ABSTRACT

In support of NASA ARMD's code validation project, we have made significant progress by providing the first quantitative single-shot multi-scalar data from a turbulent elevated-pressure (5 atm), swirl-stabilized, lean direct injection (LDI) type research burner operating on CH4-air using a spatially-resolved pulsed-laser spontaneous Raman diagnostic technique. The Raman diagnostics apparatus and data analysis that we present here were developed over the past 6 years at Glenn Research Center. From the Raman scattering data, we produce spatially-mapped probability density functions (PDF’s) of the instantaneous temperature, determined using a newly developed low-resolution effective rotational bandwidth (ERB) technique. The measured 3-scalar (triplet) correlations, between temperature, CH4, and O2 concentrations, as well as their PDF’s, also provide a high-level of detail into the nature and extent of the turbulent mixing process and its impact on chemical reactions in a realistic gas turbine injector flame at elevated pressures. The multi-scalar triplet data set presented here provides a good validation case for CFD combustion codes to simulate by providing both average and statistical values for the 3 measured scalars.
Single-Shot Scalar-Triplet Measurements in High-Pressure Swirl-Stabilized Flames for Combustion Code Validation

Jun Kojima*
Ohio Aerospace Institute

Quang-Viet Nguyen
NASA GRC (RTB)

HPGB Facility ERB/SE-5
H2-Air Flame at 20 atm

* Principal Investigator
FY06 NRA
Overview

**Goal:** Provide critical chemical and physical data in turbulent combustion at realistic subsonic/supersonic cruise condition for *validating predictive low-emissions combustor codes*

**Challenges:** Successful accurate multiscalar measurements (temperature, major species mole fractions, mixture fraction, velocity) in optically-harsh droplet-laden flows at *high pressures*.

**Strategy (tasks):**
- Develop a quantitative time-resolved *laser Raman diagnostics*
- A series of experiments of increasing flow complexity: (i) Calibration burner (e.g., flat-flame burner), (ii) Realistic concept burners (swirl-stabilized burner) at *elevated pressures* up to 10~30 atm
- Address the effects of chemical complexity: \( \text{H}_2, \text{CH}_4, \text{single-component liquid (e.g., hexane, iso-octane, n-heptane)}, \text{jet-A fuel} \)
Atmospheric Pressure Combustion Diagnostics Facility

- Temperature and species reference
- Diagnostics calibration
- Gaseous fuels
- Pre-vaporized single-component liquid fuel (electronically controlled fuel vaporizer and heating system)
- Support visible and UV laser Raman systems
- Study on optical characteristics of sooting flames and liquid fuel combustion chemistry
- Support the Aeronautics milestones to mitigate risks due to PSO holding up high-pressure experiments
Remote controlled with auto process controller
Pressure up to 30 atm (currently 10 atm requested for safety permit)
Versatile for burner platform (calibration burner, turbulent jet, LDI)
Optical access (4 ports)
Gaseous and liquid fuel capacity
Air pre-heater installed (up to 1200F)
Raman Scattering Diagnostic System

Original pulse

Stretched pulse

Time (nano seconds)

Intensity (a.u.)

High-Pressure Rig

Burner

Folding Prism

Optical Fibers

Laser line filter

CCD

• 1340 x 100 pixels
• 90% Q.E.
• 16 bit A/D

Nd:YAG Laser (800 mJ/pulse)

Laser Pulse-Stretcher (passive multiple ring-cavity) *Patent pending

Mirrors

Beamsplitters

Electro-mechanical high-speed shutter

*2007 R&D 100 Award

• 10’s μs gate width
Raman Spectra Observed in Combustion

**Advantage**
- Raman scattering – simultaneous multiple species concentration and temperature
- Time-average (mean) or Single-shot (instantaneous; rms)
- Quantitative

**Challenge**
- Spectral interference (‘Cross-talk’)

![Raman Spectra Graph](image)

**Graph Key**
- **Excitation (532 nm)**
- *H₂-air flame (10 atm, fuel-rich)*
- Rotational N₂/O₂
- N₂, CO₂, O₂, CH₄, H₂O
- Intensity (a.u.) vs. Wavelength (nm)
- Stokes, anti-Stokes
Raman Calibration Experiments & Simulation

**Platform**
- Static cell
- Calib. burner

**Fuel** (lean ~ rich)
- H2
- H2-CO
- CH4
- Single-component liquid (pre-vaporized)
- Single-component liquid
- Multi-component (jet-A)
- Air

