Application of Laser Diagnostics to the Study of Turbulence – Flame Interactions

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Outline

I. Introduction and overview of research strategy

II. Imaging of reaction rates in turbulent counterflow premixed flames

III. High-speed 3D velocity measurements for the study of localized extinctions

IV. Concluding remarks
Combustion Energy Usage

- > 80% of world energy is provided by combustion (~75% in Switzerland).
- Used in all sectors (transportation, chemical processes, electricity production, home appliances, etc).

Source: Annual Energy Review, 2011, EIA
Challenges

• Emissions (CO, NOx, CO₂, soot, etc)
• Limited resources of non-renewable combustibles (fossil fuel, coal, natural gas)
• Fuel economy independence

Technical solutions

• Clean combustion technology
• Improved efficiency
• Alternative fuels and fuel-flexible devices
Strategy: Lean Premixed Combustion

Emissions of CO, CO$_2$ and NO in methane/air combustion (thermochemical equilibrium)

Premixed Combustion allows for control of the fuel/air ratio
Strategy: Lean Premixed Combustion

Emissions of CO, CO$_2$, and NO in methane/air combustion (thermochemical equilibrium)

“The leaner, the cleaner”

Fundamental Research Challenges

- Stability of lean premixed flames in intense turbulence.
- Pollutant emissions affected by the chemistry-turbulence interaction.
- Lean flames are sensitive to external perturbations (heat losses, dilution, strain, etc).
- Safety (flashbacks)
Fundamental Research Challenges

Practical Combustion Systems

- complex kinetics
- Turbulence/chemistry
- instabilities
- particulates
- complex geometry
- spray
- pressure scaling
Turbulence-Chemistry Interaction: A Central Challenge

Turbulence-chemistry interaction

Piloted
Bluff-body
Swirl
Rod
Counterflow

Practical Combustion Systems

complex geometry
spray
pressure scaling
particulates
instabilities
complex kinetics

Well-characterized turbulent flames for canonical studies of turbulence – flame interactions
Turbulence-Chemistry Interaction: Theoretical Framework

Karlovitz number: \( Ka_t = \frac{t_{\text{chemical}}}{t_{\text{Kolmogorov}}} \)

Flamelet Regimes
- Quasi-laminar flame front structure
- Singly connected reaction zone

Non-Flamelet Regime
- Local Extinctions
- Distributed Reaction Zones
- Leakage of Reactants and Products across flame fronts
Laser diagnostics are a non-intrusive means of measuring a wide range of quantities, such as:

- **Velocity vectors** – Particle Image Velocimetry (PIV), Laser Doppler Velocimetry (LDV)
- **Intermediate species (OH, CH$_2$O, CO, etc) and forward reaction rates** – Laser Induced Fluorescence (LIF), Raman scattering, Soft X-Ray absorption.
- **Temperature** – Rayleigh Scattering
- **Scalar Mixing and Mixture fraction** – LIF imaging of “tracers” (Kr, Acetone, etc)

Features of laser diagnostics in combustion:

- Multiple simultaneous measurements
- Probe domain: point, line, plane or volume
- Spatial resolution: 10μm – to – 100μm
- Temporal resolution: 10ns – to – 100ns, ~10μs for PIV
- Data acquisition rate: 1Hz – to – 10kHz
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Motivations

Practical turbulent flames are exposed to external perturbations such as

- heat loss/gain,
- dilution by hot products,
- large bulk strain rate,
- Reactant stratification...

DLR Swirl Stratified Combustor
(Kutne et al., 2010)
Motivations

Turbulent flame stabilization often involves the mixing of reactants with products of combustion.

