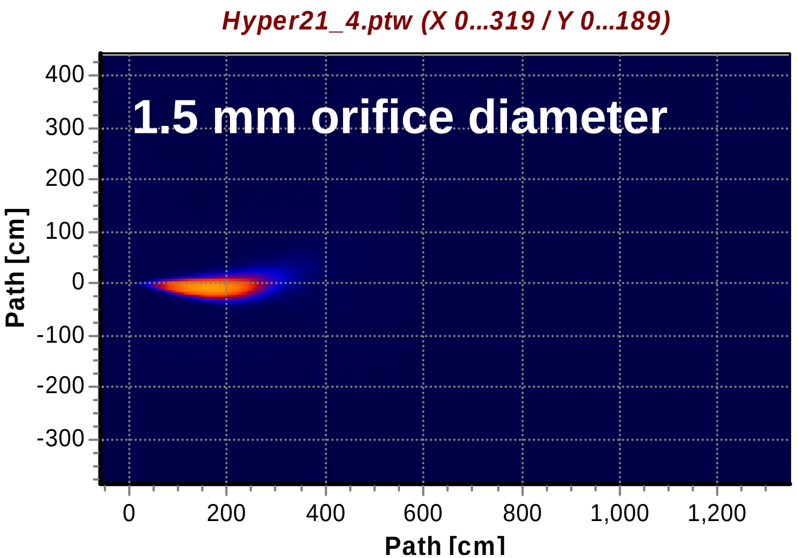
Experimentals

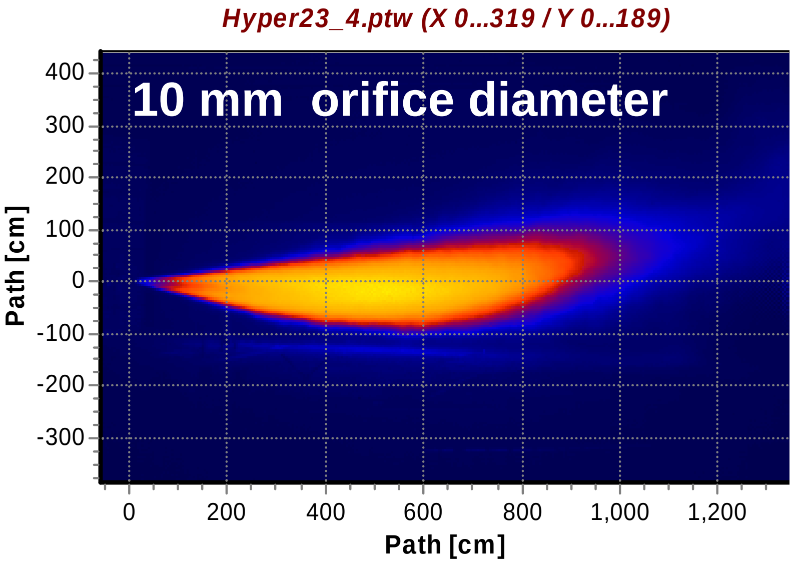
The campaign consists of 23 jet experiments

Tank Volume	100l (2x50l)
Initial tank pressure	20 MPa
Nozzle diameters	1.5 / 3.2 / 6.35 / 10 mm
Initial mass flow	40 / 160 / 450 / 670 g/s
Ignition Point	160 / 220 / 250 / 300 / 400 cm behind orifice
Ignition delay	various



