Dual-Pump CARS and OH PLIF

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National Center for Hypersonic Combined Cycle Propulsion
Background

- CFD methods employing semi-empirical models used in analysis of hypersonic airbreathing engine flow paths
  - RANS (or Favre averaged) codes have models for turbulent stresses, mass and energy transport, turbulence chemistry interactions
  - LES methods have models for subgrid scale turbulence
- Models depend upon experimental data for validation
  - Information on mean flow and statistics of the turbulent fluctuation in flow properties
- Data requirements
  - Simple well defined supersonic combustion flows with well-known boundary conditions
  - Time and spatially resolved
  - Good instrument precision
  - Converged statistics
- Approach
  - Dual-pump CARS
    - $T$, mole fraction species
  - Planar laser-induced fluorescence imaging of OH radical (PLIF)
    - Flow-visualization
Flow Fields

Laboratory supersonic flame with 10 mm center jet

Supersonic free jet flames (hot center jet with H₂ co-flow)

University of Virginia’s Dual-Mode Scramjet

Scramjet combustor

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Dual-Pump CARS

- Four-color mixing process at beam focus / intersection
  - Two narrowband pump (Green + Yellow) + broadband Stokes (Red) laser
  - Probe molecular Raman transitions
  - Two simultaneous processes
- Coherent signal beam (Blue)
  - Analyze with spectrometer
  - Fit spectra to theory to obtain T, mole fraction species
- Measurement time ~10 ns, volume ~50 µm x 1.5 mm
“Mobile” CARS System

Laser cart

Transmission

Collection

Detection

Beam Relay System (BRS)

- Narrowband and broad-band dye laser beams on top of each other
- Flame

- Laser cart
  - Nd:YAG (532 nm, 1.2 J, 20 Hz, seeded) = Green
  - YAG-pumped broad-band dye laser (~9.6 nm or 263 cm⁻¹ at 605 nm) = Red
  - YAG-pump narrow-band dye laser (~0.07 cm⁻¹ at 553 nm) = Yellow
  - Remote beam steering (picomotor mounts)
  - Control of beam size (telescopes) and energy (polarizers/waveplates)

- Detection system
  - Focusing lens, polarizer, remote beam steering
  - 1 m monochromator
  - Cooled CCD
Beam Relay System at UVa

- Moves beam crossing within flow field; 3 components, typically 2 motorized

- **CARS window**

- **Transmission**

- **Collection**

- **Measurement point**

- **Dual mode combustor**

- **Linear bearings/rails**

  *Horizontal motions are motor driven*
Transmission and Collection Optics

- Laser beams focused and combined with separate mirrors and lenses
- Focal plane imaging system
  - Beam focusing
  - Beam crossing

![Diagram of Transmission and Collection Optics](image)

- Focal plane imaging system: microscope objective and CCD camera
- Multi-pass dichroic splitter
- Signal beam
- To BRS and Detection

**Focal plane images**

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Optical Implementation at UVa
Method for Fitting Spectra

- Sandia CARSFT code
  - Computes theoretical spectra
- New algorithm* fits spectra by interpolating from library of pre-computed spectra
- Novel feature is structure of library (sparsely packed) and method for interpolation of spectra from library
  - Smaller libraries, faster library generation, faster fitting
- Allows fitting of more chemical species and faster turn around
  - Enables “WIDECARS”

*Cutler, A.D., Magnotti, G., J. Raman Spectroscopy, 2011.
Measurements in Hencken Burner

- Hencken flat flame burner
  - $\text{H}_2$-air flame
  - Flame temperature and composition known from theory
    - Computed from gas flow rates assuming adiabatic reaction to equilibrium

**Average DP CARS spectra at 3 equivalence ratios**
Typical spectra normalized and fitted
(a) $\phi=0.23$ (single shot)
(b) $\phi=1.17$ (single shot)
(c) $\phi=0.23$ (mean)
(d) $\phi=1.17$ (mean)
Fitted Temperature in Hencken Flame

- Means agree well with theory
- Actual standard deviation (SD) in flame due to unsteadiness is unknown but believed small
- Fitted parameters have noise
  - Mode noise in broad band dye laser, camera noise, photon shot noise
- SD of fitted parameters depends on selection of residual minimized by fitter
  - $R_2$ = noise-weighted least squares fit to signal intensity (Snelling et al, 1987)
  - ($R_1$, $R_3$ commonly used in the literature)
- We found $R_2 < R_3 < R_1$
- Similar results for fitted N$_2$, O$_2$, H$_2$ mole fractions

