Coherent Anti-Stokes Raman Scattering Temperature and Concentration Measurements in High-Temperature, High-Pressure Flows

Robert P. Lucht
School of Mechanical Engineering, Purdue University, W. Lafayette, Indiana

General Electric Global Research Center Workshop on Advanced Engine Diagnostics Niskayuna, NY 12 July 2012
ME 687 Lects 1 & 2
Advanced Engineering Optics: Laser Diagnostic Methods in Mechanical Engineering

Prof. Robert P. Lucht
Room 2204, Mechanical Engineering Building
School of Mechanical Engineering
Purdue University
West Lafayette, Indiana

Lucht@purdue.edu, 765-494-5623 (Phone)

August 20 & 22, 2012
ME 687 Course Overview

Course Objective: Develop working knowledge of laser techniques for species concentration, temperature, and velocity measurements in complex reacting media.

Working Knowledge of Laser Techniques?
- Laser systems
- Optical elements for laser diagnostic systems
- Species spectroscopy
- Interaction of laser radiation with the molecule or atom
- Calculation of signal levels, estimates of accuracy, precision

Complex Reacting Media?
- Laminar or turbulent flames, steep gradients in species concentration and temp, need high spatial, temporal resolution
- Collisional environment of molecule or atom is drastically different in different parts of the flame
- Collisional environment can significantly affect signal levels from laser techniques
Issues in Combustion Science: Why Use Laser Diagnostics?

- Flame Chemistry - complex reaction mechanisms, importance of free radicals that are difficult to measure by other techniques, lasers do not perturb the flow and temperature fields nearly as much as physical probes

Example: $H_2/O_2/N_2$ Chemistry

Initiation Reaction

$H_2 + O_2 \rightarrow HO_2 + H$ \hspace{1cm} \text{Initiation}

Chain-Branching Reactions

$H + O_2 \rightarrow O + OH$ \hspace{1cm} \text{Chain – Branching}

$O + H_2 \rightarrow H + OH$

$H_2 + OH \rightarrow H_2O + H$ \hspace{1cm} \text{Except for (4)}

$O + H_2O \rightarrow OH + OH$
Issues in Combustion Science: Why Use Laser Diagnostics?

Chain Termination, 3-Body Recombination

\[
(6) \quad H + H + M \rightarrow H_2 + M \quad \text{Chain–Termination}
\]

\[
(7) \quad H + OH + M \rightarrow H_2O + M \quad \text{3–Body Recombination}
\]

NO Formation: Zeldovich Thermal NOx Mechanism

\[
(8) \quad O + N_2 \rightarrow NO + N \quad \text{Very Temperature Sensitive}
\]

\[
(9) \quad N + O_2 \rightarrow NO + O \quad \text{High Activation Energy}
\]

\[
(10) \quad N + OH \rightarrow NO + H
\]

Lasers can be used to measure all T, all major species, O, H, OH, and NO. Temperature measurement by thermocouple compromised by radiation, perturbs flow and flame chemistry. Physical probes perturb flow.
Issues in Combustion Science: Why Use Laser Diagnostics?

Stagnation Flow Diamond-Forming Flame Apparatus

Diamond-Forming Flame Temperature Profile (Case I)
Issues in Combustion Science: Why Use Laser Diagnostics?

Measurement Technique

Temperature measured along stagnation-point streamline between nozzle exit and substrate surface

Data obtained in probe volume defined by overlap of the three input beams

- ~ 50 µm in diameter
- ~ 1.5 mm long
Spectroscopic Laser Techniques

- Development of commercialized tunable lasers about 30 years ago has led to routine use of laser techniques for probing flames and plasmas.

- Laser technology continues to advance, sometimes with dramatic impact on “old” laser techniques.

- Recent advances with actual or potential impact on flame and/or plasma diagnostics: blue diode lasers, DFB diode lasers, injection-seeded Nd:YAG lasers with > 1 J per pulse, picosecond laser systems, femtosecond laser systems, BBO crystals.
Rayleigh Scattering – Filtered Rayleigh Scattering

Strong signal, spatially resolved, not species-specific
Tunable Laser Absorption

Species-specific, quantitative, path-averaged
Sensors for Detection of Trace Chemical Species

Haley

Molly
NO Sensor System
Signal and Reference Beams: 100 ppm NO in Gas Cell
Theory vs. Experiment: 100 ppm NO, 2.4 kPa in Gas Cell