IR-Flame Contours





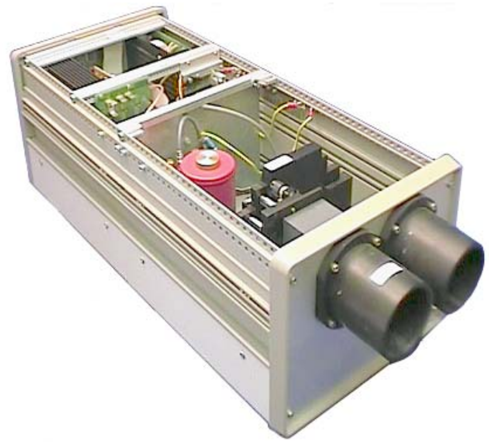
Averaged flame contours

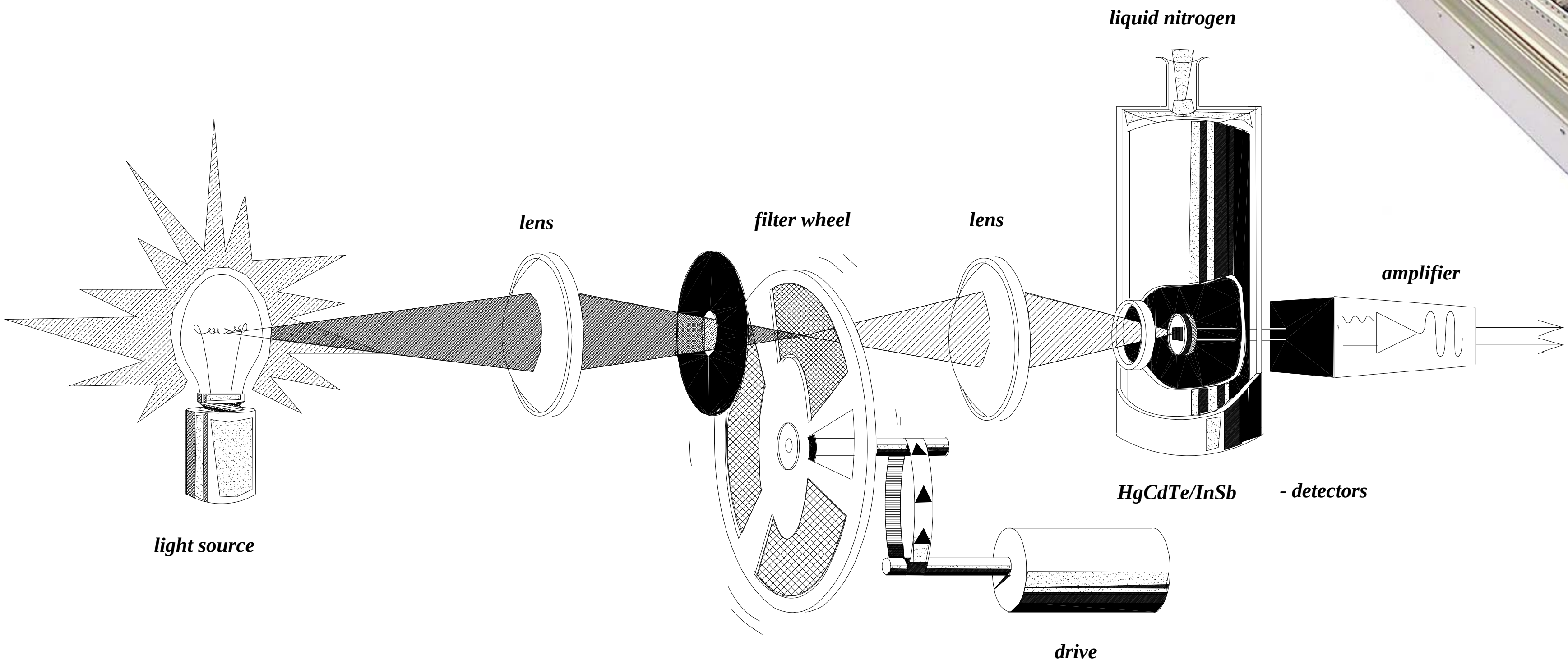
HySafe

Fraunhofer ICT

IR - Filter Wheel Spectrometer (designed and produced at ICT)

- Wavelength: 1.6 µm to 14.5 µm
- Resolution: up to 150 Spectra/s (used in this campagne: **100 Spectra/s**)
