Plasma-assisted combustion: applications and fundamental mechanisms

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Outline

• Demonstrations of plasma assisted combustion:
  • Lean flame stabilization
  • Control of thermo-acoustic instabilities

• Fundamental mechanisms:
  • Chemical and thermal effects of NRP discharges
  • Measurements of NO emissions

• Conclusions
Stabilization of Lean Premixed Flames using NRP discharges
Mini-PAC burner:
25-kW Lean Premixed Propane-Air Burner

Cylindrical wire anode

Pulse discharge generator

Bluff-body

Cathode

Air/Propane Mixture

Voltage [V]

Voltage [V]

t [ns]

0 5 10 15 20 25 30 35 0 1000 2000 3000 4000 5000 6000 7000
Mini-PAC burner
Stability regimes of mini-PAC burner

NRP: 2.3 mJ/pulse, PRF=30 kHz, Plasma power: 70 W

- NRP discharge lowers the lean extinction limit by about 10% and consumes less than 1% of the flame power

Pilla, et al 2006
Stabilization of Larger Scale Combustors
52-kW two-stage swirled gas turbine injector

Propane/air at 1 bar

Air: 105 m³/h
Propane: 2.1 m³/h
Max power: 52 kW
Exit velocity: 40 m/s

Two-stage swirled gas turbine injector

Premixed propane/air, 52 kW, 1 atm

## Lower extinction limit of the two-stage burner

<table>
<thead>
<tr>
<th>Constant air flow rate: 105 m$^3$/h</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Without plasma</strong></td>
</tr>
<tr>
<td>[Image]</td>
</tr>
<tr>
<td>2.1 m$^3$/h</td>
</tr>
<tr>
<td>$\Phi=0.47$</td>
</tr>
<tr>
<td>[Image]</td>
</tr>
<tr>
<td>1.95 m$^3$/h</td>
</tr>
<tr>
<td>$\Phi=0.44$</td>
</tr>
<tr>
<td>[Image]</td>
</tr>
<tr>
<td>1.8 m$^3$/h</td>
</tr>
<tr>
<td>$\Phi=0.4$</td>
</tr>
<tr>
<td><strong>Extinction</strong></td>
</tr>
<tr>
<td>$\Phi=0.4$</td>
</tr>
<tr>
<td><strong>Gain 70%</strong></td>
</tr>
</tbody>
</table>

| **With plasma, 30 kHz**              |
| [Image]                               |
| 2.1 m$^3$/h                          |
| $\Phi=0.47$                          |
| [Image]                               |
| 1.95 m$^3$/h                         |
| $\Phi=0.44$                          |
| [Image]                               |
| 1.8 m$^3$/h                          |
| $\Phi=0.4$                           |
| [Image]                               |
| 1.65 m$^3$/h                         |
| $\Phi=0.37$                          |
| [Image]                               |
| 1.35 m$^3$/h                         |
| $\Phi=0.3$                           |
| [Image]                               |
| 1.2 m$^3$/h                          |
| $\Phi=0.27$                          |
| [Image]                               |
| 1.05 m$^3$/h                         |
| $\Phi=0.23$                          |
200 kW Turbulent Aerodynamic Injector (ONERA/MERCATO)

Kerosene/air at 3 bar

Without plasma
Extinction: $\Phi = 0.44$

With plasma, 100 kHz
Extinction: $\Phi = 0.21$

- 52% reduction of the Lean Extinction Limit
- Power consumed by NRP discharge: < 1% of flame power

G. Heid, G. Pilla, R. Lecourt D.A. Lacoste, ISABE 2009
Dynamic control of thermo-acoustic instabilities
Closed loop control of a turbulent swirled flame

Pulse duration 10 ns
Pulse amplitude 12 kV
Pulse repetition frequency 10–50 kHz

\[ P_{\text{NRP}} / Q_{\text{th}} < 1\% \]
Closed loop control of a turbulent swirled flame

\[ \phi = 0.66, \quad Q_{th} = 43 \text{ kW} \]

FUNDAMENTAL MECHANISMS
Chemical and thermal effects of NRP discharges
Experimental approach

Study NRP discharge in air at 1000 K, 1 atm:

- 10-ns pulse
- 5.7 kV
- Gap: 4.5 mm
- 10 kHz
- 0.67±0.02 mJ/pulse
Investigation of two-step mechanism for oxygen dissociation

\[ \text{N}_2 + \text{e} \rightarrow \text{N}_2^* + \text{e} \quad (\text{N}_2^* = \text{N}_2 \ A, \ B, \ C) \]
Thresholds: 6.2, 7.4, 11.0 eV

\[ \text{N}_2^* + \text{O}_2 \rightarrow \text{N}_2 + \text{O} + \text{O} + \Delta T \]
\[ \Delta T = 1.0, \ 2.2, \ 5.9 \ \text{eV} \]

Measured quantities:
- Electrodynamics: U, I, Energy
- Discharge radius
- O atoms: TALIF
- N\textsubscript{2} A: CRDS
- N\textsubscript{2} B and N\textsubscript{2} C: OES
- Electrons: Stark broadening
- Temperature: OES (T\textsubscript{rot} N\textsubscript{2} C and T\textsubscript{rot} N\textsubscript{2}B)
Discharge radius

\[ R_0 = 225 \, \mu m \]

\[ t = 9 \, \text{ns} \]