<table>
<thead>
<tr>
<th>No.</th>
<th>Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$P_2(4)$ and $PQ_{12}(4)$</td>
</tr>
<tr>
<td>2</td>
<td>$P_2(3)$ and $PQ_{12}(3)$</td>
</tr>
<tr>
<td>3</td>
<td>$P_2(5)$ and $PQ_{12}(5)$</td>
</tr>
</tbody>
</table>

$P = 2.40$ kPa, $x_{NO} = 95$ ppm, $\Delta \nu_c = 0.42$ GHz, $\Delta \nu_d = 2.97$ GHz
Field Demonstration: Honeywell Gas Turbine Engine
Gas Turbine Measurements: High Load Condition

Absorption Results
\( x_{\text{NO}} = 56 \text{ppm} \)
\( T = 750 \text{ K} \)
\( 2\gamma_{\text{coll}} = 0.598 \text{ cm}^{-1} \)
Scaling Factor = 1.26

Sampling Probe Results
\( x_{\text{NO}} = 55-65 \text{ ppm} \)
\( T = 712-751 \text{ K} \)
OH Ultraviolet Absorption Sensor

- New Sensor for OH Developed and Applied at Wright-Patterson AFB

  - Laser radiation at 313 nm generated by sum-frequency-mixing of 100 mW of 763-nm radiation from DFB diode laser with 10 W of 532-nm radiation from Coherent Verdi

  - DFB diode laser allowed us to obtain almost 100 GHz of mode-hop-free tuning range at a tuning rate of 20 kHz (as compared to 25 GHz and 10 Hz for the ECDL in the NO sensor)
OH Ultraviolet Absorption Sensor

- Coherent Verdi 532 nm, 10 W
- Telescope Isolator
- BBO Crystal f=50 mm
- Interference Filter
- 70/30 Beamsplitter
- Sacher Laser DFB 763 nm, 50 mW
- Half-wave plate
- Polarizer
- Interference Filter
- Fiber Optic Couplers
- Reference Photodiode
- Signal Photodiode
- Removable Mirror
- Etalon
- Burner f=75 mm
- Coherent Verdi 532 nm, 10 W
OH Sensor Layout
Raw Signals of OH from Flame

763-nm DFB scanned at rates of up to 20 kHz, 1 kHz in data shown here
OH Absorption Spectra – 2 kHz

Normalized Absorption

-20  -10   0    10    20
-0.01  0  0.01

Frequency Detuning (GHz)

Normalized Absorption

-0.01  0  0.01

Residual

z=10 mm
OH Absorption Spectra – 20 kHz

Spectra acquired in single sweeps.

\( \Phi = 1.0, \ z = 15 \text{ mm} \)
Spontaneous Raman Scattering

- **Fixed Frequency Laser**
- **Flame or Plasma**
- **Beam Dump**
- **Photomultiplier or CCD Array**
- **Spectrometer**

Excited Electronic Level

Virtual Level

Species-specific, spatially resolved, quantitative, weak signal
Laser-Induced Fluorescence (LIF)

Species-selective, spatially resolved, strong signals, complicated by nonradiative decay, not all species fluoresce.
Planar Laser-Induced Fluorescence (PLIF)

**Planar Imaging System**

- **Nd:YAG Laser**
  - 6-8 ns pulse, 10 Hz
  - 600 mJ @ 532 nm
  - 120 mJ @ 266 nm

- **Sheet Forming Optics**
  - Spherical lens, f=500 mm
  - Cylindrical lens, f=-19 mm
  - Cylindrical lens, f=150 mm

- **CCD Digital Camera**
  - Thinned, back-illuminated sensor
  - 512 x 512 pixel array
Edgewave Diode-Pumped Solid State Nd:YAG Laser: 5 kHz Rep Rate, Dual-Head, 6 mJ/Pulse at 532 nm, 7 nsec Pulses

Sirah Credo Dye Laser: 5 kHz Rep Rate, 500 μJ/Pulse at 283 nm (2.5 W average power in UV)
5 kHz OH PLIF of Shear Layer Combustion for a Hydrogen Nonpremixed Jet Flame
Simultaneous High-Speed (3 kHz) OH PLIF and Particle-Imaging Velocimetry (PIV)
Recent Measurements at DLR Stuttgart

3 kHz simultaneous PIV/OH PLIF in 5 bar methane/air flame in DLR test rig, measurements performed by C. Slabaugh (Purdue) and I. Boxx (DLR)