- Quantitative calibration with blackbody radiator in $Wm^{-2}µm^{-1}sr^{-1}$
- Correction of atmospheric absorption using HITRAN database.
- Point of view: 160 nm. 300 mm and 400 mm behind orifice





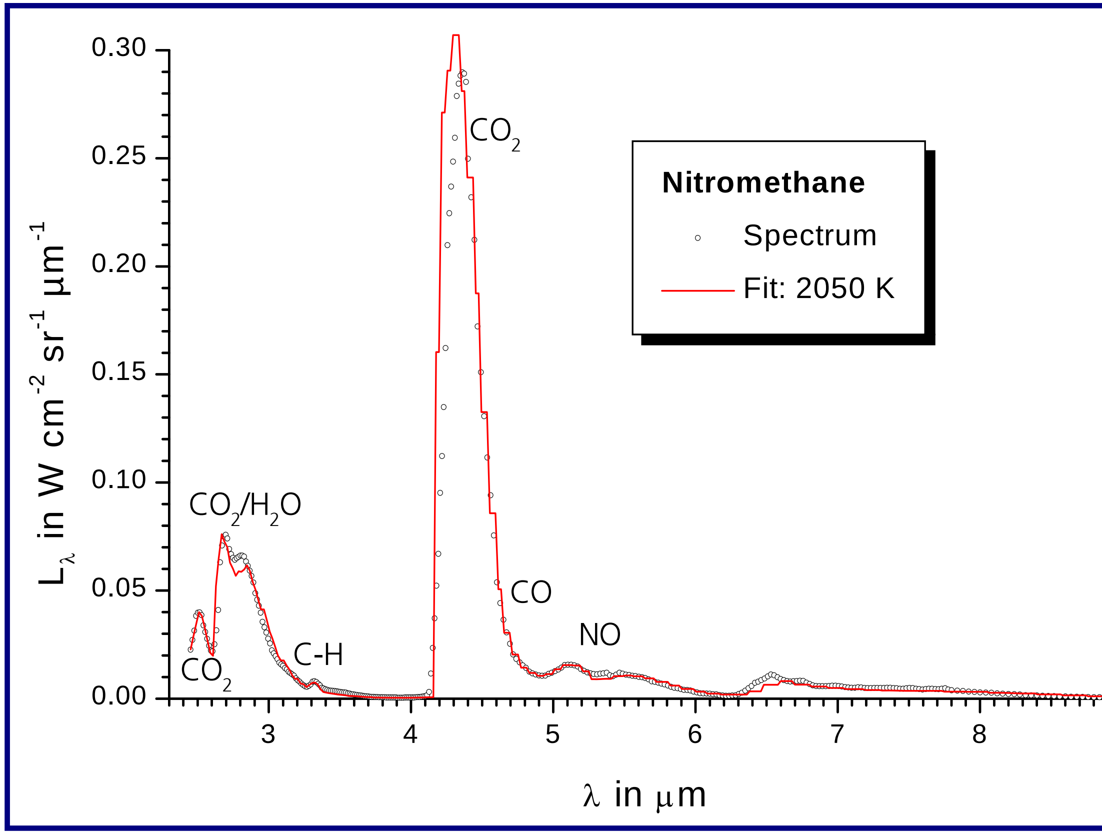
Methods of Spectroscopic Data analysis using ICT-BaM-Code

