Temperature measurements in turbulent flames using Raman spectroscopy

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Combustion diagnostics at DLR Stuttgart

Work is focused on gas turbine combustion

- Pressures 1 – 30 bar
- Thermal powers 5 kW – 1 MW
- Temperatures 300 – 2500 K
- Fuels: Methane, natural gas, hydrogen, ethylene, kerosene, oil

lab-scale burner  high-pressure test rig
Combustion diagnostics at DLR Stuttgart

Laser measurement techniques for
- Gas and droplet velocities (PIV, PDA)
- Species concentrations (LIF, Raman, LIBS, absorption spectroscopy)
- Gas temperatures (CARS, Raman, LIF)
- Surface temperatures (thermographic phosphors)
- Soot (LII)
Fundamentals of laser Raman scattering

- Determination of species densities.
- Temperature is deduced in our applications from total number density.
- Raman scattering is an inelastic scattering process of electromagnetic radiation at molecules (via polarizability).

![Diagram showing Rayleigh, Stokes, and anti-Stokes transitions]

Selection rules: $\Delta v = \pm 1, \Delta J = 0, \pm 2$ (J is rotational quantum number)
Fundamentals of Raman Scattering

• Excitation can be performed by arbitrary wavelength, because it is no resonant excitation process.
• All molecular species can be excited simultaneously with one laser.
• Wavelength shift of the Raman-scattered light corresponds to energy of a vibrational energy quantum of the molecule.
• Wavelength shift is characteristic of molecular species.

\[ \Delta E = h \cdot (v_0 - v) = E_{\text{vib}} \]
Fundamentals of Raman Scattering

Signal intensity

\[ I_{RS} = I_L \cdot N_i \cdot \frac{d\sigma}{d\Omega} \cdot \Omega \cdot \varepsilon \cdot q \cdot L \]

- \( I_{RS} \): detected Raman intensity
- \( I_L \): laser intensity
- \( N_i \): molecular density of species i
- \( \frac{d\sigma}{d\Omega} \): differential scattering cross section
- \( \Omega \): solid angle of detection optics
- \( \varepsilon \): optical efficiency
- \( q \): quantum efficiency of detector
- \( L \): length of measuring volume

- Molecular density can be determined from the Raman signal.
- The constants are typically determined by calibration measurements.
Fundamentals of Raman Scattering

Raman-shift and scattering cross sections of major species in flames

In principle, all these species can be detected simultaneously in flames
Fundamentals of Raman Scattering

Measured spectrum from a fuel-rich premixed ethylene/air flame.

C_2H_4/air
\( \phi = 1.58 \)
\( \lambda_{\text{excit}} = 489 \) nm
Fundamentals of Raman Scattering

If all (major) species are detected simultaneously the total number density $N_{total}$ can be determined:

$$N_{total} = \sum N_i$$

With knowledge of the pressure $p$ the temperature can be determined via the ideal gas law:

$$T = \frac{p}{k \cdot N_{total}} \quad k: \text{Boltzmann constant}$$

Temperature and major species concentrations can be determined simultaneously → wonderful measuring technique! But, …

Low signal levels, high laser power needed, only applicable in “clean” flames.
Calibration devices

- Cold and electrically heated gas flows, temperatures known from thermocouples.
- Flat laminar flames, temperatures known from CARS measurements.

Burner with sintered bronze matrix (McKenna type)
Lasers for Raman scattering

Flashlamp-pumped dye laser
• Pulse energy 2.5 J, pulse duration 2 µs, wavelength $\lambda = 489$ nm, repetition rate 5 Hz, only suited for point measurements

Nd:YAG laser cluster
• Pulse energy 1.7 J, pulse duration with pulse stretcher 350 ns, $\lambda = 532$ nm, repetition rate 10 Hz, suited for 1D measurements
Experimental setup for 1D Raman scattering

Spatial measurement resolution $\approx 0.5$ mm
Measurement uncertainties

Systematic uncertainties
- Calibration procedure (T of calibration flames, flow meters, …)
- Laser pulse energy
- Drifts of alignment of optical setup
- For T: ±3-4%

Statistical uncertainties of single shot measurement
- Shot noise of detected photons
- For T: ±2.5%

Uncertainties depend on experimental arrangement and flame condition.
Measurements in partially premixed CH$_4$/air swirl flames
Thermal power 25 kW

Combustion chamber with quartz windows
Burner nozzle with swirler
Correlation between temperature and mixture fraction

500 single-shot Raman measurements at each radial location

measurements along radius at h=8 mm

Large variation of composition and temperature

mixture fraction = (mass of fuel) / (total mass)
Radial profiles at h=8 mm in oscillating flame

- Thermo-acoustic oscillation at frequency of 400 Hz
- Phase-averaged mean values for 8 different phase angles
Raman measurements in high-pressure test rig
Industrial gas turbine burner installed in DLR optical test rig

- Premixed natural gas and air
- pressure up to 6 bar, Power = 0.335 – 1.08 MW, \( T_{\text{air}} = 670 \text{ K} \)
Flame structures from OH-PLIF measurements

Siemens G30 DLE swirl burner from SGT-100 turbine

Re$_{in}$ \approx 93000
Scatterplot of temperature vs. mixture fraction
Single shot results from inner shear layer

Temperature / K

Mixtite Fraction f

single shot results:
- exhaust gas
- intermediate states
- fresh gas
Instantaneous profiles of temperature and species
From single-shot 1D Raman measurement

Profile with large gradients → indication of flame front
Conclusions

- Single-shot laser Raman scattering is an established technique for combustion diagnostics.
- Difficulties arise from small scattering cross section: Need of high laser pulse energy; signal interferences in flames with liquid fuels.
- Calibration measurements needed.
- Improvement of accuracy desirable.
- Advantages: Simultaneous line (1D) measurement of temperature and species concentrations yields huge amount of information about thermo-chemical state of flames.
Thank you for your attention
Backup
Challenges for laser Raman measurements in high-pressure test rigs

- Limited optical access, laser beams and signals must pass several windows.
- Window degradation by high thermal loads.
- Beam degradation and steering.
- Depolarization in windows by stress-induced birefringence.
- Non-traversable rigs → measurement technique must be traversed.
- Costs.