Absolute \( N_2(C) \) Density, \( \text{cm}^{-3} \)

\[ 4 \times 10^{15} \]
\[ 3 \times 10^{15} \]
\[ 2 \times 10^{15} \]
\[ 1 \times 10^{15} \]
\[ 0 \]

Radius from center of discharge, \( \mu m \)

Absolute \( N_2(B) \) Density, \( \text{cm}^{-3} \)

\[ 3 \times 10^{16} \]
\[ 2 \times 10^{16} \]
\[ 1 \times 10^{16} \]
\[ 0 \]
Synchronized measurements of V, I, temperature, densities

Ultrafast heating: 900 K in 20 ns

50% dissociation of O₂

Electric energy: 670±20 μJ/pulse

η_{heating} = 21±5%

η_{diss.} = 35±5%

Rusterholtz et al., J. Phys D., 2013, in press
Measured and predicted temporal profiles of O and Temperature

- Confirmation of the two-step mechanism of ultrafast heating and oxygen dissociation
- Full reference test case for numerical simulations
Synchronized measurements of V, I, temperature, densities

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Rusterholtz et al., J. Phys D., 2013, in press
Quenching rates of $\text{N}_2\text{C}$ by $\text{O}_2$ at high temperature

- Recommended rate: $3 \times 10^{-10}(T/300)^{0.3}$
- Same value obtained at 2000 K by Packan (NRP glow with no O atoms) and present work (NRP spark with 50% $\text{O}_2$, 50% O)
TALIF measurements of O density during one pulse cycle (100 $\mu$s)

- O lifetime in air: 25 $\mu$s

Processes involved in flame stabilization by NRP discharges

Chemical effects: \( RH + O \rightarrow R + OH \)

Thermal effects: \( \Delta E \) and \( \Delta T \)
CH* emission and OH PLIF
Propane/air $\phi = 0.8$, 1 bar, Flame power: 1.2 kW, Discharge power 12 W, PRF 30 kHz
Dynamic response of flame to discharge
Propane/air $\phi = 0.8$, 1 bar, Flame power: 1.2 kW, Discharge power 12 W, PRF 30 kHz

- Stabilization when OH reaches incoming fresh gases
Relative importance of Thermal and Chemical Effects
Temporal evolution of flame front vs discharge power
Propane/air $\phi = 0.8$, 1 bar, Flame power: 1.2 kW

Lacoste, Xu, Moeck, Laux
Proc. Comb. Institute, 2013
Effect of pulse frequency on heating and O production at fixed discharge power = 12 W

- Heating increases with PRF
- O density decreases with PRF
Effect of pulse frequency on flame front evolution at fixed discharge power = 12 W
Thermal vs chemical effects

<table>
<thead>
<tr>
<th>Pulse frequency</th>
<th>10 kHz</th>
<th>80 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average discharge power</td>
<td>12 W</td>
<td>12 W</td>
</tr>
<tr>
<td>Energy per pulse</td>
<td>1.2 mJ</td>
<td>0.15 mJ</td>
</tr>
<tr>
<td>Normalized O density at end of pulse</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Temperature at end of pulse</td>
<td>2300 K</td>
<td>2600 K</td>
</tr>
<tr>
<td>Time to reattach flame</td>
<td>5 ms</td>
<td>5 ms</td>
</tr>
</tbody>
</table>

- Stabilization does not depend on whether the energy goes into heat or dissociation. It only depends on the TOTAL discharge power.
NO measurements
Setup for NO measurements

- Sb1770 DN model (Alpes laser)
- 2mW maximum power
- Interpulse (10 ns pulse, at 200 kHz)
- Spectral range: 10 cm\(^{-1}\), [1899 cm\(^{-1}\); 1909 cm\(^{-1}\)]
- Spectral width: 0.006 cm\(^{-1}\)

\[(X_{1/2}, \nu = 0) \rightarrow (X_{1/2}, \nu = 1)\] R6.5 at 1900.076 cm\(^{-1}\)

Stancu, Simeni, Laux, ICPIG 2013
NO measurements in a premixed methane/air flame (mini-PAC)

PRF = 30 kHz

![Graph showing NO density vs. ER for Flame and Flame + plasma]
Conclusions

• NRP discharges can efficiently stabilize lean flames, with < 1% of flame power:
  • Mini-Pac: propane/air at 1 bar, 25 kW
  • Two-stage injector: propane/air at 1 bar, 52 kW
  • Aerodynamic injector: kerosene/air at 3 bar, 200 kW
  • Dynamic control of combustion instabilities

• Fundamental processes:
  • Complete reference test case for 2 D simulations of NRP discharge in pin-pin geometry
  • High temperature quenching rates for $N_2$ C and $N_2$ B
  • Chemical and thermal effects (ultrafast heating and $O_2$ dissociation) inducing production of OH. Appear to have equivalent impact on flame stabilization

• Need to investigate
  • How to reduce NOx emissions
  • Higher pressure applications