Lecture 15: Application Examples of LIF, PLIF
Large Molecules (Tracers)

1. Introduction to flow tracer PLIF
2. Acetone PLIF to image fuel mixing
3. 3-pentanone PLIF as a flow tracer
4. 3-pentanone PLIF in IC-engines
5. CW PLIF for high-frame-rate imaging
6. Toluene PLIF for temperature (1 camera)
7. Toluene PLIF for temperature (2 camera)
8. The future

Temperature image; single-shot PLIF of acetone in flow around heated rod

Thurber et al. (1997)
1. Introduction to Flow Tracer PLIF

**Planar Laser-Induced Fluorescence**

\[
S_f = \frac{E}{h\nu} n \sigma(\lambda,T) \phi(\lambda,T,p_i) \eta
\]

- History of PLIF begins at Stanford
  1982 - Kychakoff, Howe, Hanson, and McDaniel using OH

- Now we examine PLIF from tracers, mostly ketones, to control \( \phi \)
1. Introduction to Flow Tracer PLIF
LIF of tracer molecules added to flow

Planar Laser-Induced Fluorescence

\[ S_f = \frac{E}{h\nu} n\sigma(\lambda,T)\phi(\lambda,T,p_i)\eta \]

Collection Efficiency

Incident Photons | Photons Absorbed | Fluorescence Quantum Yield

Tracer LIF signal

Inflow with tracer
1. Introduction to Flow Tracer PLIF

Biacetyl and acetone first tracers used

- Background: Addition of a fluorescent tracer enabling LIF and PLIF in air (neither O₂ nor N₂ are readily accessible)

- 1980’s at Stanford HTGL
  Biacetyl ((CH₃CO)₂), but had two problems:
  1) smelly and hard to handle
  2) highly quenched by O₂

- Early 1990’s by Lozano’s survey
  Acetone (CH₃COCH₃), has become a popular laser diagnostic in laboratories worldwide
1. Introduction to Flow Tracer PLIF

Ketones are good flow tracers

How can PLIF be used to study mixing?

Use Ketones as Tracers: Acetone and 3-Pentanone

- Advantages of Ketones as Tracers
  + Strong signals
    - Accessible absorption feature
    - Non-resonant fluorescence
  + Resistant to bath gas effects
  + Similar to common hydrocarbon fuels

- Applications
  - Fundamental fluid/heat transfer studies
  - Fuel/air mixing in combustion systems

⇒ Application is straightforward in isothermal, isobaric flows, i.e., Signal is proportional to mixture fraction of tracer
1. Introduction to Flow Tracer PLIF
A brief overview of acetone LIF

- Acetone photophysics

- Vapor pressure is 180Torr at room temperature
- Cheap, non-toxic, easy to handle
- Fluorescence lifetime is approximately 2ns and is independent of O₂
- Constant fluorescence yield of about 0.2% at room temperature
- Each state is a manifold of vibrational levels
- “Intramolecular intersystem crossing” at rate Qₜ dominates, therefore the FY = A₁₀/(A₁₀ + Qₜ) ≈ A₁₀/Qₜ ≈ 0.2% and SF ∝ n_{acetone} I_v (or E)!
- Absorption and fluorescence are broadband
2. Acetone PLIF to Image Fuel Mixing
Absorption and fluorescence wavelengths

- Acetone: A tracer for concentration measurements in gaseous flows by planar LIF (Lozano, Yip & Hanson, 1992)

Acetone absorption spectrum corresponding to excitation from the ground state to the first excited singlet
  - Reveals range of suitable excitation wavelengths

Acetone fluorescence spectrum when excited at 308nm: the dashed line corresponds to the detected signal; the solid line is the same curve corrected for the detection system responsivity
  - Reveals separation of emission wavelength from excitation
2. Acetone PLIF to Image Fuel Mixing

Example of acetone PLIF to investigate jet in crossflow: isothermal, isobaric mixing study

Side-view

- $U_{crossflow} = 5 \text{ m/s}$
- $d_{jet} = 5 \text{ mm}$
- $U_{jet}/U_{crossflow} = 20/1 = r$
- $1 \text{ rd} = 10 \text{ cm}$

- For isothermal, isobaric case, fluorescence signal is proportional to tracer mole fraction

Smith 1998

- Acetone vapor seeded into air
- $\lambda_{ex} = 308 \text{ nm}$
2. Acetone PLIF to Image Fuel Mixing

Example of acetone PLIF to investigate jet in crossflow: isothermal, isobaric mixing study