Motivations

Premixed Reactants

\( \phi_u \)

Hot Products of Combustion

\( \phi_b \)

Stratified Premixed Reactants (\( \phi_u \neq \phi_b \))

Recirculation zone

DLR Swirl Stratified Combustor (Kutne et al., 2010)
Turbulent Counterflow Burner

Large range of flow conditions:

- Bulk Strain Rate, \( K_{\text{bulk}} = 2U_u/d_{\text{nozzle}} \)
- Turbulent Reynolds Number, \( Re_t = u'l'/\nu \)
- Non-adiabaticity, \( T_b \neq T_{\text{ad}} \)
- Stratification, \( \phi_u \neq \phi_b \)

<table>
<thead>
<tr>
<th>( K_{\text{bulk}} )</th>
<th>1400/s – 2240/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Re_t )</td>
<td>470 - 1050</td>
</tr>
<tr>
<td>( T_b )</td>
<td>1500K – 2000K (1850K)</td>
</tr>
<tr>
<td>( \phi_u )</td>
<td>lean (0.7) to rich (1.2)</td>
</tr>
<tr>
<td>( \phi_b )</td>
<td>lean (0.7) to rich (1.2)</td>
</tr>
</tbody>
</table>

\[
K_d = \frac{t_{ch}}{t_{\eta}} = \left(\frac{v'\nu}{S_L}\right)^{3/2} \left(\frac{l_F}{l_l}\right)^{1/2} = O(1-10)
\]
Turbulent Flame Phenomenology

- Turbulent Premixed Reactants
- Gas Mixing Layer Interface (GMLI)
- Local Extinction
- Hot Product Stream
- \( T_b, \phi_b \)
- \( \Delta = 0 \)
- Turbulent Flame Front

Mathematical Expressions:
- \( \phi_u \)
- \( \Delta \)
- \( \Delta = 0 \)
Laminar Premixed Flame Structure

Flame chemistry involves many species and chemical reactions.

Two reaction-zone regions:

- **Fuel-consumption layer**: CH2O + OH → H2O + HCO correlates with peak of heat release rate (Najm *et al.*, 1998).
- **CO oxidation layer**: CO + OH → CO₂ + H dominant pathway for CO oxidation

Laser diagnostics are the only way to measure reaction rates in turbulent flames.
Reaction Rate Imaging

\[ \text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H} \]

Simultaneous recording of single-photon OH-LIF and two-photon CO-LIF.
Reaction Rate Imaging

**CO + OH → CO\(_2\) + H**

- Simultaneous recording of single-photon OH-LIF and two-photon CO-LIF.

- In combination, OH-LIF and CO-LIF signals yield a quantity proportional to the forward reaction rate (RR) for CO + OH → CO\(_2\) + H.

\[
RR = k(T)[CO][OH] \\
\propto f_{CO}(T)f_{OH}(T)[CO][OH]
\]

- \(f_{CO}\) and \(f_{OH}\) account for the temperature dependence of the CO-LIF and OH-LIF signals, respectively.

- \(f_{CO}(T)f_{OH}(T)\) proportionality to \(k(T)\) is estimated with a deviation of ±5% for the premixed flames studied.
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Turbulent Flame Front Structure

Flow Conditions:
• $K_{\text{bulk}} = 1400/\text{s}$
• $Re_t = 1050$
• $\phi_u = 0.8$
• $T_b = 1850\text{K}$
Turbulent Flame Front Structure

\[
\text{CH}_2\text{O} + \text{OH} \rightarrow \text{H}_2\text{O} + \text{HCO}
\]
Plot along line (1)

\[
\text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H}
\]
Plot along line (2)
• Turbulent flame structure is flamelet-like.

• We are going to monitor $RR_{\text{max}}$ as a function of $\Delta_f$ (distance from GMLI).
Effect of combustion products on

\[
CO + OH \rightarrow CO_2 + H
\]
Effect of combustion products on
\[ \text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H} \]

- \( \text{RR}_{\text{max}} \) scattering is due to turbulence – chemistry interaction.
Effect of combustion products on 
\( \text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H} \)

- \( \text{RR}_{\text{max}} \) scattering is due to turbulence – chemistry interaction.

- Two regions:
  - Near-field \((\Delta_f < 1.7\, \text{mm})\)
  - Far-field \((\Delta_f > 1.7\, \text{mm})\).

- Attenuation of burning rate in the near field.

- \( \text{RR}_{\text{max}} \) is unaffected by counterflowing products in the far-field.

Scatter plot of Peak \( \text{RR}_{\text{CO+OH}} \)
Decrease in reaction rates correlates with depletion of OH radicals in the vicinity of the GMLI.
Depletion of OH radicals near the GMLI is responsible for RR attenuation.

