Atmospheric Pressure Plasma Based Flame Control and Diagnostics

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Supported by AFOSR MURI

Fundamental mechanisms, predictive modeling, and novel aerospace applications of plasma assisted combustion.
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Significant MURI Accomplishments

- Single pulse (10 nsec) quantitative Filtered Rayleigh imaging of temperature fields
- Pulsed microwave control of flames
  - Greater than 20% Flame speed enhancement
    - Coupling efficiency greater than 50%
    - < 10% of the flame power
  - Factor of two reduction in equivalence ratio limit.
- Radar REMPI measurement of NO and radicals in flames.
- Pulsed microwave coupling to laser pre ionization
  - Distributed ignition
- Femtosecond Laser Electronic Excitation Tagging (FLEET) for velocity and temperature profiles
Filtered Rayleigh Scattering

for Quantitative Temperature Imaging

at constant pressure
Rayleigh Signal

\[ P_{DET} = \eta I_I N V \int_{\Delta \Omega} \frac{\partial \sigma_{ss}}{\partial \Omega} d\Omega \]

- \( N \) = the number of dipoles per unit volume
- \( V \) = the illuminated volume of the sample
- \( \Delta \Omega \) = the collection solid angle
- \( \eta \) = the detector and optical system efficiency
- \( I_I \) = the incident laser intensity
Rayleigh Scattering Interactions leading to line broadening

- \( Y = \text{scattering length} / \text{mean free path} \)

**Thermal motion and acoustic waves are in all directions.**

Rayleigh scattering is sensitive to motion along the bisector of the angle between the source and detector.

\[
|k_1 - k_2| = |K| = \frac{2\pi}{\Lambda}
\]

\[
\Lambda_{\text{max}} = \frac{\lambda_{\text{laser}}}{2}
\]
If $Y < 1$, then in the Knudsen Regime – no collective effects. The Rayleigh line is Gaussian in this regime – low density, high temperature.

If $Y > 1$, then in the hydrodynamic regime – collective effects dominate - high density, low temperature.
Modeled Rayleigh-Brillouin Line Broadening (Pan S7)

Narrow-linewidth molecular iodine filter to block background laser light. Eliminates particle and surface scattering.

Assuming constant pressure (one atmosphere for flame studies) and constant species (nitrogen is a good approximation) the signal coming through the filter is only a function of temperature.

Calibrate using the ratio of the signal from the high temperature to that of air or nitrogen at room temperature (often in the same frame)
FRS sensitivity to laser wavelength
• At high temperature the slopes of the calibration curves are almost identical, leading to robust measurements of temperature differences above \( \sim 1000K \).
• Provides a single pulse (10 nsec) image of the temperature field.
FRS Thermometry Calibration

- Research Technologies RD1x1 Hencken Burner
- With line scattering can obtain Rayleigh signal-to-background > 20:1
- Normalize flame Rayleigh scattering to that of N₂ co-flow
- Accuracy and precision better than 5%

H₂/Air Hencken Burner Measurements with averaged FRS

Calibration

\[
\text{Normalized FRS Signal} = \frac{S_{\text{hot}}}{S_{\text{cold}}}
\]

![Graph showing the relationship between gas temperature and normalized FRS signal.](image)
Microwave interactions with flames
Couples to natural ionization in the flame
CH + O $\rightarrow$ HCO$^{++}$ electron
Microwave coupled Laminar Flame Set up

High Q Microwave resonator cavity with flat plate stabilized flame

Reflected power measurement of power deposition into flame
Uniform velocity at exit $v_e < 100 \text{cm/s}$
- Large $L/D \sim 3.8$ leads to low strain rates
- Flame stabilized by aerodynamic strain rate
- Cavity limited optical access
  - ‘Meshed’ windows
  - Narrow laser slots
Flame Speed Enhancement with cw microwaves

CH₄/Air

\[ v_{\text{ext}} = 85 \text{ cm/s} \quad \phi = 0.78 \]

0 Watts
\[ S_{\text{ref}} = 33.7 \text{ cm/s} \]

700 Watts
\[ S_{\text{ref}} = 40.6 \text{ cm/s} \]

1200 Watts
\[ S_{\text{ref}} = 45.3 \text{ cm/s} \]
**Flame Speed Enhancement**

CH₄/Air laminar stagnation flame speed enhancement with 1.3kW cw-microwave radiation

- 2% error in DPIV measurement propagates to ~4% error in flame speed enhancement percentage
- Peaking at $\phi=0.75$ might be an outcome of experimental procedure

~25% enhancement seen with 1.3 kW magnetron, ~10-20W absorbed power
The OH level is increased and the OH decay rate away from the flame front is reduced
FRS Thermometry