SD in $T$ reduced x2 by proper selection of residual! Important for turbulence studies
Saturation Effects

- Signal $\propto I_{p1} I_{p2} I_S d^2 L^2$
  - Want to minimize $L$
  - Must maximize $I_{p1} I_{p2} I_S$ to maintain signal
  - Saturation effects limit $I_{p1} I_{p2} I_S$

- Saturation effects studied in Hencken flame
  - Mixture of Stark shift and stimulated Raman pumping

- Fitted mole fraction more sensitive than temperature
  - Error in $O_2$ up to 30%
  - $H_2$ most sensitive to saturation
  - Saturation thresholds determined
  - We now know how to avoid saturation
Status of CARS

• CARS data base in laboratory supersonic flame
  – Data acquisition completed
  – Data analysis in progress

• CARS system currently installed at UVa
Supersonic Flame*

- Center jet 10 mm, hydrogen vitiated air, variable Mach (0.75-2.0) and temperature
- Unheated, low-speed coflow
- 10 test cases; variables
  - Nozzle exit Mach number ($M_e$)
  - Center jet temperature (equivalent flight Mach $M_h$)
  - Coflow gas
    - $C = H_2$ coflow, combustion
    - $M = N_2$ coflow, mixing but no combustion
- Nominally 100,000 spectra for each test case, fitted for $T$, and mole fractions $N_2$, $O_2$, $H_2$
  - Sampled at 5 axial locations, 23-30 radial locations at each
- Will be used by NCHCCP modelers

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Typical Results in Supersonic Flame

Plots of mean T vs. radial distance at several axial locations

Mixing (coflow = N₂)
$M_e=1.6$
$M_h=7$

Combustion (coflow = H₂)
$M_e=1.6$
$M_h=6$

Center jet diameter = 10 mm, surveys are at ~1, 15, 35, 65, and 100 mm
“WIDECARS”*

- Enable DP CARS in C₂H₄ + H₂ – air flames
- New broadband Stokes laser
  - 2x increase in spectral width allows additional chemical species to be simultaneously probed
- Temperature, mole fraction N₂, O₂, CO₂, C₂H₄, H₂ and CO measured at 300 K.
  - Most species ever simultaneously measured with CARS!
  - Fit with new software
- Future development required
  - Validate at flame temperature
  - Modeling/calibration for C₂H₄

*Collaboration with Tedder and Danehy (LaRC)
Tedder et al., Appl. Optics, 2010

Demonstration in a room T gas cell
OH PLIF Preliminary Setup

• Modified CARS laser cart to produce UV light needed for OH PLIF
  – Installed doubling crystal
  – Optimized laser for power

• Performed OH PLIF measurements in laboratory
  – Set up sheet forming optics
  – Set up laminar OH combustion with water welder
  – Investigated camera settings
  – Determined optimal PLIF transitions

• Flow visualization only
  – Signal roughly ~ OH density (not calibrated)
Planar Laser-Induced Fluorescence (PLIF)

- Tunable Laser
- Laser sheet excites molecules
- $\text{H}_2$ $\rightarrow$ $\text{O}_2$ (Water welder provides reactants for combustion)
- Excited molecules fluoresce
- CCD camera detects
- $\lambda = 281.135 \text{ nm}$
- $A^2\Sigma^+ \leftarrow X^2\Pi(1,0)$
- $\text{LIF} \sim n_{\text{OH}}$
Ongoing Work and Future

- **Summer 2011**
  - Acquire CARS data bases in UVa Dual Mode Scramjet Configuration B (no isolator) and C (with isolator)
  - OH PLIF flow visualization (same cases)

- **2011-2013**
  - Develop and validate “WIDECARS” for $C_2H_4 (+ H_2)$ in Hencken flame
  - Acquire CARS data base supersonic flame with $C_2H_4 + H_2$ coflow
  - Acquire CARS/PLIF data base in UVa scramjet with ethylene flame/cavity flame holder
Summary

• Motivation
• Dual pump CARS
• “Mobile” system and implementation at UVa
• Method of fitting spectra
• Measurements in a Hencken burner (H₂-air) and supersonic jet
• Saturation effects
• Measurements in a supersonic flame
• WIDECARS
• OH PLIF setup and preliminary data
• Ongoing and future work