- Detail provided by PLIF provides important tests of model predictions
3. 3-pentanone PLIF as a Flow Tracer

Photophysics Database and Modeling: Fundamentals

- PLIF with ketone/aromatic tracers widely used, but not quantitative at high P & T

\[
S_f = \frac{E}{h\nu} \times L \times n_{ab} \times \sigma(\lambda, T) \times \phi(\lambda, T, P) \times \eta\Omega/4\pi
\]

- Measurements and modeling needed for \( s(l, T), f(l, T, P) \) at high P & T

\[
\phi = \sum_{n=0}^{\infty} \frac{k_f}{k_f + k_{vib} + k_{nr}(E_n) + k_{O2}(E_n)} p(E_n)
\]

- Model has four parameters, \( \alpha, k_{nr}, k_{O2}, k_f \)
  - \( k_{nr} \) & \( k_{O2} \) measurable from lifetime data
  - \( \alpha, k_f \) from \( f \) data over range of P,T

- \( k_{vib} \) = collisional rate (s\(^{-1}\))
  - \( n = n^{th} \) collisional time step
  - Energy at \( n^{th} \) step: \( E_{n+1} = E_n - \Delta E_{coll} = E_n - \alpha(T)[E-E_{thermal}] \)
3. 3-pentanone PLIF as a Flow Tracer

3-pentanone: Better match to physical properties of fuels
Photophysical behavior qualitatively similar to acetone but quantitatively different

- 308 nm, T < 550K - ideal regime for straightforward concentration imaging
- 248 nm highly T-sensitive – good for temperature imaging

- Long/short wavelength ratios are most temperature sensitive
- 3-pentanone is more T-sensitive than acetone

3-pentanone
Single Excitation Wavelength

Acetone and 3-pentanone
Dual Excitation Wavelength

P=1 atm N₂
3. 3-pentanone PLIF as a Flow Tracer
Simultaneous Imaging of $\chi_i$, $T$

- Strong $T$ dependencies of 3-pentanone enable quantitative imaging

- Laser excitation at 308 and 266 nm
- Frame transfer CCD camera acquires 2 images within 2 $\mu$s
- Instantaneous $T$, $\chi_i$ images from a heated 3-p/air jet after 308/266 nm excitation
- Flowfield contains 1-4% 3-pentanone (2.9% is stoichiometric)

Koch and Hanson 2003
4. 3-pentanone PLIF in IC-Engines

Homogeneous Charge Compression Ignition (HCCI)

- Natural thermal stratification (TS) important for HCCI engine ignition
- Increase of TS could extend high-load operation
- PLIF of temperature and residuals an important tool to study TS

- Tracer-based PLIF strategies used
  - Two-line (277nm/308nm ratio) – simultaneous T and $\chi_i$
  - Single-line (277nm) – T (homogeneous composition)
  - Tracer selection: 3-Pentanone – good sensitivity, minimal effect of oxygen quenching

- Investigate the thermal stratification in HCCI engine: motored & fired operation
  - Early residual mixing
  - Thermal stratification evolution during compression
**4. 3-pentanone PLIF in IC-Engines**

Mixing of Residuals with Fresh Intake Can Produce Stratification

- Incomplete mixing of hot retained residuals (internal EGR) with fresh intake can result in TS
- Two-line PLIF of $T$ and $\chi_{\text{air}}$ to track evolution of intake-air/residual gas mixing

<table>
<thead>
<tr>
<th>Temp. 2L [K]</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
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<tbody>
<tr>
<td>20°</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>X_{\text{Air}} [%]</th>
<th>0</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°</td>
<td></td>
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</table>

- Mixing complete after 100° of CA (bottom of stroke at 180°)
- Mixing of EGR and fresh intake does not increase the thermal stratification for these conditions

Snyder et al. 2011
4. 3-pentanone PLIF in IC-Engines

One-line PLIF in Engines:
Natural Thermal Stratification (TS) Increase Near TDC

- Single-line (277nm) PLIF of temperature to monitor TS evolution during compression
- High sensitivity of measurement (4-5K) allows detection of small variations – important for HCCI
- Initial TS is small (305°C) but drastically increases throughout remaining compression
  - TS near TDC results in sequential auto-ignition that reduces the rate of heat release – important for extension to high-load operation

Heat transfer with wall surfaces in boundary layer leads to pockets of cooler gas that convect into core cylinder region and affect auto-ignition

Fueling – 14% 3-Pent., 86% Iso-octane [liq. Vol.] – φ=0.4
5. CW PLIF for High-Frame-Rate Imaging

