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

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H2-Air Flame at 20 atm

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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: H₂, CH₄, single-component liquid (e.g., hexane, iso-octane, n-heptane), 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
High Pressure Burner Facility (SE-5)

- Remotely 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

Electro-mechanical high-speed shutter
*2007 R&D 100 Award
• 10’s μs gate width

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

Holographic spectrograph (f/1.8)

Near-Pressure Rig
Burner
Folding Prism

Nd:YAG Laser (800 mJ/pulse)
Laser Pulse-Stretcher (passive multiple ring-cavity) *Patent pending

Beamsplitters
Mirs
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](image-url)
Raman Calibration Experiments & Simulation

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

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

Raman spectrum simulation
Determine the ‘Cross-talk’ Calibration Matrix

**Raman Spectra Library**

- \( S_i = \frac{1}{E_{\text{laser}}} k_{i,j}(T) S_j \)

**Calibrated Results**

- 10 atm, H\(_2\)-air flame

**Experiments or Simulations**

- Fuel-Lean
- Fuel-Rich

**Mole frac.**

- Fuel-Lean
- Fuel-Rich

**Calibration factor** (10\(^{19}\) molecules cm\(^{-1}\) \(\mu\)W\(^{-1}\) nm)
NASA Lean Direct Injection (LDI) Swirl-Stabilized Research Burner
— Preliminary Test —

- 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
Processing the Single-Shot Data

Number density

\[10^{19} \text{molec/cm}^3\]

Large scatter

Homogeneous

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

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

LDI model

burner

Air

Fuel

\[n_{CH_4} \text{ Number density} \]
Probability Density Functions: PDF’s
(Temperature, CH₄, and O₂)

CH₄-air LDI flame (5 atm, Phi = 0.5)

- Oxidizer, O₂ (10¹⁹ molec/cm³)
- Fuel, CH₄ (10¹⁹ molec/cm³)
- Temperature (K)

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)

Averaged value
Multiscalar Analysis in 5-atm CH₄-Air LDI Flame

‘Production-mode’ data:
- Direct output from a MATLAB code
  1. Temperature PDF’s
  2. Temp. vs species correlations (red: O₂; blue: CH₄)
  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 CO2 and H2O (except hydrocarbon) is under development to complete the calibration matrix.
- Pressure Safety Office safety permits, variances in process.