AFRL Research in Plasma-Assisted Combustion

23 October 2013

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With input from Bish Ganguly and Steve Adams

Aerospace Systems Directorate
Air Force Research Laboratory
Overview
Research within My Division

*Focus on hypersonic flight: scalability, performance, operability*

**Research Includes…**

- *Extramural* programs such as
  - SJ Engine Demonstrator, X-51
  - HIFiRE: US-Aus. flight-test program

- *In-house* programs on
  - *Scramjet propulsion*
  - Non-equilibrium flows
  - Diagnostics for scramjet controls
  - Boundary-layer transition
  - Structural sciences for hypersonic vehicles
  - Computational sciences for hypersonic flight

**X-51A – Flight 4: May 1, 2013**
**Achieving M-5.1 flight**
**Overview**

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**HIFiRE-5 Vehicle**
Launched 23 April 2012

transition section
Orion
payload
can
S-30
Overview

• A few highlights not covered today (in lovely quad-chart fashion), showing broad focus of basic research program

• Specific Focus
  ▪ Bish Ganguly’s research: *Role of Sub-Breakdown E-Fields on flames*
  ▪ Steve Adams’ research: *REMPI-Assisted Gas Breakdown*
  ▪ Our work: *Flame Speed Enhancement (by O₃)*
Overview
Highlights of Basic Research Program

**RANS-LES Simulations of Cavity Flowfield**

- **x = 0.2**
- **3.0**
- **5.4 cm**

**Peterson (NRC); Tuttle (NRL); Hagenmaier**

Comparison with *Tuttle*-PIV dataset (nonreacting shown here)

**Laser-Induced Breakdown Spectroscopy**

- **Do (Notre Dame)**

Measurements in reacting and nonreacting flows; now applied in cavity flowfield

**Inlet Distortion Effects on Cavity Flowfield**

**Goyne, Kirik (UVa); Peltier (NRC); Hagenmaier**

**Mean axial velocity**

- **Shock on cavity**

**kHz Imaging for Cavity Flameholding**

**Hammack, Lee (UI); Hsu**

Setup for OH PLIF

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**Diagram:**

- Test Burner
- Control Room
- 283 nm Pulse Generator
- Slot Injector
- Wind Tunnel
- Cavity
- IRO Controller
- Pulse Generator
- High-speed Nd:YAG
- Tunable Dye Laser
- 532 nm
- 10 kHz CMOS Camera
Overview
Highlights of Basic Research Program

Digital Holography for Aerated Sprays

Olinger, Sallam (OSU)
Lin

Drop diameter (mm) in crossflow

Study of Efficacy of Tomo-PIV in Flames

Boxx, Meier (DLR)

Application to lifted jet flame

OH & T in a Repetitively Pulsed Ns Discharge

Yin, Montello, Adamovich, Lempert (OSU)

CH₄-air

Konnov mech.

Measurements vs. kinetics calcs.

Supercritical C₂H₄ Injection: Drop Sizing

Zuo (ANL); Lin

Small-angle x-ray scatt.
(SAXS)
Objective: Study dynamics of laminar flame with applied sub-breakdown, pulsed E-field

Payoff: Potential for improved flameholding/efficiency in AF combustors

Progress:
- Dynamics studied with kHz-rate imaging (both chemiluminescence imaging and particle image velocimetry, PIV)
  - Relatively small amount of electrical power can cause an otherwise steady, laminar flame to highly unsteady behavior
- Flame thickness quantified, via OH/acetone planar laser-induced fluorescence, showing substantial increase
- Flame recovery mechanism after (applied voltage) is fluidic in nature
Role of Sub-Breakdown E-Fields

Background

• Direct experimental evidence & robust modeling of exact mechanism by which sub-breakdown E-field modifies flame fluidics/kinetics lacking:
  ▪ Liftoff and blowoff limits of flames in AC/DC field by Kim et al.
  ▪ Relationship between burning velocity and imposed current through thermal power release and/or direct chemical reaction rate for DC fields by van den Boom et al.
  ▪ Electric field control of small capillary diffusion flames has been explored by Borgatelli et al.