New Diagnostic for Real-time Measurements of Turbulent Mixing

- **Problem:** Use of pulsed lasers limits temporal resolution of tracer-based PLIF
- **Strategy:** Use CW laser at 266 nm and toluene (high $\phi$) tracer for CW-LIF/PLIF
- CW-LIF/PLIF would offer useful diagnostic for turbulent/fluctuating flows
  - Turbulent mixing of injected fuel streams
  - Studies of jet noise
- Apply CW PLIF to a toluene-seeded, steady $N_2$ jet to study fluctuation detection limits
  - CW UV light @ 266nm from cavity doubling of commercial 532 nm lasers (5-20W)
  - LIF signal imaged with intensified CCD camera
5. CW PLIF for High-Frame-Rate Imaging

CW PLIF Detection Limits for 266nm Excitation of Toluene

- What is the minimum detectable fluctuation in $\chi_i$?

- Data consistent with shot-noise detection limit as $\text{SNR} \propto (\text{signal})^{1/2}$
- Mixture fraction fluctuations < 1% can be detected with 100 $\mu$s resolution!
  - 10 kHz frame rate equivalent at each 0.4x0.4x0.4mm pixel

Cheung 2011
5. CW PLIF for High-Frame-Rate Imaging

CW PLIF Imaging of Mixing in Turbulent Jet: First Demonstrations

- N\textsubscript{2} jet seeded with 4\% toluene (Re = 10700) in N\textsubscript{2} coflow
- Single-shot images of X\textsubscript{mixture} show time-varying features of mixing

**The Future:**
- Improve laser intensity with higher power source, beam homogenizer
- Demonstrate high-speed imaging

- 10 \(\mu\)s exposure time
  (100 kHz frame rate equivalent)
- 200 mW laser power
- 0.05x0.05x0.4 mm/pixel
6. Toluene PLIF for T Imaging: (1-camera)

Planar Laser-Induced Fluorescence

\[ S_f = \frac{E}{h\nu} n \sigma(\lambda,T) \phi(\lambda,T,p_i) \eta \]

- **Incident Photons**
- **Photons Absorbed**
- **Fluorescence Quantum Yield**

**Tracer LIF signal**  **Temperature**

Inflow with tracer
6. Toluene PLIF for T Imaging (1-camera)

- Critical need for accurate targets to validate CFD simulations of shock/boundary layer interactions
  ➡ PLIF Imaging in a Shock Tube

- Development of new high-sensitivity temperature measurement strategy for imaging
  ➡ Toluene-Based PLIF Temperature Measurement

- Shock tube viewing section enables imaging of reflected shock wave/boundary layer interaction

Four-Window Square Endwall Viewing Section: Stanford Shock Tube
6. Toluene PLIF for T Imaging (1-camera)

PLIF of Incident Shock Wave Arrival

Camera PLIF Image

Shock tube

Toluene-Seeded Test Gas Mixture

Pulsed UV laser

ICCD camera

PLIF signal

UV mirror

Sheet forming optics

Shock Flow Conditions:

\[ T_1 = 296K, \quad T_2 = 438K, \]
\[ P_1 = 44\text{torr}, \quad P_2 = 0.24\text{atm}, \]
\[ X_f = 7\%, \quad \text{Incident } V_s = 605\text{m/s} \]

Yoo 2011
6. Toluene PLIF for T Imaging (1-camera)

Shock Wave/BL Interaction: Reflected Shock
Bifurcation Time Sequence

- First toluene PLIF images of shock bifurcation
- Interaction of reflected shock wave with boundary layer
- Toluene provides sensitive data for temperature and flow structure for CFD validation
- Opportunity to apply to other shock/boundary layer flowfields

Shock Flow Conditions:
\[ T_1=296K, \quad T_2=498K, \quad T_5=696K \]
\[ P_1=32\text{torr}, \quad P_2=0.25\text{atm}, \quad P_5=1.05\text{atm} \]
\[ X_f=8\% \text{Tol}/N_2 \quad \text{Incident} \quad V_s=710\text{m/s} \]
6. Toluene PLIF for T Imaging (1-camera)

PLIF Signal Comparison with CFD Simulation

Experiment  

Simulation (Charles)

Shock Flow Conditions:
\[ T_1 = 296K, \quad T_2 = 498K, \quad T_5 = 696K \]
\[ P_1 = 32\text{torr}, \quad P_2 = 0.25\text{atm}, \quad P_5 = 1.05\text{atm} \]
\[ X_i = 8\% \text{Tol/N}_2 \quad \text{Inc.} \quad V_s = 710\text{m/s} \]
6. Toluene PLIF for Temperature Imaging

