Plasma-Assisted Combustion Studies at AFRL

MURI Kickoff Meeting
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*With contributions from S. Adams, M. Gundersen et al., B. Ganguly & T. Lee
Areas where plasmas and E-fields can have an influence

- Enhance reaction rate & flamespeed
  - Important for high-speed combustors (& other combustors too):
    - Ignition, from cold state especially & with liquid fuel
    - Steady operation, through flamespeed enhancement and flameholding
  - Potentially important for lean, gas-turbine (powerplant) operation
    - Might one also mitigate/influence acoustic fluctuations?
    - Potential for uniform performance with nonuniform fuel source

- Enhance fuel-air mixing & penetration
  - Potential alternative to intrusive mechanisms (struts/pylons)
  - Potential for dynamic control of penetration/mixing
  - Potential for creating recirculation region for flameholding

- Boundary-layer & surface interactions
  - Trip boundary layer; hold shock
Overview

Fun Facts on US Energy Consumption

• HC sources provide ~85% of nation’s energy
  ▪ 97% for transportation

• Transportation’s consumption about 28% of total
  ▪ ≈ 1 million gallons/minute

• Quads = quadrillion ($10^{15}$) BTU
  ≈ $10^{18}$ J

See also Report of the Basic Energy Sciences Workshop on Basic Research Needs for Clean and Efficient Combustion of 21st Century Transportation Fuels
Overview

Plasma/E-field Effects on Ignition & Flame Behavior

μ-W E-field Effects on Flame Propagation
Stockman, Miles, Zaidi (Princeton), Ryan

Diagnostics of Plasma Enhanced Flames
Lee (MSU)

Planar FRS Thermometry with pulsed μ-W Source

Direct coupled plasma torch: flame OH vs. μ-wave power:

μ-W E-field Effects on Flame Propagation

Plasma-assisted Ignition
Cathey, Gundersen, Wang, Cain (USC), Ryan

Combustion Chamber

Effects of Gliding Arc on Flame Chemistry
Ombrello, Ju (Princeton), Gutsol, Fridman, (Drexel)

Ignition event
Enhancement of Flamespeed through Plasma Activation*

- **Goal:** Study flame propagation increase with plasma-excited oxidizer
- Integrate plasma source with custom *Hencken* burner
  - Gases mix at burner exit
  - Quartz coating of metal surfaces
- Operate at low P
  - Reduced reaction rates
  - Allow mixing of fuel & oxidizer upstream of flame

*Ombrello, Ju, Sun, Carter, Brown, Katta
Enhancement of Flamespeed through Plasma Activation*

- Decrease chamber $P$ to lift flame from surface
  - Flame has fully premixed character at low $P$
- Apply diagnostics to characterize plasma species, $T$ & $V$
  - Species of interest: $O_3$, $O_2(a^1\Delta_g)$, $O_2(b^1\Sigma_g)$, O, O($^1D$)

*Ombrello, Ju, Sun, Carter, Brown, Katta
Enhancement of Flamespeed through Plasma Activation*

• Use low-\( P \) lifted jet flame: lift-off height \( \Delta H_L \) sensitive to flamespeed, \( S_L \)
• Characterize \( S_L \) increase with \( \Delta H_L \) measurement
• Produce & quantify \( O_3 \) and \( O_2(a^1\Delta_g) \)
  • measure \( \Delta H_L \)

*Ombrello, Ju, Won, Williams
Enhancement of Flamespeed through Plasma Activation*

- Graph shows isolated effect of $\text{O}_3$ and $\text{O}_2(a^1\Delta_g)$
  - $P = 27$ or 51 Torr
- Concentrations of $\text{O}_2(a^1\Delta_g)$ as large as $\sim X = 0.6\%$
- Conversion of $\Delta H_L$ to $S_L$ requires additional measurements and/or modeling
- Work with Hencken flame will be follow-on effort

*Ombrello, Ju, Won, Williams
**Goal:** Determine physical mechanism, primarily for transient plasma ignition

