MEASUREMENTS OF GAS FLOW PARAMETERS BY ABSORPTION SPECTROMETRY WITH DIODE LASERS

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Outline for this talk

1. Motivation & basics
2. Selection of analytical lines
3. Laboratory measurements
4. Optimization of the fitting model
5. TDLAS at the Joint Institute for High Temperatures
6. Imaging of experimental data
7. Instrumental and software improvements
8. Examples of $T$-measurements in combustion
Measurements of the temperature if TDE is established

Ratio of the integral line intensities \( S \) for the temperature \( T \) is:

\[
R = \left( \frac{S_1}{S_2} \right)_T = \left( \frac{S_1}{S_2} \right)_{T_0} \exp \left[ -\frac{hc\Delta E}{k} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right]
\]

\( \Delta E \) - low energies difference
Task parameters for test setup at the Joint Institute for High Temperatures (JIHT RAS)

Type of combustion: plasma-assisted
Discharge: transverse filament
Fuel: H₂, ethylene
Flow velocity: M ~ 2 (supersonic flow)
Temperature: 300-2000 K
Total pressure: 100-300 Torr
H₂O concentrations: 1-10 %
Optical length: 70 mm
Duration of the run: ~500 ms
Duration of the discharge: ~100 ms
Spatially and temporally-resolved measurements are desired
Time resolution: ~1 ms
Spatial resolution: ~1-2 mm
Test Section

Plasma-assisted combustion

Electrodes

Injectors

C2H4 injection
Main problems

- Bright plasma emission
- Electrical noises
- Strong vibrations
- \( \text{H}_2\text{O} \) absorption in free-path outside the cell
- No reproducibility of baseline
Selection of analytical lines

Criteria:
- commercially available diode lasers
- high sensitivity to temperature variation
- reasonable intensity
- several appropriate lines within a DL tuning range of ~ 1 cm\(^{-1}\)
- minimal spectral overlapping
- minimal experimental error:

\[
\frac{\Delta T}{T} = \frac{T}{T_{\text{eff}}} \left( \frac{1}{S_1^2} + \frac{1}{S_2^2} \right)^{1/2} \Delta S
\]

\[
T_{\text{eff}} = \frac{hc\Delta E}{k}
\]

The computer program was written for selection of the optimal pairs of absorption lines in the 1.3-1.4 \(\mu\)m region, which could provide the best signal-to-noise ratio for measurements in the temperature range 300 – 2000 K.
<table>
<thead>
<tr>
<th>$\nu$</th>
<th>$S$ (cm/mol)</th>
<th>$\gamma$ (air)</th>
<th>$\gamma$ (H2O)</th>
<th>$E''$ (cm$^{-1}$)</th>
<th>No.</th>
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<td>7189.199</td>
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</table>
Modeling of absorption spectra at different temperatures

296K

700K

400K

1000K

500K

1500K
Design of the heated cell

Parameters of a gas medium \( (T, P, C_{H2O}) \) are obtained as the result of the experimental spectra fitting

\[
Y_i = \alpha l_{0i} \sum_j S_j(T) g_j(v_i - v_{0,j}) \theta P L + b_i + \varepsilon_i
\]

\( S(T) \) – line integral intensity
\( g(v-v_0) \) – line shape ,
\( v_{0,j} \) – center of \( j \)-th line,
\( \rho = \theta P \) – partial pressure of the absorbing component ,
\( P \) – total pressure of the gas mixture,
\( L \) – optical length of the absorbing layer,
\( \alpha \) – amplification coefficient of the electronics,
\( b_i \) – baseline,
\( \varepsilon_i \) – residual.
Models checked:

- **Profile fitting** – Voigt profile, equal Gaussian width for both lines

- **Spectrum fitting**
  Fitting parameters: frequency scale, temperature, gas pressure, \( \text{H}_2\text{O} \) concentration, baseline parameters. Simulated spectra have been constructed using the HITRAN and HITEMP databases.

The baseline \( b_i \) was approximated by the polynomial, linear or quadratic.
Temperature evaluated by TDLAS vs temperature measured by the thermocouple

- **Voigt profile fitting**
- **spectrum fitting**
Experimental spectrum of heated water vapors at 1200 K (circles), result of spectrum fitting (red line), and residuals for spectrum fitting (SF) and Voigt profile (VP) model
Numerical simulation of experimental data

\[ T = 1200 \, \text{K}, \quad P = 100 \, \text{Torr}, \quad c_{\text{H}_2\text{O}} = 10\% \]
Fitting of the weak line

- simulated profile
- simulated profile + white noise (S/N~10)

fitting by individual Voigt profiles
fitting by spectrum
Comparison of two fitting algorithms for numerical simulation

<table>
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<th>Fitting Algorithm</th>
<th>S/N = 100</th>
<th>S/N = 10</th>
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<td>$T$ [K]</td>
<td>$\sigma$ [K]</td>
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<td>Individual profiles</td>
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<td>17.8</td>
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<td>Spectral interval</td>
<td>1200.8</td>
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Conclusions

• Fitting of the spectra was found as good strategy for temperature evaluation.

• Noteworthy! Fitting of the individual line profiles can be done with lower residuals as compared to spectrum fitting.