- $U_{\text{exit}} \sim 60 \text{ cm/s}$
- $D_{\text{exit}} = 0.6 \text{ cm}$
- $\varphi = 0.6 - 0.9$
- 532 nm, injection seeded Nd:YAG for tunable, narrow linewidth
- 95 K increase in post flame temperature
- Temperature rise is just after flame sheet
  - Implies microwave energy deposition is in flame sheet
Microwave interactions with flames
Using microsecond duration pulsed microwaves
Comparison of Flame Speed enhancement CW and pulsed microwaves

Princeton University
Flame Speed Enhancement with Pulsed Microwaves

Pulsed 1 kHz, 5 mj/ pulse = 50 Watts

Reduction in average power by a factor of 26

CW – 1.3 kW
Deposition localized near flame front/reaction zone
- 25 mJ, 1 us pulse gives 200 K rise
- 50 mJ, 2 us pulse gives 350 K rise
- With 30 Watts average pulsed power the flame speed is enhanced as much as with a 1.3 kW continuous microwave
- Coupling efficiency is ~60%.
High efficiency coupling of pulsed microwaves
Further enhanced by seeding the fuel with sodium.
Microwave/laser measurement configuration. The focused laser creates a small region of ionization and the microwaves are scattered from that region into the microwave detector.
NO spectrum via 1+1 Radar REMPI

$A^2\Sigma^+ \leftarrow X^2\Pi$ molecular electronic transition

- 1+1 REMPI of NO with 226 nm laser
- 100 GHz probes the plasma.
- The mixer output is proportional to the scattering amplitude, hence electron density
- Linear signal from ppm to ppb
- Sub-nanosecond temporal resolution
Nitric Oxide production with pulsed microwaves using Radar REMPI

NO measured in the post flame product gas and averaged over time
Increase of NO with microwave power

Predicted nitric oxide increase as a function of temperature over $\phi = 0.8$ equilibrium.
- Good signal linearity with Xe concentration observed at 20 mm above the burner surface, where atomic O concentrations are expected to approach equilibrium values
- Xe detection limit in a flame $\sim 130$ ppm ($10^{14} - 10^{15}$ cm$^{-3}$)
Inferred Atomic O Concentrations Using Xe Calibration

- Reasonable agreement close to stoichiometric conditions but overshoot in the fuel rich and lean regime
Schlieren imaging of Microwave coupling for laser ignition and preionization studies
Enhanced kernel growth rate following laser designated, pulsed microwave ignition.

Laser-MW ignition with additional MW pulses at ms intervals.
Multi-point ignition

- 2 laser ionization regions in one standing mode
  maximumSingle 75 mJ, 3 μs MW pulse

Reduction of lean limit with 1 Khz microwave pulses
Air heating of 600 μJ femtosecond seed by Subcritical Microwave

LASER

0 μs  0.5 μs  1 μs  2 μs  4 μs  6 μs  10 μs

LASER + 50 mJ MW

Weak shock (M = 1)
Line ignition using microwave coupling to fsec laser preionization line
Femtosecond Laser Electronic Excitation Tagging (FLEET)

For Velocity and Temperature Profile Imaging
Nitrogen Emission

Prompt Emission From Molecular nitrogen

Recombination Of atomic nitrogen

800 nm = 1.55 eV
Each progression includes about 10 line displacement shots due to the long lifetime in pure N2

- Measured centerline velocity ~150m/s
FLEET in Supersonic flow
FLEET measurements of Pulse Detonation Engine at AFRL
The rotational temperature of a gas is closely linked to translational temperature.

The rotational temperature equilibrates with the translational temperature within a few collisions – less than a nanosecond in atmospheric pressure air.

Second positive UV emission is used – prompt emission.

By measuring the distribution of rotational states, we extract the instantaneous temperature profile.
Nitrogen Second Positive Spectral Variation with Temperature

![Graph showing spectral variation with temperature](image-url)
Temperature profiles can be measured, since images capture displacement on one axis and spectrum on the other.

Profile measurements based on ratio between systems show good agreement with thermocouple measurements.

Temperatures calculated based on rotational spectra are slightly warmer than measured, perhaps due to laser heating of focal region.
FLEET: Hyperspectral imaging

Spectra over 4mm of filament

Wavelength (nm)
Summary

- Control of atmospheric pressure flames with pulsed microwave energy
  - High efficiency coupling (>50%)
  - Small percentage of flame power (~3% to 10%)
  - Flame speed enhancement (>20%)
  - Extension of lean limit (factor of two)
  - Distributed ignition

- Development of new diagnostics
  - Quantitative Temperature images with Filtered Rayleigh Scattering
  - Measurement of NO and radicals with Radar REMPI
  - Imaging velocity and temperature profiles with FLEET
Thank you!

Questions?