Computer code for generation and fitting of NIR/IR spectra (1-10 µm):

- band modelling based on single line group model, Curtis-Godson- approximation and tabulated data of H_2O and CO_2
- based on data of "Handbook of Infrared Radiation from Combustion Gases", NASA
- inhomogeneous gas mixtures of
  - H_2O (bands at 1.3, 1.8, 2.7 and 6.2 µm)
  - CO_2 (bands at 2.7 and 4.3 µm)
  - CO (band at 4.7 µm)
  - NO (band at 5.4 µm)
  - HCl (band at 3.5 µm)
  - particles (e.g. soot)
- temperature range 300 - >3000 K
- emission or transmission calculations
- single or multi-layer model of radiation transfer
- Fitting parameter:

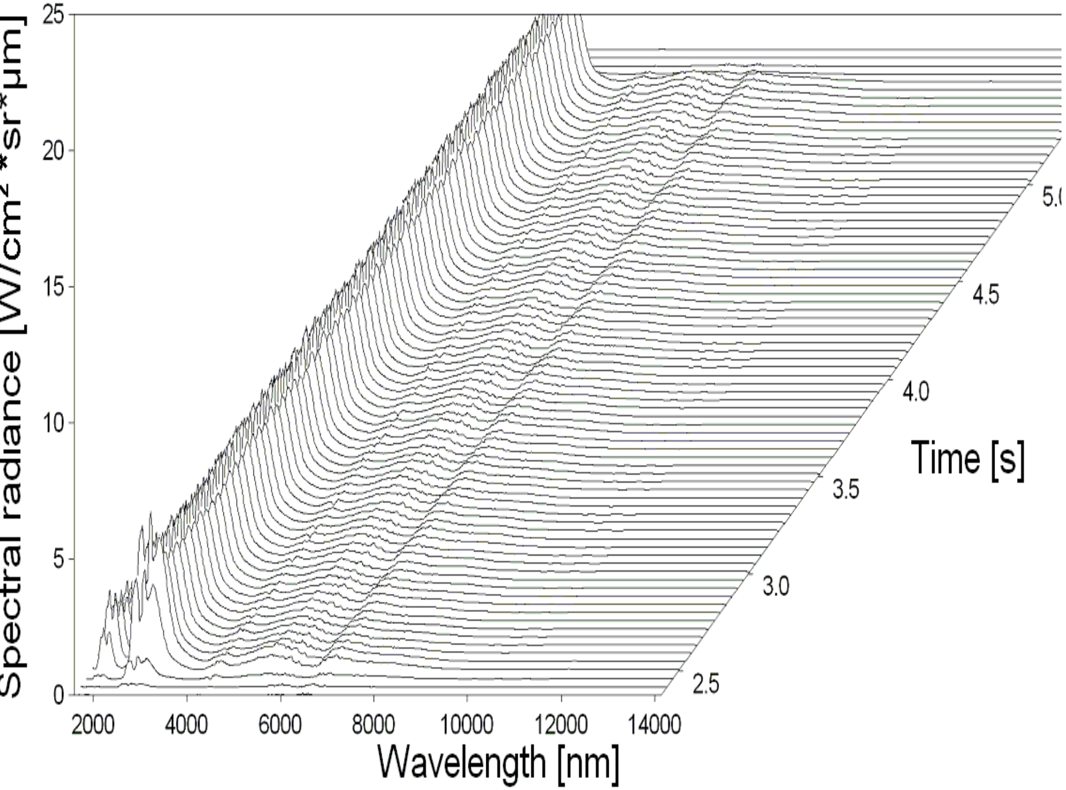
  Temperature

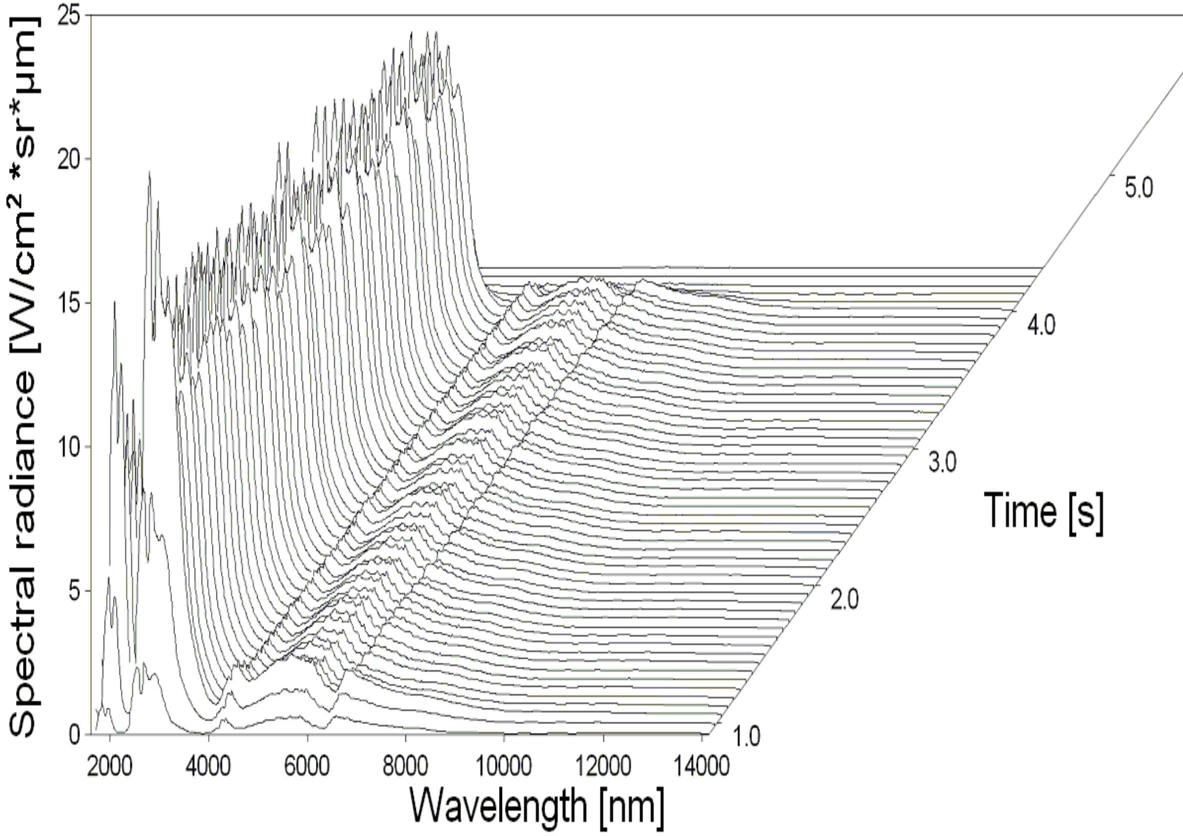
  concentration * path length



Time resolved IR spectra

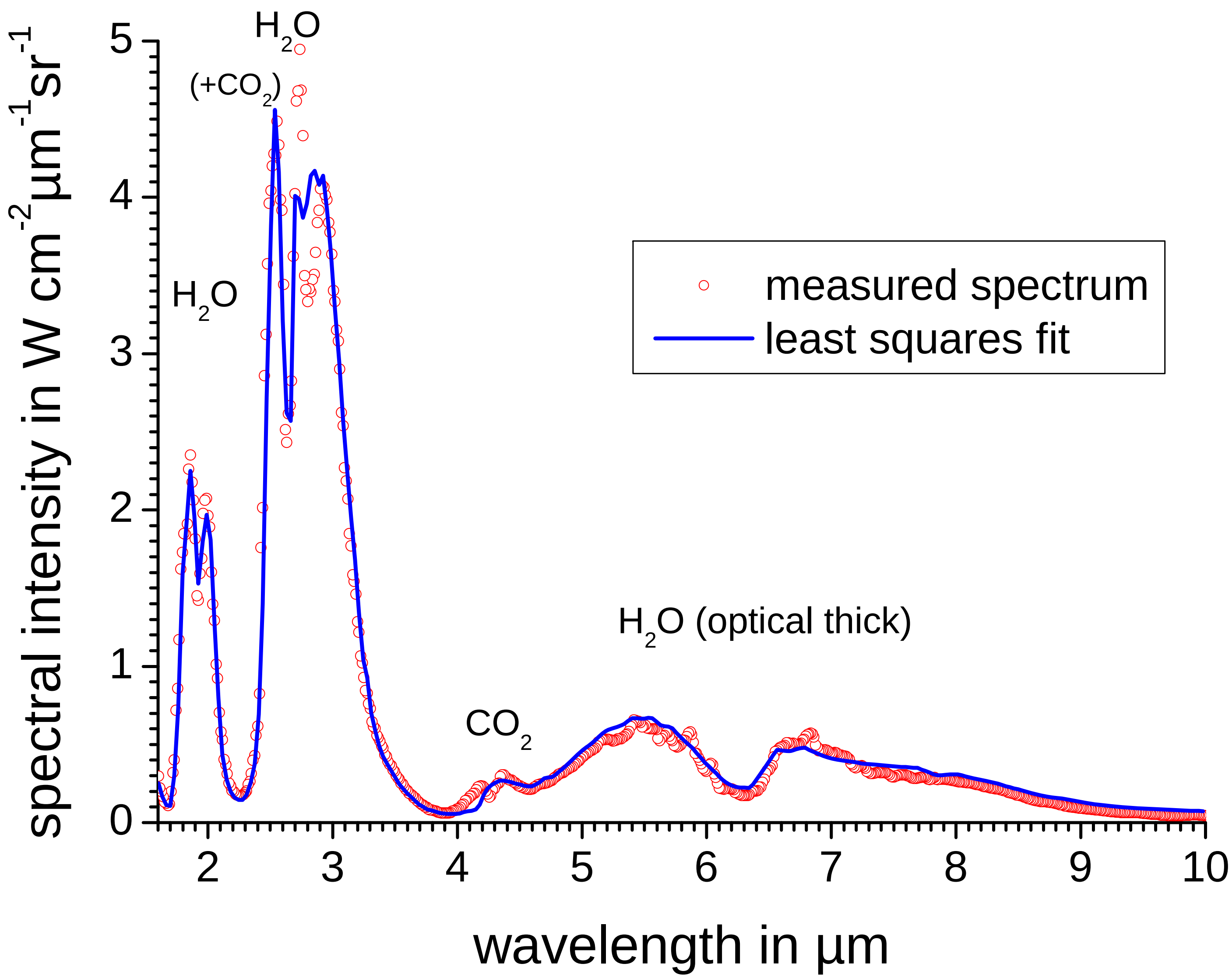
- Immediately after ignition: highest intensity emission → expanding explosion
- Then turbulent jet burning with stable emission