• Spectrum fitting provides much better accuracy for temperature evaluation.
Experimental setup at JIHT RAS - 2008

DL – diode laser NEL NLK1E5GAA,
DL controller ($T$, $I$) - Thorlabs TED350 and LDC202,
PD - InGaAs photodiodes Hamamatsu G8370-2,
oscilloscope - Agilent 54621A (8 bit, $2 \times 10^6$ points per channel),
generator – saw-tooth voltage generator

Located in another room
General view of the experimental chamber at JIHT RAS

Schematic diagram

TDL Spectroscopy in perpendicular direction
Time scale of a run

Single Run Record

10^6 points has been recorded with 8-bit ADC in 250 ms
Single run record

First 250 ms of the run (300 scans of DL)

Absorption spectra recorded in 3 successive scans of DL

DL intensity variations during wavelength scanning. The frequency of saw tooth current modulation was ~1.2 kHz.
At first step of data processing the detected transient absorption spectra were transformed into 2D image. This procedure greatly simplified the general overview of data and selection of the most important periods of process evolution.

Digital processing of 2D images was based on ImageJ, the free, open source program.
ImageJ

Key features:

- platform-independent, can run without modifications on Windows, Linux and MacOS;
- open many different image formats and raw data;
- extended by developing plugins and macros, more than 500 plugins and 300 macros are available;
- the world’s fastest image processing software.

ImageJ toolbar and submenus used for TDLS data processing

ImageJ author: Wayne Rasband, U.S. National Institute of Health (NIH)
H$_2$O absorption

upper reading – oscilloscope one-dimension trace

lower image – the corresponding 2D presentation
2D image of raw data and traces integrated over 30 scans

Room T

Supersonic flow
Water freezing

Hydrogen/air combustion
T ~ 1000K

Combustion process is ended

(1) – 7189.344 cm\(^{-1}\), (2) – 7189.541 cm\(^{-1}\), (3) – 7189.715 cm\(^{-1}\).
The initial stage of a run
(parameters: $P_{\text{total}} \sim 0.3$ atm, $T \sim 20^\circ\text{C}$)
Beginning of supersonic flow
The stage of intense combustion
Jitter removing (software)

TDL frequency jitter from scan to scan is observed in image as a light twisted line. The jitter can be removed by converting image to stack consisting of images corresponding to sequential rows and using Image Stabilizer. This plugin aligns images in stack using geometrical transformations.
For each row in image (single TDL scan) background was constructed in the simplest way. Macros selects the first and last active points and constructs a line between them.
Signal-to-noise ratio increases considerably
Background correction (instrumental)
Differential detection scheme with sample & hold circuit

without sample&hold circuit

with sample&hold circuit
Examples of using of the developed technique in real situation of the combustion in mixing supersonic flows
Schlieren pictures of combustion. Combination of images from two windows.
Temperature (a) and H$_2$O vapor pressure (b) distribution measured by DLAS in plasma-assisted combustion zone for ethylene-air pair.

Z is the distance from the wall.
X axis is along the flow direction.

DLAS Measurements on H₂O Molecule in Experiments on Plasma Assisted Ethylene Combustion in Supersonic Flow (December 2010)

09.08.2013 9:42

TDLS - 2013 38
01.06.2011. Section Window 2, x = 130mm. Ethylene Long Combustion. $T=800-500$ K
01.06.2011; Run 10; Section Window 2; x = 130mm.
Dynamics of the probing zone temperature

Temperature, K

Number of scan

Precision (statistical error)
\( \sigma = 40 \text{ K} \)
**Instrumental improvements:**

Data Acquisition System - **NI USB-6351** (16-bit resolution),
DL and DAS controller – **GPI TDLS complex**
Instrumental improvements:

- big aperture, mirror optics,
- compensation of absorption in a free-path,
- signal optimization,
- new differential scheme
**Instrumental improvements:**

- precise manual translational stages
Semi-automatic data processing

- Import Raw Data
- Delete Outliers
- Set Brightness & Contrast
- Correct Background
- Divide by Laser Intensity
- Select Region of Interest
- Subtract Water Freezing Region
- Compare with Model Spectra
Ethylene combustion. Choice of combustion parameters: mass of injected fuel, initial air temperature, discharge parameters
DLAS Measurements on H₂O Molecule in Experiments on Plasma Assisted Ethylene Combustion on the Plane Wall in Supersonic Flow 30.05.2012
Temperature Map from TDLAS Measurements in Plasma Assisted Ethylene Combustion
30.05.2012
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Publications

• М.А. Большов, Ю.А. Курицын, В.В. Лигер, В.Р. Мироненко, С.Б. Леонов, Д.А. Яранцев. Применение диодной лазерной спектроскопии для измерения параметров газа при плазменно-индукционном сверхзвуковом горении. *Квантовая Электроника*, 2009, т.39, № 9, с. 869-878
• М.А. Большов, Ю.А. Курицын, С.Б. Леонов, В.В. Лигер, В.Р. Мироненко, К.В.Савелкин, Д.А. Яранцев. Измерение температуры и концентрации паров воды в сверхзвуковой камере сгорания методом абсорбционной спектроскопии. *Теплофизика Высоких Температур*, 2010, т.48, №1, с.9-22
• М.А. Большов, Ю.А. Курицын, В.В. Лигер, В.Р. Мироненко. Разработка метода абсорбционной спектроскопии с диодными лазерами для определения температуры и концентрации молекул в удалённом объекте. *Оптика и спектроскопия*, 2011, т. 110, № 6, с. 900-908.
Thank you for attention!