• Numerical model by Starikovskii et al. suggests that weak E-fields influence areas with a charged particle density gradient

Ganguly et al.
Typical Voltage and Current

- 30 ms in duration @ 10Hz
- 3 kV, 200µA, 0.25 Watt (max)

Ganguly et al.
Image sequences exemplify flame fluctuations and repeatability of process.
Role of Sub-Breakdown E-Fields

**Frequency Spectrum**

- FFT of recorded current traces to show the dominant frequencies of the induced perturbation process
  - Current used due to high sensitivity to conductivity and therefore overall flame shape (compared to OH/OH*/broadband emission)

![Frequency Spectrum Graph](image-url)
Role of Sub-Breakdown E-Fields

Experimental Setup: PLIF

**OH excitation**
Q₁(8), A-X(1,0) transition; λ = 283.55 nm; 5 mJ/pulse

**Acetone excitation**
λ = 266 nm; 10 mJ/pulse
Algorithm finds gradients of $S_{\text{LIF}}$

Reaction zone thickness ($\delta$ between gradient locations) normal to local flame shape

Iterative process finds reaction zone to be 0.6 to 0.8 mm for unperturbed laminar flame

- much larger for perturbed flame
Objectives:
- Investigate Resonance-Enhanced Multi-Photon Ionization, REMPI, assisted laser gas breakdown
- Reduce breakdown voltage along laser path
- Guide laser and spark into fuel rich volume
- Determine effects of fiber optic coupling

Payoff:
- Potential for ignition away from walls/surfaces
  - Quasi-volumetric (or at least 1-D) ignition
- Potential for increased reliability of relight for engine flame-out

Progress:
- Ignition demonstrated in simple flows
- Resonant laser is advantageous in inducing air breakdown
- Photoionization of fuel closes the gap (for ignition) between resonant and off-resonant laser performance
• Resonance-enhanced multi-photon ionization (REMPI) with UV laser pulse creates *pre-ionized* path

• High voltage applied: *spark is guided along pre-ionized path*

• High reliability of ignition within fuel-rich region
  ▪ Ignition away from walls

*Adams et al.*
• Laser sent through aperture in high voltage electrode

• Breakdown and arc follow laser pulse along pre-ionized path

• Arc-path follows laser *pre-ionization* path, even when laser is angled compared to applied electric field
• Use Radar-REMPI (in air) to characterize induced electron concentration vs. $\lambda_{\text{laser}}$

• Use $\lambda_{\text{laser}} = 287.5$ nm ($\sim$ max e concentration) for resonant & 266 nm for nonresonant comparison
  
  • resonant threshold is $\sim$1/3 of theoretical air self-breakdown

*Wu et al., Chem Phys Lett 2011
REMPI-Assisted Gas Breakdown
Resonant vs. Nonresonant UV Excitation

• Now compare spark/ignition with laser resonance ($\lambda_{\text{laser}} = 287.5$ nm) vs. nonresonance ($\lambda_{\text{laser}} = 266$ nm) in air/C$_3$H$_8$-air

- **Much** lower E-field threshold to create spark
- **Slightly** lower threshold for ignition
- Fuel tends to enhance non-resonant breakdown effects
- What about effects with fuel sprays?