Series of IR spectra on the progress of the jet combustion with 100 spectra per second

Exemplary spectrum and ICT-BaM Fit

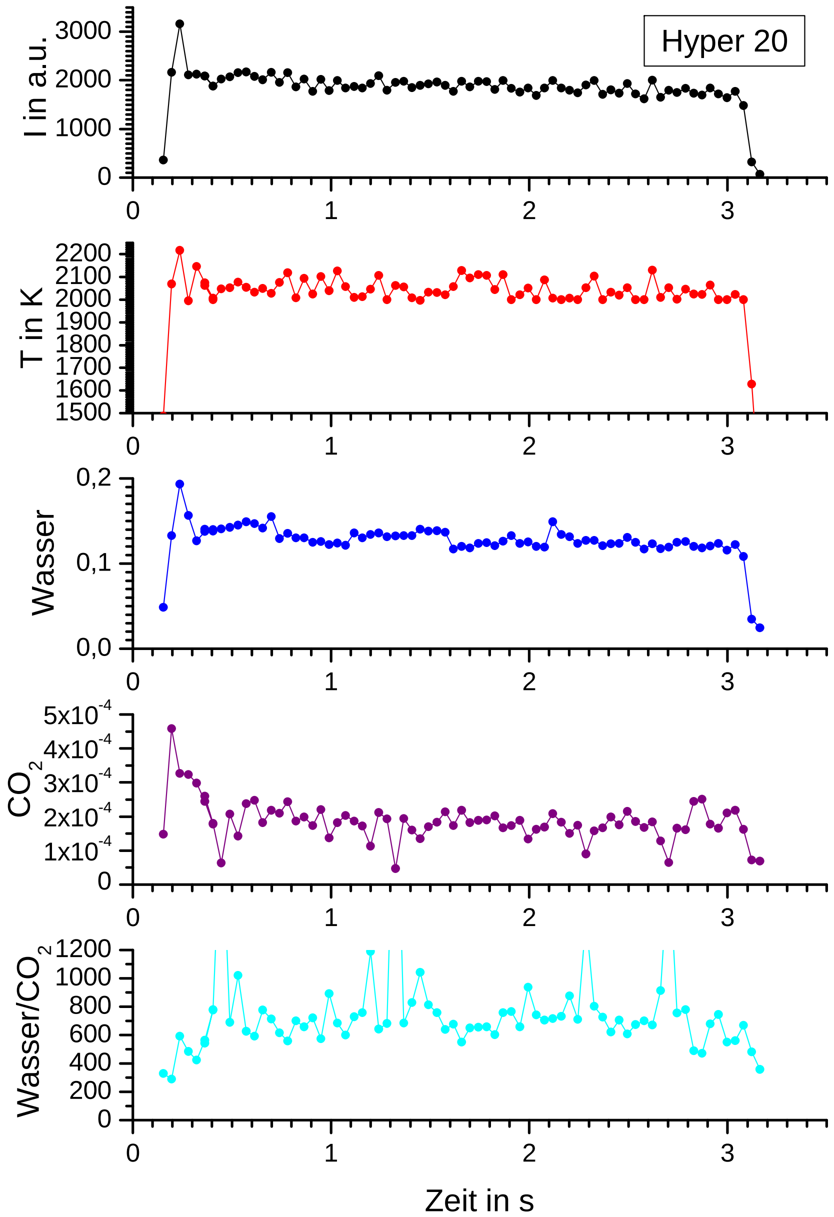


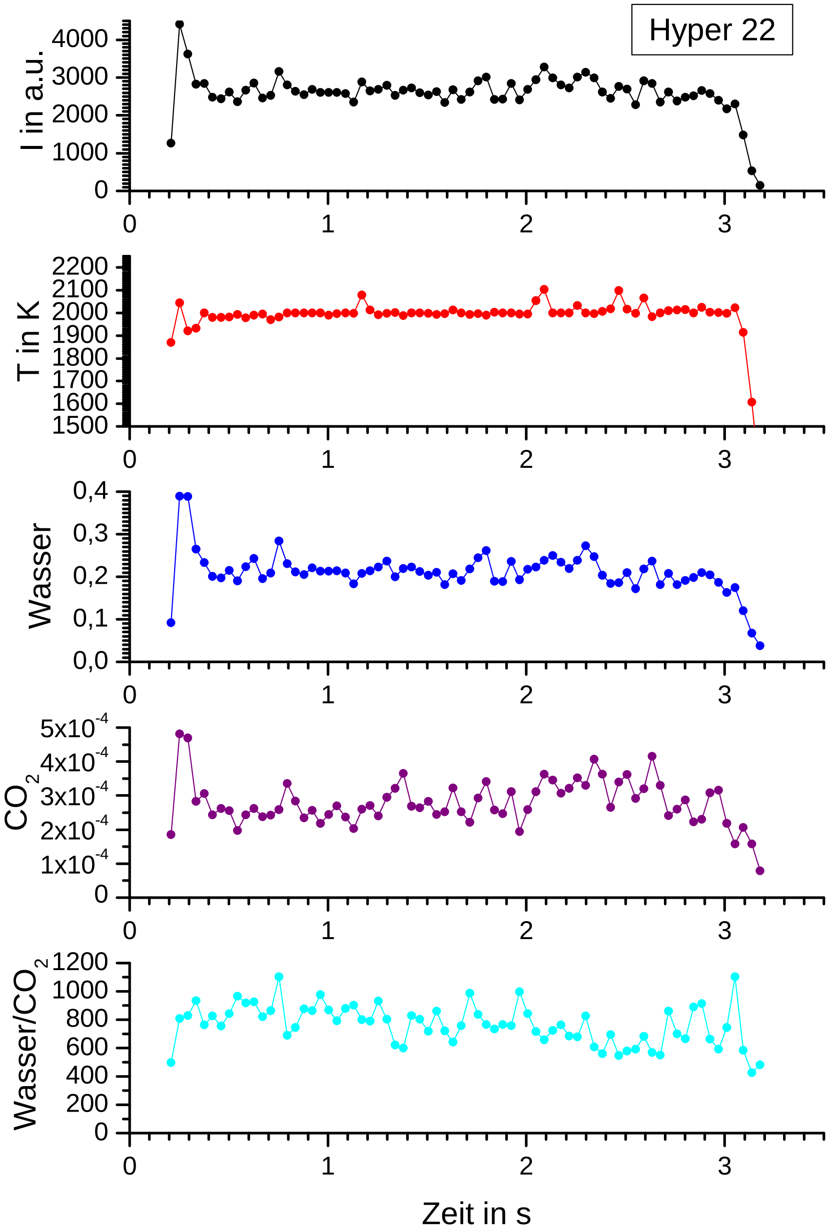
Results:

