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

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Timothy Ombrello, Campbell Carter
Air Force Research Laboratory

Viswanath Katta
Innovative Scientific Solutions
**Report Documentation Page**

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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

- Hypersonic Missiles
- Medium Scramjets
- Large Scramjets and CCE’s
- Operationally Responsive Spacelift (Robust and Responsive)

- X-51 Program
- Large Hypersonic Missiles
- Small Launch Systems

- Hypersonic Missiles/Small Launch Systems
- Small Scramjets

- Ramjets

Hypersonic Missiles (Time-Critical Targets)
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

M=2

Spark Igniter

Fuel
Motivation

Restrictive Combustion Environments
e.g. High-Speed Air-Breathing Propulsion Systems

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

Necessitates Development of Techniques for Enhancing the Rate of Chemical Heat Release

The Application of Plasma
Providing Radicals, Intermediate Species, Excited Species, Ions, Electrons, and Elevated Temperatures

Understand the Key Species and Mechanisms of Enhancement
Allowing for Optimization and Practical Application

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
Investigating $\text{O}_3$ and $\text{O}_2(a^1\Delta_g)$

$\text{O}_3$

Stable But Weakly Bound O to $\text{O}_2$  
Long Lifetime
Deposition of O  
Into Flame Front

$\text{O}_2(a^1\Delta_g)$

$\text{O}_2(a^1\Delta_g) \rightarrow \text{O}_2(3\Sigma^-_g)$  
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

$\text{O}_2(b^1\Sigma^+_g)$ at 1.6 eV  
$\text{O}_2(a^1\Delta_g)$ at 0.98 eV

Detailed Kinetic Mechanisms for $\text{O}_2(a^1\Delta_g)$ Effect on $\text{H}_2$, $\text{CO}$, and $\text{CH}_4$  
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

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

![Diagram of Lifted Flame Platform](image)

![Graph showing mole fraction over time](image)
C_2H_4 Lifted Flame Speed Enhancement by O_3 and O_2(a^1Δ_g)

Coupled Equivalence Ratio, Stretch, and Curvature Effects

Lack of Quantitative Experimental Data of Effects of O_2(a^1Δ_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

- 19.5 cm/s
- 26.0 cm/s
- 32.5 cm/s
- 42.3 cm/s
- 55.3 cm/s
- 61.8 cm/s
- 74.8 cm/s

740 Torr

Enhanced Mixing at Low Pressure

125 Torr

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

Burner Exit Flow Velocity [cm/s]

Flame Liftoff Height [mm]

Diffusion Mode
Premixed Mode
Plasma-Integrated Hencken Burner System

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

125 Torr

25 Torr

Rapid Mixing at 300 K Prior to Flame Front

Optical Access Through Entire Flame Structure

Hencken Burner

O2/Inert

Plasma Discharge

Emission/Absorption Measurements

Fuel

Emission/Absorption Measurements

Fuel

Flame

Oxidizer

O2/Inert

Plasma Discharge

Burner Exit

10 mm
Flame Speed and Stretch Rates

Increased Stretch Rates with Velocity and Height Above Burner

But Low Stretch Rates (10-100 s⁻¹)
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
The Hencken Burner Platform for Plasma-Assisted Combustion Studies

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 $\text{C}_2\text{H}_4$ Flame Liftoff Height with $\text{O}_3$ Addition

Flames Enhanced More for Lean and Rich versus Stoichiometric

More Liftoff Height Change with Higher Liftoff Heights

Photographs of $\text{C}_2\text{H}_4/\text{O}_2/\text{Ar}$ Flames w/ and w/o $\text{O}_3$

$[\text{O}_3] \approx 1400$ ppm

$[\text{O}_3] \approx 1800$ ppm

Burner Exit

Flame Liftoff Height Change [mm]

Flame Liftoff Height [mm]

Flame Liftoff Height Change [mm]

Flame Liftoff Height [mm]
Computations of Flame Speed and Stretch Rate with O₃ Addition

C₂H₄/Ar/O₂, Φ=1.0

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

CH₄/Ar/O₂, Φ=1.0

Possible Implications

~2000 ppm O₃

15+ % S_L Enhancement at a=1000 s⁻¹
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 $O_2(a^1\Delta_g)$

Mixing with Fuel at 300 K for times on the order of milliseconds

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^1Δ_g)  
Silica Coating Makes Surface Fairly Inert
Using Surface Reactions For Selective Species Removal

Filter Housing

Other Materials
Metal Oxides (e.g. HgO)
Catalytic Surfaces

P = 3 kPa

O₂(a) Concentration [ppm]

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

Below 300 ppm
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

More Change in Flame Liftoff Height But Difficult to Quantify

Burner Exit

Preliminary Results

3000-4000 ppm of $O_2(a^1\Delta_g)$ ➞ Change in Flame Liftoff Height Can Be Quantified
New Plasma-Assisted Combustion Platform

Combustion Platform Allowing for:

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2. Quantification of Combustion Parameters - Flame Speed and Radical Concentrations

Plasma Platform Allowing for:

1. Higher Production of $O_2(a^1Δ_g)$ at Higher $O_2$ Loadings and Higher Pressures
2. Quantification of Plasma Species Concentrations
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 O₃ and O₂(a¹Δɡ) Demonstrated

3. Optimization of O₂(a¹Δɡ) Production at Higher Pressures and O₂ Loadings

4. New Diagnostic Technique for O₂(a¹Δɡ)
Working With AFRL
Collaborations Encouraged

“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
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

Plasma Activation of Fuel to Change Chemical Reactivity

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

Use Plasma to Change Local Flow Structure
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