**Adams et al.**
Objective: Study effect of plasma-derived species on flame speed enhancement

Payoff: Increased flame propagation speeds in AF combustors, particularly high-speed combustors
  • Potentially more robust flame stabilization & improved ignitability

Progress:
  • Characterization of O₃ enhancement (flame speed) for C₂H₄ flames
    ▪ working on measurements with liquid fuels
  • Initial tests within cavity flameholder in M-2 crossflow: infer flame speed enhancement during ignition transient
Flame Speed Enhancement by $O_3$

Past Efforts: $O_2(a^1\Delta_g)$ flame speed enhancement

Oxidizer is Only $O_2(a^1\Delta_g)$ in $O_2$/Ar/NO

**Dependence of enhancement on $\phi$, following other predictions:**

- CH$_4$-air, Starik *et al.* (Combust. Flame 2010)

**Plasma Discharge**

- $O_2$/Ar
- NO

**Hencken Burner**

- Fuel
- Oxidizer

**Graph:**

- Change in flame liftoff height = change in flame speed

On the order of 1000 ppm $O_2(a^1\Delta_g)$
• Used alumina particles for particle image velocimetry (PIV)
  ▪ Confirmed that particles do not quench O₃

• Measured flame speeds and enhancement with high accuracy vs. stretch rate
Flame Speed Enhancement by O$_3$

Measurement vs. Computational Results

**Measurement**

- **Conditions:**
  - Equivalence ratio $\Phi = 1$
  - O$_3$ concentration $X = 12,500$ ppm (in air mix)
Flame Speed Enhancement by O$_3$

Flame Speed vs. Stretch Rate

Primary O$_3$ Reactions

$O_3 + H \rightarrow OH + O_2$

$O_3 + N_2 \rightarrow O + O_2 + N_2$

Sensitivity Analysis

inhibits $S_L$

enhances $S_L$
Flame Speed Enhancement by O$_3$
Trend vs. Stretch Rate

Flame speed enhancement increases with increasing stretch rate

Model over-predicts absolute flame speeds and enhancement, but trend is correct

Doubling stretch rate
Doubling of flame speed enhancement
Flame Speed Enhancement by O₃

Why Does Flame Speed Increase?

- Low velocity/stretch rate
- High velocity/stretch rate

Decreasing flame thickness

Enhancement of flame speed follows trend of change in flame thickness
What’s Next?

Why not try to enhance ignition in the flameholder of a highspeed crossflow?
Flame Speed Enhancement by \( O_3 \)

Effect of \( O_3 \) in Cavity – in M-2 Crossflow

\( O_3 \) absorption imaging: integrated view of concentration across cavity

M-2 Crossflow

\[ P_{cavity} = 65 \text{ kPa}; \ T_{cavity} = 550 \text{ K} \]

Absorption cross section


![Absorption cross section graph](image)

- Absorption cross-section formula: \[ y = -5.54E-21x + 1.29E-17 \]
Flame Speed Enhancement by O₃

Effect of O₃ in Cavity – in M-2 Crossflow

**RC-19 Optical Setup:** 100-kHz chemi imaging + O₃ absorption imaging
Flame Speed Enhancement by $O_3$
Effect of $O_3$ in Cavity – in $M$-2 Crossflow

RC-19 Windtunnel Facility
Flame Speed Enhancement by $O_3$

Effect of $O_3$ in Cavity – in $M$-2 Crossflow

### Average $O_3$ Concentration

<table>
<thead>
<tr>
<th>Less</th>
<th>More</th>
</tr>
</thead>
</table>

**Injection from Middle Row in Cavity Ramp**

- $M=2$
- $O_2/N_2/O_3$
- 70 slpm
- 260 ppm
- 189 ppm
- 322 ppm

**Injection from Bottom Row in Cavity Ramp**

- $M=2$
- $O_2/N_2/O_3$
- 70 slpm
- 217 ppm
- 277 ppm
- 432 ppm

### Upstream $X_{O_3}$

- $X_{O_3} = 3,850$ ppm
- $X_{O_3} = 13,100$ ppm
Flame Speed Enhancement by O₃
Effect of O₃ in Cavity – in M-2 Crossflow

• Basics:
  ▪ Spark ignition from two igniters
  ▪ C₂H₄ and O₃ from separate ports on ramp face (as shown above)
  ▪ P₀ = 4.8 atm; T₀ = 600 K
  ▪ Image ignition at 100 kHz!
    ➢ Top & side views