- Temperature: 2300 K
- Relative concentration of emitting species

➔ H_2O, CO_2

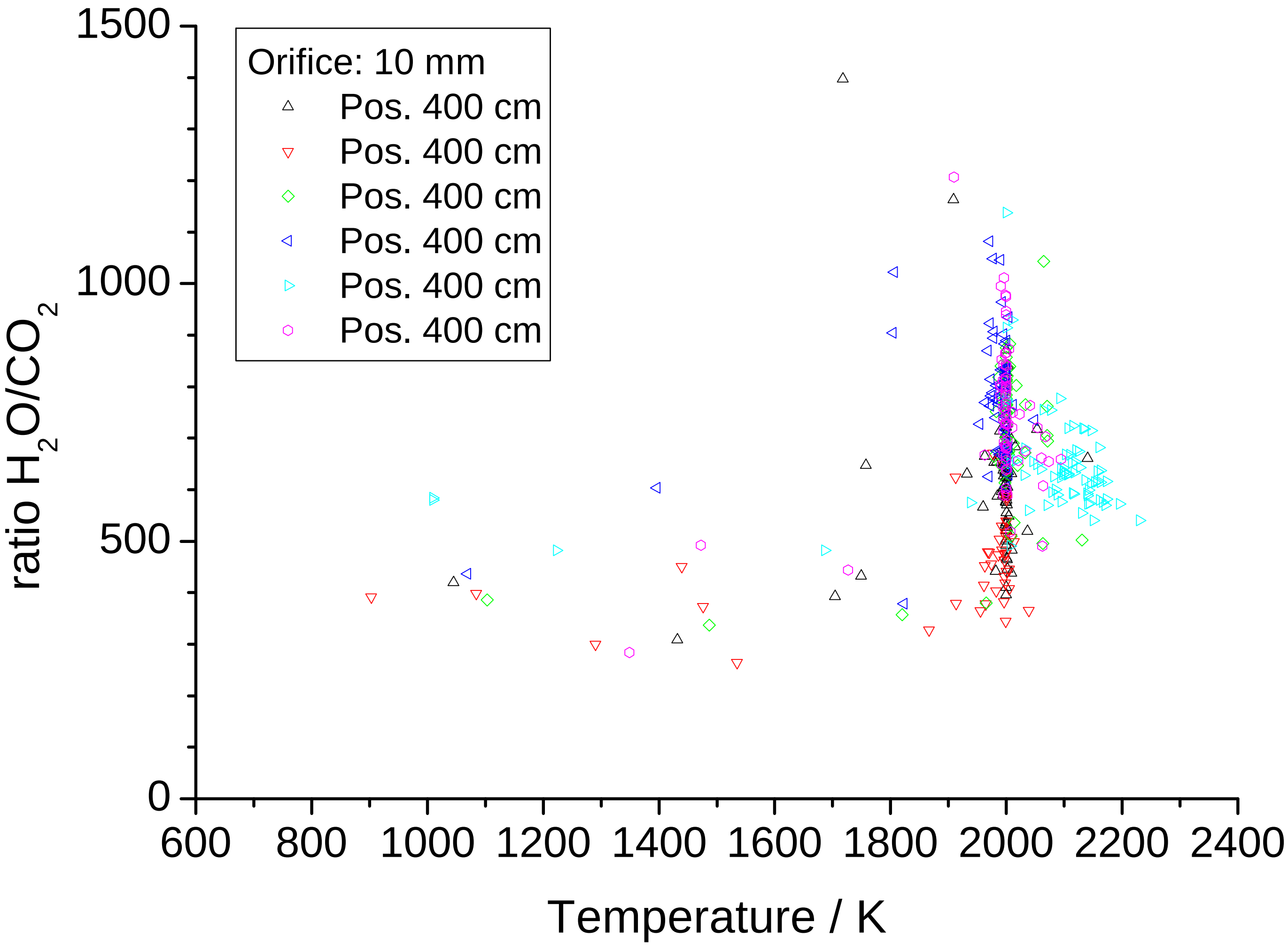
Evaluation with ICT-BaM code





Temperatures and ratios of water/CO_2, obtained by ICT-BaM code

- Naturally there are 0.058% CO_2 in atmospheric air.
- H_2O/CO_2 correlates with entrained air concentration in the free-jet.