Both CO and CH$_2$O species remain produced by fuel pyrolysis/oxidation.
Part II – Summary

• Significant RR attenuation and localized extinctions occur along the GMLI.
• No extinction outside the zone of influence of counterflowing products.
• Zone of influence of combustion products: ~1.7 mm.
• Depletion of OH correlates with extinction
• OH LIF signal can be used as a marker of localized extinctions in these flames.
Part II – Impact

Peer-reviewed publications:


Collaborations with modeling groups:

- Joe Oefelein, Jackie H. Chen (Sandia National Labs)
- Steve B. Pope (Cornell University)
- Andreas M. Kempf (Univ. of Duisburg-Essen)
- CRAFT Tech - Combustion Research and Flow Technology, Inc.
- “Target burner” – TNF workshops
Dynamics of flame extinction/re-ignition - High Speed OH-LIF Image Sequence -

Flame edge propagation ($\varphi_u=1.0$)

Localized Ignition ($\varphi_u=0.5$)

Extinguished region

Ignition Spot
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Velocity Gradient Tensor

\[ \nabla \mathbf{v} = \begin{bmatrix} \partial u/\partial x & \partial u/\partial y & \partial u/\partial z \\ \partial v/\partial x & \partial v/\partial y & \partial v/\partial z \\ \partial w/\partial x & \partial w/\partial y & \partial w/\partial z \end{bmatrix} = \frac{1}{3} \Delta I_3 + \Omega + S \]

- **Divergence**: \[ \Delta = \nabla \cdot \mathbf{v} \] (unavailable in 2D)

- **Rate of Rotation**: \[ \Omega = \frac{1}{2} (\nabla \mathbf{v} - (\nabla \mathbf{v})^T) \] (biased in 2D)

- **Vorticity**: \[ \omega = \nabla \times \mathbf{v} \] (only out-of-plane component in 2D)

- **Rate of Strain**: \[ S = \frac{1}{2} (\nabla \mathbf{v} + (\nabla \mathbf{v})^T) \] (biased in 2D)
Particle Image Velocimetry (PIV) Principle
Planar PIV
2 velocity components in 2-D

\[ \mathbf{v} = u \mathbf{i} + v \mathbf{j} + w \mathbf{k} \]

\[ \nabla \mathbf{v} = \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} & \frac{\partial u}{\partial z} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} \\ \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} & \frac{\partial w}{\partial z} \end{bmatrix} \]
Particle Image Velocimetry Configurations

Stereoscopic PIV
3 velocity components in 2-D

\[ \mathbf{v} = u\mathbf{i} + v\mathbf{j} + w\mathbf{k} \]

\[ \nabla \mathbf{v} = \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} & \frac{\partial u}{\partial z} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} \\ \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} & \frac{\partial w}{\partial z} \end{bmatrix} \]
Particle Image Velocimetry Configurations

Tomographic PIV
3 velocity components in 3-D

\[ \mathbf{v} = u\hat{i} + v\hat{j} + w\hat{k} \]

\[ \nabla \mathbf{v} = \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} & \frac{\partial u}{\partial z} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} \\ \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} & \frac{\partial w}{\partial z} \end{bmatrix} \]
Experimental Apparatus

OH PLIF camera

OH PLIF high-speed dye laser

λ=283.3nm

TPIV high-speed laser

λ=532nm

4 TPIV cameras

X

Y

Z

50°
Principle of Tomographic PIV

Data Acquisition

Frame A

Frame B

Probe Volume Reconstruction

Δt

Volume Cross-Correlation
Compressive Strain Rate in Turbulent Partially-Premixed Jet Flames

Turbulent DME/Air Flame
\( \text{Re}_D \sim 29,300 \)

Strain rate isosurfaces for \( |s| = 15,000 \text{ s}^{-1} \)
Strain Rate Intermittency and Clustering

The level of localized extinctions in turbulent flames may well depend on the *agglomeration, occurrences and lifetime* of structures of very high strain rate.