**Raman Instrumentation**
- Pump lasers: 532/355/266 nm
- Thermometry: Vib. / Rot.
- Polarization property

**Matrix elements, \( k_{ij}(T) \)** (Cross-talks)
- Major species (H2, O2, N2, CO, CO2, H2O, HC’s)
- H2 \(\rightarrow\) CO
- H2 \(\rightarrow\) CO2
- H2 \(\rightarrow\) H2O
- N2 \(\rightarrow\) CO
- O2 \(\rightarrow\) CO2
- CO2 \(\rightarrow\) N2
- C2* \(\rightarrow\) N2, CO, HC’s
- PAH \(\rightarrow\) Broadband background
Determine the ‘Cross-talk’ Calibration Matrix

Raman Spectra Library

Calibration matrix

\[ N_i = \frac{1}{E_{laser}} k_{i,j}(T) S_i \]

Mole frac.

Calibrated Results

Experiments or Simulations

10 atm, H₂-air flame
Swirl-stabilized direct fuel injection design (gaseous)
- Integrated with existing high-pressure rig
- 6 jets (0.8 mm in dia.) angled at 45 deg to burner axis
- Initial test on H₂ and CH₄ fuels with unheated air at 5 atm
- Collaborating with National Combustor Code (NCC)
Single-Shot (Time-Resolved) Raman Measurements

- One shot = One instance (space-time point)
- Single-shot Raman data shows “random” change due to turbulence
- Direct and simultaneous measurement of fuel/oxidizer concentrations and temperature (with data processing with calibration matrix)
- Developed new thermometry approach (rot. bandwidth) with high SNR

Temperature from the rotational spectra has been measured with accuracy 7%

Data permits statistical PDF’s of temperature and species

Provides a signature for characterizing degree of mixing and reaction

Rotational N2 Raman band

Raman shift (or wavelength)

Time variation of single-shot Raman spectra in CH4-air LDI flame
(5 atm, Phi = 0.5)
Processing the Single-Shot Data

Number density

\[1.019 \text{ molec/cm}^3\]

Large scatter

Homogeneous

\((r, x) = (0, 33)\)

\((r, x) = (14, 9)\)

LDI model burner

Air

Fuel

Number density

\([10^{19} \text{ molec/cm}^3]\)
Spatially-mapped multi-scalar PDF “library” in given conditions provides excellent validation data for a predictive combustion code.

Difference between mean and distribution (statistical value)
Multiscalar Analysis in 5-atm CH$_4$-Air LDI Flame

‘Production-mode’ data
: Direct output from a MATLAB code
1. Temperature PDF’s
2. Temp. vs species correlations
   (red: O$_2$; blue: CH$_4$)
3. Triplet correlations (temp-ox-fuel)
   (with a global Phi of 0.5 line)

Data interpretation
✓ Hot spots (high NOx)
✓ Unique bi-modal PDF’s — recirculation zone, or combustion oscillations
✓ Turbulent-chemistry interaction
✓ Fuel-air mixing characteristics
✓ Unburnt pockets
Multiscalar Analysis in 5-atm CH₄-Air LDI Flame

Data interpretation

✓ Gaussian-like narrow Temp. distribution (centered around the adiabatic temp. at Phi of 0.5)
✓ No fuel (CH₄) residual = fully consumed
✓ No hot or cold spots

✓ Homogeneous, well-reacted post-flame zone
Conclusions

- A single-shot (time-resolve) capability of a laser Raman diagnostics has been confirmed.
- Preliminary data of time-resolved multiscalar data in a high-pressure (turbulent) swirl-stabilized flame has been acquired.
- A new single-shot data-processing scheme (computer code) has been developed for ‘production mode’ thermo-chemical analysis.
- Scalar PDF’s and 3D (temp-oxy-fuel) correlations showed promising capability of future use in code validation.

Work-in-progress

- APCD (atmospheric pressure combustion diagnostics) facility is under construction to calibrate and improve the Raman diagnostics applicable to liquid fuels.
- Modified visible and UV Raman diagnostic systems is under development to cope with harsh environments.
- Computer code to simulate Raman spectra of major species including CO$_2$ and H$_2$O (except hydrocarbon) is under development to complete the calibration matrix.
- Pressure Safety Office safety permits, variances in process.