Plasma Excited Oxygen Effects on Combustion and Perspectives on Applications to High-Speed Propulsion

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Innovative Scientific Solutions
Focus on Scramjet Scaling, Performance, and Operability

Extramural research, including:
- Scramjet Engine Demonstrator, X-51
- HIFiRE: U.S.-Australian flight-test program

Inhouse research, including
- Ignition and Flameholding in high-speed flow
- Flowfield characterization
- Sub-atmospheric pressure flame studies
- Flame speed, stabilization, and detailed structure
- Kinetic mechanism validation
- Plasma-assisted combustion
- Plasma system design and optimization
- Plasma species measurement
- Mechanism development

X-51 Vehicle

Mach 6-8 HiFIRE-2 Vehicle
Hypersonics: Stair-Step Approach Building Upon Prior Success

Development of New Technology for the Next Generation of High-Speed Flight

- **Ramjets**
- **Small Scramjets**
- **Medium Scramjets**
- **Large Hypersonic Missiles and CCE’s**
- Operationally Responsive Spacelift (Robust and Responsive)
- X-51 Program

- Hypersonic Missiles/Small Launch Systems
- Hypersonic Missiles (Time-Critical Targets)
- Large Hypersonic Missiles Small Launch Systems

Development of New Technology for the Next Generation of High-Speed Flight
Crucial Areas for Success

**Cold Start/Ignition**
cold combustor surfaces, sub-atmospheric pressure, and limited residence time

**Flame Stabilization**
anchoring/stabilizing a flame in Mach 2-4

**Complete Combustion/Heat Release**
limited time for complete chemical heat release and therefore conversion to thrust

Developing techniques to enhance fuel reactivity and heat release are extremely important for the success of high-speed propulsion systems such as scramjets

Scaling Up to Larger Systems:

What about 100 lbm/s or even 1000 lbm/s?
Dynamics of an Ignition Process in High-Speed Flow

High Speed Imaging Captured at 100,000 fps (10 μs per frame)
Slowed 10,000 times

Shadowgraph

Chemiluminescence

M=2 Spark Igniter

Fuel
Motivation

Restrictive Combustion Environments  
\textit{e.g.} High-Speed Air-Breathing Propulsion Systems

\textbf{Short Residence Time for Chemical Reactive Processes}  
Specifically Ignition, Flame Stabilization, Flame Propagation, Extinction, and Flammability Limits

\textbf{Necessitates Development of Techniques for}  
\textbf{Enhancing the Rate of Chemical Heat Release}

\textbf{The Application of Plasma}  
Providing Radicals, Intermediate Species, Excited Species, Ions, Electrons, and Elevated Temperatures

\textbf{Understand the Key Species and Mechanisms of Enhancement}  
Allowing for Optimization and Practical Application

\textbf{Develop Simplified and Decoupled Plasma-Assisted Combustion Platforms for Detailed Studies}
Taking a Selective Approach

Building Block Approach
1. Isolate the effect of specific plasma-produced species
2. Validate kinetic mechanism
3. Optimize the production of specific plasma species
4. Apply knowledge to practical systems

Plasma Energy

- Translational
- Dissociation
- Rotational, Vibrational & Electronic
- Ionization

Temperature
- Stable Species [NOₓ, O₃, CₙHₘ, etc.]

Radicals
- [O, H, OH, etc.]

Excited Species
- [O₂(a¹Δg), N₂(C²Πu), O₂(v), etc.]

Ions & Electrons

Thermal Effects

Transport Effects

Kinetic Effects

Enhancement

Multiple Combustion Processes
- Ignition
- Flame Propagation
- Flame Stabilization
- Extinction
- Flammability Limits
Investigating $O_3$ and $O_2(a^1\Delta_g)$

$O_3$

Stable But Weakly Bound O to $O_2$

Long Lifetime

Deposition of O

Into Flame Front

$O_2(a^1\Delta_g)$

$O_2(a^1\Delta_g) \rightarrow O_2(3\Sigma^-_g)$

Magnetic Dipole Transition

(singlet-triplet inter-combination)

Long Lifetime

Efficient production at

$1 \text{ eV} \approx 10 \text{ Td}$

Pulsed or Low Power

Discharge

Unpaired Valence Electrons

High Chemical Reactivity

Detailed Kinetic Mechanisms for

$O_2(a^1\Delta_g)$ Effect on $H_2$, CO, and CH$_4$

Flames But Little Experimental Data

(Multiple Publications by Starik and co-workers from 2001 to the present)
Lifted Flame Platform