- *What is role of humidity:* $X_{H2O}$ affects detonation wave speed in PDE but not $t_{ign}$
- Measure $X_{OH}$ and $X_{O3}$ vs. $X_{H2O}$ in air
  - OH from PLIF & O$_3$ from absorption
  - Need to sample along anode, especially since flame originates from anode surface
- Highly desirable: O-atom distribution
  - Also CH$_3$ and CH$_2$O

*Combustion chamber*
- Variable anode lengths & materials
- Optical access: windowed-slits (not shown) & end-flange window

*Singleton, Pendleton, Gundersen (USC), Stockman, Carter, Brown*
Ignition Enhancement with TP*

• Effect of anode length & comparison to spark plug (2 cm from back wall)
  ▪ Significant reduction in $t_{ign}$ even with 3-mm length protrusion
• Flame propagates from anode to wall
  ▪ Flame initiation and propagation approx. uniform along perimeter & length

*Singleton, Pendleton, Gundersen (USC), Stockman, Carter, Brown

stoichiometric $\text{C}_2\text{H}_4$-air
$P = 1$ atm
$E_{pulse} = 550$ mJ (75 kV)
$t_{pulse} \approx 100$ ns
Ignition Enhancement with TP*

- Camera looking down into chamber
- Continuous flow of moist air
  - 1-Hz pulse frequency
  - $X_{\text{H}_2\text{O}}$ measured with TDLAS
- PLIF of OH: Peak signals $\sim 10^{15}$ cm$^{-3}$

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*Singleton, Pendleton, Gundersen (USC), Stockman, Carter, Brown*
Ignition Enhancement with TP*

- UV LED beam positioned over washer
  - Undetectable $X_{O_3}$ with normal config.
- 1-ms LED pulse synched to TPI pulse
  - 200 o-scope waveforms recorded
  - Presumably, $X_{O_3}$ distribution nonuniform

*Singleton, Pendleton, Gundersen (USC), Stockman, Carter, Brown
Resonant Laser Induced Breakdown for Fuel-Air Ignition*

**Goal:** Investigate effectiveness of low-energy REMPI laser pulse to control spatial & temporal behavior of ignition spark in air crossflow

**Approach:**
- Apply potential (below breakdown value)
- Focus UV laser pulse at REMPI transition & ionize channel between gap

*To be presented at ASM-2010*

*S. Adams, J. Miles, and A. Laber (AFRL/RZPE)*
Resonant Laser Induced Breakdown for Fuel-Air Ignition*

• Sample photo of a laser induced arc
  ▪ Main arc follows laser path
  ▪ Secondary arcs & plasma glow occur after main arc; result of leakage current as capacitor recharges

*S. Adams, J. Miles, and A. Laber (AFRL/RZPE)
• **Goal:** Study effect of pulsed plasma on a C$_3$H$_8$/air Bunsen flame
• Quantify with phase-averaged Raman scattering and CH chemiluminescence & time-resolved OH chemiluminescence

*Non-thermal Plasmas to Modify Combustion Kinetics*

*B. Ganguly, J. Schmidt (AFRL/RZPE)*
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Non-thermal Plasmas to Modify Combustion Kinetics*

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*V-I Characteristics

Electrode

Raman probe beam

Voltage applied; plasma formed

Bunsen Burner

C₃H₈-air

*B. Ganguly, J. Schmidt (AFRL/RZPE)
Non-thermal Plasmas to Modify Combustion Kinetics*

- 200 Hz rep rate pulsed discharge
  - Few mJ of energy input; significant perturbation
- Phase-locked measurement of $T$ and CH chemiluminescence
  - Finite response of flame; some recovery before next pulse

*B. Ganguly, J. Schmidt (AFRL/RZPE)
Three final thoughts:

• Understanding the role of electric fields, plasma & plasma-derived species in initiating and sustaining combustion of critical importance to more effective use
  ▪ Potential for impacting many areas related to use of hydrocarbons

• We (AFRL) welcome collaborations!
  ▪ Many already with MURI team members
  ▪ We’ll even do some crazy stuff

• Good luck on efforts!