Free-jet with orifice: 10 mm

Temperature: **1900 to 2300 K**

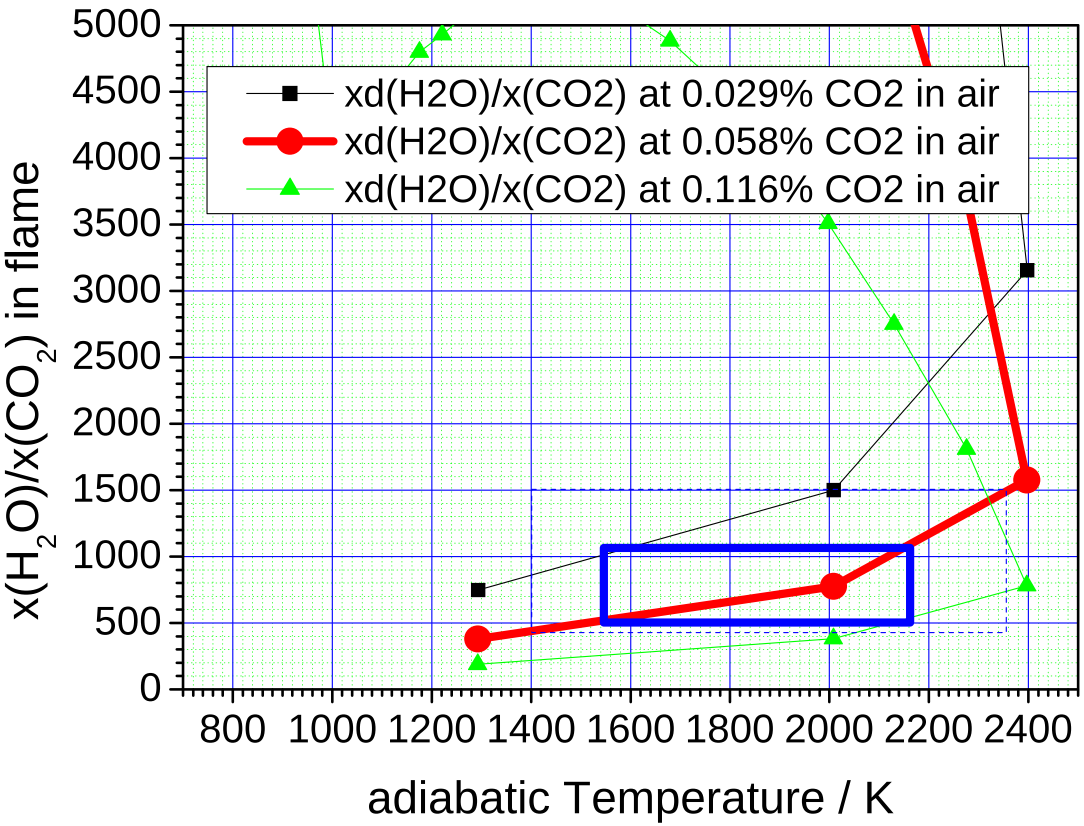
Accumulation at **2000 K**

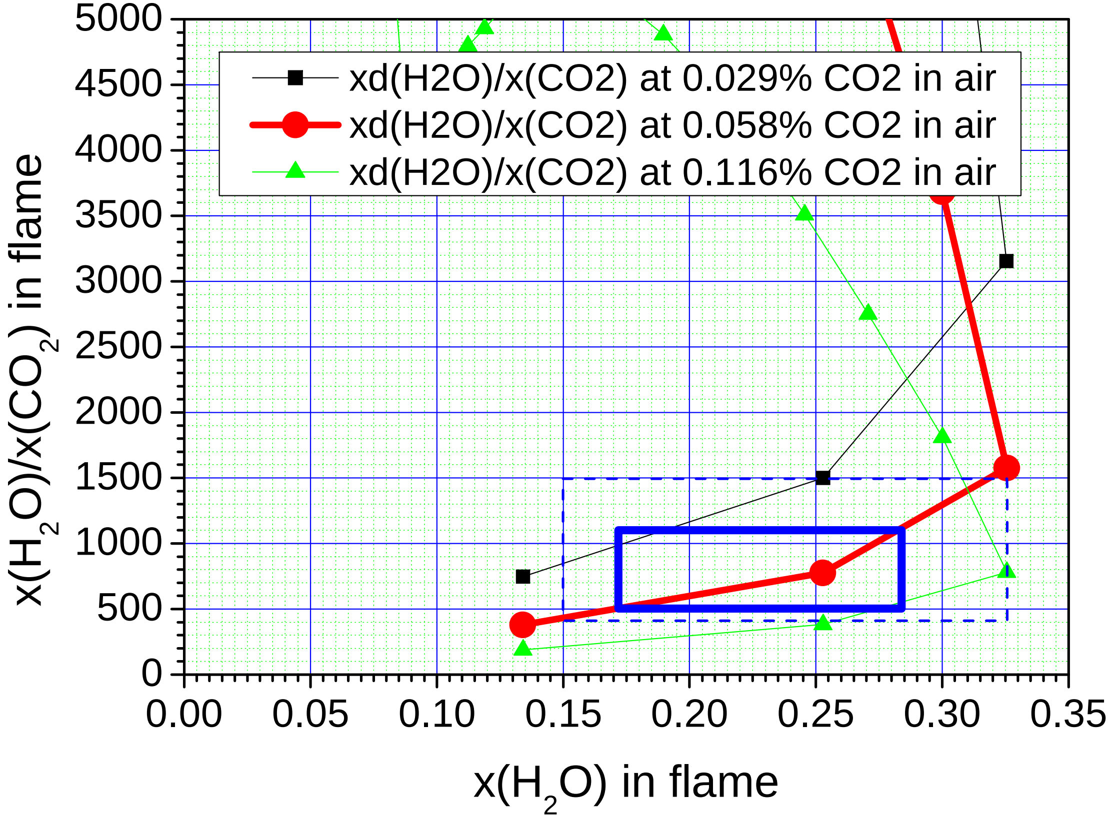
H_2O/CO_2 ratio: **400 to 1000**

Similar to other experiments

Ratios of H_2O/CO_2 related to water concentration and temperatures in the flame

- By thermodynamic calculations these measured ratios can also be calculated in dependence of the temperature and water concentrations in the flame.





HySafe

Fraunhofer ICT

Conclusion

A series of experiments of H_2 jets were investigated with flow rates of 40 to 670 g/s achieving flame lengths from 3 to 10 m. The analysis of the spectroscopic results by modelling the bands of water and carbon dioxide result in the following conclusions:

- Fast scanning spectrometers and the ICT-BaM code enables a detailed analysis of a spot area as function of time
- Emission temperatures of the flame accumulate at **2000 K** reaching to **2300 K**
- By comparison of spectral emission bands of water with CO_2 (by air entrainment) correlated with thermodynamic combustion calculation the concentration of water can be correlated simultaneously with temperature as function of time.
- Combustion seems to take place in the area of lean mixture ratios.
- A quantitative estimation of the total emitted radiation is only possible by a correlation of the flame contours assuming air entrainment according to the jet expansion on its length by using the ICT-BaM code. **This evaluation is planned for the future.**