Shock Wave/BL Interaction

- Two different color renditions
- Structure formation revealed

Shock data

- $P_1 = 21$ torr  $P_2 \approx 0.143$ atm  $P_5 \approx 0.517$ atm
- $T_2 \approx 521K$  $T_5 \approx 772K$
- $V_5 \approx 737$ m/s
- 0.6% Toluene/N$_2$
7. Toluene PLIF for T Imaging (2-camera)

• Two cameras simultaneously image different spectral regions of fluorescence spectrum

• Select target species or tracer based upon conditions and quantity of interest (e.g., T or $x_{O_2}$)

• e.g., toluene, 3-pentanone, acetone
7. Toluene PLIF for T Imaging (2-camera)

- Two cameras simultaneously image different spectral regions of fluorescence spectrum
- Select target species or tracer based upon conditions and quantity of interest (e.g., T or \( X_{O2} \))
- e.g., toluene, 3-pentanone, acetone
- With understanding of photophysics of fluorescing species, physical quantities (e.g., T) can be inferred from ratio of images
- Allows for measure of quantity independent of tracer number density
7. Toluene PLIF for T Imaging (2-camera)

- Toluene fluorescence is function of temperature

\[ S_f = \frac{E}{h \nu RT} \frac{P_i}{\sigma(T)\phi(T, \lambda)\eta} \]
7. Toluene PLIF for T Imaging (2-camera)

- Toluene fluorescence is function of temperature

\[ S_f = \frac{E}{h \nu} \frac{P_i}{RT} \sigma(T) \phi(T, \lambda) \eta \]

\[ S_f = \frac{E}{h \nu} n \sigma(T) \eta \int \phi(\lambda, T) F(\lambda) \]

From Koban, Koch, Hanson, Schulz, 2005
7. Toluene PLIF for T Imaging (2-camera)

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\[
\frac{S_1}{S_2} = \frac{\int \phi(\lambda, T)F_1(\lambda)}{\int \phi(\lambda, T)F_2(\lambda)}
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7. Toluene PLIF for T Imaging (2-camera)

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\[ \frac{S_1}{S_2} = \frac{\int \phi(\lambda, T)F_1(\lambda)}{\int \phi(\lambda, T)F_2(\lambda)} \]

- Three sets of filters examined.

From Koban, Koch, Hanson, Schulz, 2005
7. Toluene PLIF for T Imaging (2-camera)

- Toluene fluorescence is function of temperature

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\]

From Koban, Koch, Hanson, Schulz, 2005
7. Toluene PLIF for T Imaging (2-camera)

Experimental setup

Laser sheet

Laser sheet
0.5mm thick

Wedge/Cylinder
7. Toluene PLIF for T Imaging (2-camera)

Wedge Flow: Temperature Imaging

\[ M = 2.3 \]
\[ P = 1 \text{ bar} \]
7. Toluene PLIF for T Imaging (2-camera)

Cylinder Flow: Temperature Imaging

M = 2.3
P = 1 bar
7. Toluene PLIF for T Imaging (2-camera)

Cylinder Flow: Temperature Imaging

$M = 2.3$
$P = 1 \text{ bar}$
Jet in Crossflow: Temperature Imaging

M = 2.3
P = 1 bar

7. Toluene PLIF for T Imaging (2-camera)

Raw Signal

Temperature
9. The Future for PLIF Imaging in Complex Flows

- **Applications**
  - Non-ideal effects in shock tubes (shock/boundary layer)
  - IC-Engines (EGR, T, radicals, pollutants)
  - SCRAMJETS (mixing, flame structure)
  - Fluid dynamics (mixing, turbulent combustion)
  - Plasma-enhanced combustion (flame structure, species)

- **Species**
  - Tracers (toluene, ketones, NO)
  - Naturally present (CO$_2$, UHC, OH, NO)

- **Strategies**
  - High-speed PLIF
  - Multi-parameter imaging (T, species)
  - IR PLIF
Quantitative Laser Diagnostics for Combustion Chemistry and Propulsion

Closing Comments: The Future

- Use of laser diagnostics will become increasingly routine
- Availability of packaged systems will continue to grow
- Availability and cost of mid-IR TDLAS will improve
- Sensitivity improvements will be found (e.g. CEAS)
- Use of hi-rep PLIF systems will become more common
- New PLIF tracers and techniques employing traces will be found
- Laser diagnostics will play a key and expanding role in future research on combustion

- The future for laser diagnostics is bright!
- Thanks for attending this short course!
- Best wishes for your future!