Effect of $O_3$ and $O_2(a^1\Delta_g)$

- Quantitative $O_3$ Measurement
- Quantitative $O_2(a^1\Delta_g)$ Measurement
- Extended $O_2(a^1\Delta_g)$ Lifetime with Catalytic Removal of O and $O_3$ with NO Injection

$O_3 + NO \rightarrow O_2 + NO_2$
$O + NO_2 \rightarrow O_2 + NO$

DISTRIBUTION STATEMENT A – Unclassified, Unlimited Distribution
C$_2$H$_4$ Lifted Flame Speed Enhancement by O$_3$ and O$_2$(a$^1\Delta_g$)

Coupled Equivalence Ratio, Stretch, and Curvature Effects

Lack of Quantitative Experimental Data of Effects of O$_2$(a$^1\Delta_g$) on Flame Propagation
New Plasma-Assisted Combustion Platform

Combustion Platform Allowing for:

1. Full Optical Access to Detailed Structure of Flame
2. Quantification of Combustion Parameters
   - Flame Speed and Radical Concentrations

Plasma Platform Allowing for:

1. More Production of $O_2(a^1\Delta_g)$ at Higher $O_2$ Loadings and Higher Pressures
2. Quantification of Plasma Species Concentrations
The Hencken Burner

Typically Used as a Calibration Source for Laser Diagnostic Measurements
Not for Flame Speed Measurements
Burner Platform at Sub-Atmospheric Pressure

Average Flow Velocity from Burner Exit

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<th>Torr</th>
<th>19.5 cm/s</th>
<th>26.0 cm/s</th>
<th>32.5 cm/s</th>
<th>42.3 cm/s</th>
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Enhanced Mixing at Low Pressure

Unwrinkled Flame Front at Low Pressure
Flame Liftoff Height vs. Flow Velocity

Different Modes of Operation

Regime I: weakly burning with considerable losses from the flame
Regime II: little change in liftoff height with flow velocity
flame propagates to region of mixing and has small amount of heat loss to the burner surface
Regime III: flame is in a dynamic balance with the local flow velocity, i.e. freely propagating

Concentration and Momentum Differences at Burner Surface Does Not Affect Flame

Approximately Equal to the Freely Propagating Laminar Flame Speed
Plasma-Integrated Hencken Burner System

Optical Access Through Entire Flame Structure

O₂/Inert

Plasma Discharge

Emission/Absorption Measurements

Fuel Oxidizer

Flame

O₂/Inert

Plasma Discharge

Emission/Absorption Measurements

Fuel

Burner Exit

Burner Platform Can be Used for Plasma Activation of Fuel or Oxidizer and Quantification of Enhancement via Flame Speed and Detailed Flame Structure Measurements

10 mm

Rapid Mixing at 300 K Prior to Flame Front

125 Torr

25 Torr
Flame Speed and Stretch Rates

PIV Measurements

Flame Speeds & Associated Axial Stretch Rates

Increased Stretch Rates with Velocity and Height Above Burner

But Low Stretch Rates (10-100 s⁻¹)
Flame Speed and OH Profiles: Comparison to 1-D Simulations

Good Agreement Between Experiments and 1-D Simulations with Minimal Corrections and Extrapolations
2-D Effects: Simulations

2-D Simulations Allow for Exploration of Stretch Rate Effects
PIV Velocity Profile Comparisons

Velocity Profiles from 2-D Simulations in Good Agreement With Experiments

2-D Simulations of Flame Speed In Limit of Zero Stretch in Good Agreement With 1-D Simulations
Nearly 1-D, Adiabatic, and Freely Propagating Flame

Weakly Stretched, But Can Investigate a Range of Stretch Rates (~10-100 s⁻¹)

Diffusion Mode – Fuel and Oxidizer Separated Until Burner Exit

Full Optical Access to Flame Structure

Towards Quantification of the Effect of Specific Plasma Species on Flame Propagation
Change in C\(_2\)H\(_4\) Flame Liftoff Height with O\(_3\) Addition

Photos of C\(_2\)H\(_4\)/O\(_2\)/Ar Flames w/ and w/o O\(_3\)

More Liftoff Height Change with Higher Liftoff Heights

Flames Enhanced More for Lean and Rich versus Stoichiometric
Computations of Flame Speed and Stretch Rate with O$_3$ Addition