**Objectives**

- Quantify the clustering and intermittency of elevated strain rate structures
- Evaluate the influence of combustion on the strain rate field

**Approach: high-speed tomographic PIV**

- Measure properties of strain rate in turbulent jets
- Compare the strain rate field in 3 turbulent jets of similar Reynolds numbers:
  - stable turbulent flame
  - unstable turbulent flame with frequent extinctions
  - turbulent air jet
## Flow Conditions

### Turbulent Flames

<table>
<thead>
<tr>
<th>Cases</th>
<th>Air Jet</th>
<th>Flame $C_{LP}$</th>
<th>“Sandia” Flame C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air/Fuel</td>
<td>N/A</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$V_{jet}$ (m/s)</td>
<td></td>
<td>27.5</td>
<td></td>
</tr>
<tr>
<td>$Re_{jet}$</td>
<td></td>
<td>13,500</td>
<td>13,000</td>
</tr>
<tr>
<td>$V_{pilot}$ (m/s)</td>
<td>0.0</td>
<td>1.8</td>
<td>6.8</td>
</tr>
</tbody>
</table>

“Sandia” Flame C – Ref.: Barlow and Frank, 1998
10 kHz OH PLIF Recordings of Flames $C$ and $C_{LP}$

Flame $C$:
Flame is stable with rare occurrence of localized extinctions

Flame $C_{LP}$:
High probability of localized extinction and intermittent blowoffs
Bursts of Strain Rate Structures

**Air Jet**

- Bursts of strain rate
- Spotty structures in the core of the *Air* jet
- Large elongated structures in the flames

**Flame $C_{LP}$**

- **Flame $C$**

Isosurfaces for $|s_{thrs}| = 7,000 \, s^{-1}$

- Flame $C_{LP}$ has features of both the *Air* jet and Flame $C$
How to quantify the agglomeration of strain rate structures?

- A *cluster* is a singly-connected group of voxels where $|s| > |s_{thrs}|$.

- $N_c(t) = \text{number of clusters in probe volume at an instant } t$. 

Turbulent Air Jet 

Isosurfaces for $|s_{thrs}| = 9,000 \text{ s}^{-1}$
Visualization of Strain Rate Clusters

$|s_{\text{thrs}}|$ (x 1,000/s)

6 7 8 9 10 11 12

Turbulent Air Jet

$N_c$ varies with both time and $|s_{\text{thrs}}|$.
Visualization of Strain Rate Clusters

$|s_{thrs}| \times 1,000/s$

Turbulent Air Jet

Turbulent Flame C
Bursts of Strain Rate Structures

- Intermittent appearances of high strain rate structures.
Bursts of Strain Rate Structures

- Intermittent appearances of high strain rate structures.
- Strain rate field is less connected in flame $C$ than in $Air$. 
Temporal Intermittency

\( t_i = \) time interval between appearances of clusters

- \( \langle t_i \rangle \sim 0 \text{ ms for } |s_{\text{hrs}}| < 5|s|' \)
- Structures for \( |s_{\text{hrs}}| \) increasing above \( 5|s|' \) become rapidly intermittent.
Temporal Intermittency

\( t_i = \text{time interval between appearances of clusters} \)

- \( \langle t_i \rangle \approx 0 \text{ ms for } |s_{\text{thr}}| < 5|s|' \)
- Structures for \( |s_{\text{thr}}| \) increasing above 5|s|’ become rapidly intermittent.
- Combustion has negligible effect on temporal intermittency.
Part III – Summary

• High-speed tomographic PIV has the potential to unveil new information on the dynamics of turbulent flames at both the fundamental and practical levels.

• All the components of the gradient tensors are determined (vorticity, strain rate, invariants of the gradient tensor).

• Reduced uncertainty of out-of-plane motion and bias of 2D measurements in turbulent flows

• Identification and tracking of coherent structures and their interaction with flame fronts.
Part III – Impact

1st Demonstration of high-speed, tomographic PIV in reactive flows

- 8th US National Combustion Meeting, 2013
- Gordon Research Conference, 2013
- 35th International Symposium on Combustion, 2014

Peer-reviewed publications:


Collaborations:

- Nicholas Ouellette (Yale University)
- Dula Parkinson (Lawrence-Berkeley National Labs)
- Adam M. Steinberg (University of Toronto)
Concluding Remarks

• Combustion will continue to provide a major portion of the world energy mix in the future.

• Fundamental understanding of combustion is necessary to develop future combustion technologies.

• The improvement of laser and imaging diagnostics make the study of advanced combustion processes possible.