Data analysis in process
Laser-Induced Polarization Spectroscopy (LIPS)

Species-selective, spatially resolved, wide range of species, coherent signal, complicated physics
Coherent Anti-Stokes Raman Scattering (CARS)

- Conventional “Single-Pump” CARS
- Noninvasive
- Coherent Laser-Like Signal
- Spatially and Temporally Resolved
- Excellent Gas Temperature Data (especially at higher temperatures)
Nitrogen CARS is widely used for temperature measurements in flames, sophisticated models of the nitrogen CARS spectrum have been developed.
CARS Temperature Measurements

T = 1500 K

T = 2000 K
Dual-Pump Coherent Anti-Stokes Raman Scattering (CARS) Spectroscopy
Single-Shot CARS Temperature Measurements
Ns CARS for Gas-Phase Diagnostics

\[ \omega_{as} = \omega_{p2} - \omega_s + \omega_{p1} \]

\( v = 1, J \)

\( v = 0, J \)

2330 cm\(^{-1}\)
Dual-Pump CARS of N$_2$/CO$_2$

**N$_2$ CARS**

\[ \omega_{as} = \omega_{p1} - \omega_s + \omega_{p2} \]

\[ v=1, J \]

\[ v=0, J \]

2300 cm$^{-1}$

**CO$_2$ CARS**

\[ \omega_{as} = \omega_{p2} - \omega_s + \omega_{p1} \]

\[ v=1, J \]

\[ v=0, J \]

1300 cm$^{-1}$
CO$_2$/N$_2$ Dual-Pump CARS: Funding from NASA Glenn
CARS System for GTCF Measurements

Grad students: Mathew Thariyan, Aizaz Bhuiyan
Temp PDFs Along Centerline

Combustor Pressure: 104 psia, Equivalence Ratio: 0.4

Temperature PDF: Z = 10 mm, R = 0 mm
Mean Temp. = 2020 K
Std. Dev. = 370 K

Temperature PDF: Z = 15 mm, R = 0 mm
Mean Temp. = 1820 K
Std. Dev. = 340 K

Temperature PDF: Z = 25 mm, R = 0 mm
Mean Temp. = 1595 K
Std. Dev. = 267 K

Temperature PDF: Z = 50 mm, R = 0 mm
Mean Temp. = 1340 K
Std. Dev. = 180 K
Temperature and $\text{CO}_2/\text{N}_2$ Correlation Plot

Combustor Pressure: 150 psia., Equivalence Ratio: 0.48

Temp. vs $\text{CO}_2/\text{N}_2$ Correlation: Z = 30 mm, Y = 0 mm

$R^2 = 0.571$

---- Adiabatic Equilibrium
A larger window combustor with a 4.2in x 4.2in (106.68mm x 106.68mm) cross-section window combustor was fabricated with a optical area of 3in x 4in (76.2mm x 101.6mm).

Grad students: Warren Lamont, Mathew Thariyan
In May of 2012, H2/N2 CARS experiment was carried out to map the temperature with the bigger window combustor. The axial fuel was premixed natural gas and air 10mm nozzle.
H₂/N₂ Dual-Pump CARS

- Tunable ω₂
- Broadband ωₛ

ω₁, ωₛ, ω₂, ωₐs

2330 cm⁻¹ Nitrogen

4070 cm⁻¹ Hydrogen
H$_2$/N$_2$ Dual-Pump CARS
H$_2$/N$_2$ Dual-Pump CARS
H$_2$/N$_2$ Dual-Pump CARS

- Data
- Theory
- Residual

$T = 1746$K
$H_2/N_2 = 0.032$
Both N$_2$/CO$_2$ and N$_2$/H$_2$ dual-pump CARS measurements performed at pressures up to 10 bar.

Dual-pump CARS spectra, backgrounds, and nonresonant reference spectra are acquired automatically under computer control.

Spatial probe volume is translated using prisms mounted on computer-controlled translation stages.

Probe volume dimension measured to be 600 microns for N$_2$/CO$_2$ measurements.
Other Laser Diagnostic Techniques

- Particle Imaging Velocimetry
- Resonant Four-Wave Mixing, Degenerate Four-Wave Mixing (DFWM)
- Photoacoustic Spectroscopy
- Resonant Photoionization Spectroscopy, Resonant Multi-Photon Photoionization Spectroscopy (REMPI)
- Laser-Induced Incandescence (LII)