$C_2H_4/Ar/O_2$, $\Phi=1.0$

$CH_4/Ar/O_2$, $\Phi=1.0$

Increased Flame Speed Enhancement with Increased Stretch Because of Relative Deposition of O Within Reaction Zone

Possible Implications
~2000 ppm O$_3$

15+ % $S_L$ Enhancement at $a=1000$ s$^{-1}$
OH Profile Differences with O₃ Addition

Can Deposition of O From O₃ Relative to Flame Structure Significantly Affect Enhancement?
On To $O_2(a^1\Delta_g)$ Compatibility With Hencken Burner

- Large Surface Area to Volume Ratio
- Multiple Types of Flow Surfaces That Will Quench $O_2(a^1\Delta_g)$

Exploration of $O_2(a^1\Delta_g)$ Quenching vs. Surface Composition
Filter Based System For Surface Quenching Study

Plain 304 SS Quenches $O_2(a^1\Delta_g)$

Silica Coating Makes Surface Fairly Inert
Using Surface Reactions For Selective Species Removal

Filter Housing

10 mm

49 mm

Other Materials

Metal Oxides (e.g. HgO)

Catalytic Surfaces

![Graph showing concentration of O₂(a) with different materials at P = 3 kPa](image)

- No Filter
- Aluminum
- Silica Material Surface
- 304 SS
- Nickel
- Copper

Below 300 ppm

P = 3 kPa
Coated Hencken Burner
For $O_2(a^1\Delta_g)$ Flame Studies

Solution:
Silica Coating on All Flow Surfaces

Conditions at 3-4 kPa:
20% $O_2$ in Ar
with 600 ppm NO Injection

3000-4000 ppm of $O_2(a^1\Delta_g)$

~1-2% Conversion of $O_2$
to $O_2(a^1\Delta_g)$
Quantitative Measurements of Enhancement by \( O_2(a^1\Delta_g) \)

Looking Back at the Lifted Flame Experiments

Hencken Burner Experiments

PIV for Flame Speed
Detailed Flame Structure Measurements (e.g. PLIF)
Comparison to 1-D Simulations

Preliminary Results

More Change in Flame Liftoff Height But Difficult to Quantify

3000-4000 ppm of \( O_2(a^1\Delta_g) \) ➞ Change in Flame Liftoff Height Can Be Quantified

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Source of $O_2(a^1\Delta_g)$ at Higher Pressure and $O_2$ Loading

Higher $O_2$ Concentrations and Higher Pressures Create Significant Challenge for $O_2(a^1\Delta_g)$ Production

Tandem Discharge
Prof. Svetozar Popovic (Old Dominion Univ.)
Measurement Techniques of $O_2(a^1\Delta_g)$

ICOS

Highly Sensitive and Quantitative
Temporally and Spatially Averaged

Emission (634 nm and 1268 nm)
Minimal Averaging
Requires Knowledge of Quenching Species and Their Kinetics

Radar REMPI (Prof. Zhili Zhang, Univ. Tenn.)
Demonstrated on Multiple Platforms
Successful for CH$_3$ Detection in Flame Front
Summary

1. New Plasma-Assisted Combustion Platform Developed

2. Preliminary Results of Enhancement by $O_3$ and $O_2(a^1\Delta_g)$ Demonstrated

3. Optimization of $O_2(a^1\Delta_g)$ Production at Higher Pressures and $O_2$ Loadings

4. New Diagnostic Technique for $O_2(a^1\Delta_g)$
“Bench Top” Scale

New Optical Diagnostics Laboratory With Array of Diagnostic Capabilities, Including:
- PIV, LIF, Raman Spectroscopy, Rayleigh Scattering, TDLAS, etc.
- Low-Pressure Chamber for Combustion and Plasma Studies

Collaborations Encouraged
Working With AFRL
Collaborations Encouraged

Application to High Speed Flows
Continuous Flow Wind Tunnel with Peak Stagnation Conditions of 2860 kPa, 922 K, 15.4 kg/s
Rectangular Duct or Cavity Geometry to Investigate Ignition, Flame Stabilization, etc.
Plasma Application to High-Speed Flow

Apply Minimum Energy To System for Maximum Enhancement

→ Utilize Chemical Energy

Cold M=2

Fuel

Recirculation

Shear Layer

Fuel

Activation of Local Portion of Flow With Plasma and Rely Upon System Dynamics For Propagation

Use Plasma to Change Local Flow Structure

Plasma Activation of Fuel to Change Chemical Reactivity
Acknowledgements

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Questions?