• Any difference? None that we can tell (based on several tests)
  ▪ Need much more O₃ in cavity to enhance flame speed
That’s all Folks
Backup
Evidence from bench-top experiments indicate that flame speed should be enhanced in a turbulent flow and also possibly at higher pressures.
Role of Sub-Breakdown E-Fields

Ionic Wind / Body Force Comparison

• If a cathode sheath forms, $n_i >> n_e$. We can rewrite for the ionic wind-induced body force on the flame across the cathode sheath neglecting contributions from electrons:

$$f = E \cdot e \cdot n_i = E \cdot \frac{I}{v_d}$$

where $f = \text{body force per area}$, $E = \text{electric field strength}$, $e = \text{charge}$, $n_i = \text{total number of ions}$, $I$ is the current, and $v_d = \text{ion drift velocity}$

• Provides a body force per unit area of about 500 N/m$^2$ localized along reaction zone (200 $\mu$m$^+$) near cathode

• Suggests that disturbances seen near burner head may be due to collisional interactions between ions and neutral gas

• Magnitude of effects would be proportional to the electric field strength, ion current density, and applied pulse width time
Emission spectra in air during initial arc with $\lambda_{\text{laser}} = 287.5$ nm

Emission spectra in $\text{C}_3\text{H}_8$-air during initial arc with $\lambda_{\text{laser}} = 266$ nm: breakdown of fuel indicated by $\text{C}_2$ and CN bands
Characterization of Burner Platform with CH$_4$-Air

PIV and 2-D Simulations

- Flame speed can be quantified with PIV
  - Change in flame liftoff height also gives good indication
- Good comparison between measurements and simulations, but absolute flamespeed slightly off measured value
Silica Coated Hencken Burner For $O_2(a^1\Delta_g)$ Flame Studies

All Flow Surfaces of Hencken Burner Coated With Silica

1000s ppm of $O_2(a^1\Delta_g)$ at Exit of Coated Burner When Using 20% $O_2$ in Ar with NO Injection

Absorption Techniques
- Tunable Diode Laser Absorption Spectroscopy (TDLAS)
- Intracavity Laser Absorption Spectroscopy (ICLAS)
- Integrated Cavity Output Spectroscopy (ICOS)

Emission Techniques
- 634 nm and 1268 nm

Spatially Averaged Can Require Knowledge of Quenching Species and Their Kinetics

But What About a More Spatially Resolved Measurement Above Burner Surface and Upstream of Flame?
Radar REMPI Measurements of $O_2(a^1\Delta_g)$

Two photon resonance with the $O_2$ transition of $d^1\Pi_g \leftarrow a^1\Delta_g$ and the subsequent one photon ionization

Detection Threshold/Sensitivity
ICOS $\approx$ Radar REMPI
$\sim 1 \times 10^{14}$ molecules/cm$^3$

*Wu, Zhang, Ombrello (AIAA ASM 2013)
Where Does This Bring Us With Regard to $O_2(a^1\Delta_g)$?

• New Burner System Provides a Good Platform to Interrogate Enhancement by Specific Plasma-Produced Species

• Serves Purpose to Validate Kinetic Models that are Showing Significant Enhancement But Require Experimental Validation

• New Diagnostic Techniques Being Developed for Spatially Resolved Measurements

• For $O_2(a^1\Delta_g)$, Increased Flame Speed Enhancement for Off-Stoichiometric Equivalence Ratios Confirmed, But Quantification Still Necessary

**Besides $O_2(a^1\Delta_g)$**

**The Other “Low Hanging Fruit”...$O_3$**

Can Be Produced, Measured, and Transported Easily With Minimal Special Care and Can Yield Significant Enhancement
If Flame Thickness Dictates the Amount of Enhancement then...
The Enhancement Should Increase with an Increase in Pressure

Flame Thickness \( \delta \sim \frac{1}{\rho S_L} \)