INVESTIGATION OF
TURBULENT OXY-FUEL JET FLAMES
USING RAMAN/RAYLEIGH LASER DIAGNOSTICS

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I. Background and motivations

a. Oxy-fuel combustion

BIGCO2 project considers it as a great potential among the CCS technologies

CO₂ capture achieved through simple water removal from flue gas

High flame temperature reduced by using flue gas recirculation

Great potential for retro-fitting current gas-fired plants

Main limit: O₂ supply is energy-consuming

Literature:
- Well documented for system and processes
- Not well documented about fundamentals on CO₂-diluted oxy-fuel flames
Aims of the research:
- Look at turbulent oxy-fuel flame structure
- Create data library eventually used for validation of turbulent combustion codes

Specific objective:
- Investigate turbulent non-premixed CO₂-diluted oxy-fuel jet flame from a coflow burner

Flame properties:
- 32 % O₂ in oxidizer
- Overall equivalence ratio: 1.25

<table>
<thead>
<tr>
<th>Flame</th>
<th>%H₂ in fuel</th>
<th>Re₉fuel</th>
<th>Jet speed (m/s)</th>
<th>Coflow speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>55</td>
<td>15,000</td>
<td>98.2</td>
<td>0.778</td>
</tr>
<tr>
<td>A-2</td>
<td>45</td>
<td>15,000</td>
<td>84.4</td>
<td>0.755</td>
</tr>
<tr>
<td>A-3</td>
<td>37</td>
<td>15,000</td>
<td>75.8</td>
<td>0.739</td>
</tr>
<tr>
<td>B-1</td>
<td>55</td>
<td>12,000</td>
<td>78.6</td>
<td>0.622</td>
</tr>
<tr>
<td>B-2</td>
<td>55</td>
<td>15,000</td>
<td>98.2</td>
<td>0.778</td>
</tr>
<tr>
<td>B-3</td>
<td>55</td>
<td>18,000</td>
<td>117.8</td>
<td>0.933</td>
</tr>
</tbody>
</table>

Coflow burner
- Fuel nozzle:
  - Fuel: CH₄/H₂
  - 5mm ID
  - Wall thickness 0.5 mm
  - Squared-off end
- Coflow tube:
  - Oxidizer: O₂/CO₂
  - 96.5 mm ID
- Air coflowing at 0.5 m/s
II. Experimental methods

a. Experimental setup

Capture on a single-shot basis:
- Local flame temperatures
- Local Concentrations of CO$_2$, O$_2$, CO, N$_2$, CH$_4$, H$_2$O and H$_2$.

Note: CO-LIF and OH-PLIF not used here.

Laser system:
- 3 frequency-doubled Nd:YAG
- Pulse stretcher
- 1 J/pulse at 532 nm for 400 ns

Spatial resolution:
- 0.104 mm along 6-mm section of focused beam

Simultaneous line imaging of Raman/Rayleigh laser diagnostics
b. Data processing technique

Hybrid method (Fuest, 2011):

- Based on RAMSES spectra simulation code (Geyer, 2005)
  -> Generates Raman spectra libraries for most species over large temperature range (290 K to 2500 K) relatively to optical setup
  -> Short series of calibration measurements (one per species) are sufficient to provide most Raman and cross-talk coefficients

- CH₄ and some cross-talk coefficients are not available through RAMSES and are found with calibration measurements over the temperature range

Corrections:

- Signals corrected for CCD background, flat-field, total Nd:YAG laser energy, interferences from laser induced fluorescence, broadband flame luminosity, beam steering through flames and bowing effect through Raman optics
II. Experimental methods

c. Limits and uncertainties

Limits:
- Soot formation at the flame tip leading to interferences on spectra
- OH-PLIF and CO-LIF could not be applied
- Jet Reynolds number limited by CO$_2$ supply

Uncertainties:

<table>
<thead>
<tr>
<th>Scalar</th>
<th>Precision $\sigma$ (%)</th>
<th>Accuracy (flat flames, %)</th>
<th>Accuracy (turbulent flames, %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>0.6</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$N_2$</td>
<td>0.7</td>
<td>2</td>
<td>3</td>
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<tr>
<td>CO$_2$</td>
<td>3.0</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>2.2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>$F_B$</td>
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<td>5</td>
<td>8</td>
</tr>
<tr>
<td>CO</td>
<td>5</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>H$_2$</td>
<td>7.5</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

(Barlow, 2009)
III. Results analysis

a. Localized extinction (1/3)

Localized extinction:
- Occurs when turbulent mixing rates between fuel and oxidizer become competitive with critical rates of chemical reactions
- Takes place in the near-field
- Probability of localized extinction increases with decreasing H$_2$ content in fuel and increasing jet Reynolds number.
III. Results analysis

a. Localized extinction (2/3)

Leads to local temperatures drops due to increasing heat removal rates from convection and diffusion along with decreasing chemical reaction rates.

**Fully burning probability:**
- Enables to quantify the degree of extinction
- Based on pdf of temperatures above $T_b$ in the mixture fraction region $F_{B-St} \pm \sigma$
- Here, with $T_b = 1700 \text{ K}$ and $\sigma = 0.02$
III. Results analysis

a. Localized extinction (3/3)

Flame structure:

- Unburnt oxidizer shows up in the fuel-rich region (cf. O₂ mass fraction)
Comparison with laminar diffusion flame calculations:
- Match made with CO mass fraction
- Near-field: strong influence of differential diffusion
- Downstream: shift towards equal diffusivities transport regime
III. Results analysis

b. Differential diffusion (2/3)

Differential diffusion parameter:  \( z = F_H - F_C \)

- Strong influence in near-field but plays minor role farther downstream
- Rich-side less affected by differential diffusion
- Calculations show that influence of differential diffusion is reduced with lower H₂ content in fuel.
III. Results analysis

b. Differential diffusion (3/3)

Reaction zone:

Stronger influence when the reaction zone is very thin compared to molecular diffusivity length scales.

-> Helps diffusion of small molecules such as H₂ through the reaction zone.

-> Less influence farther downstream as the reaction zone thickens.
c. High CO levels

Conditional mean of CO mass fraction locally reached up to 0.18

Due to high CO₂-dilution levels:

- CO₂ was not inert but competed primarily with O₂ for atomic hydrogen and lead to formation of CO through the reaction \( CO₂ + H \rightarrow CO + OH \)
The objective was to investigate the influence of H$_2$ content in fuel and jet Reynolds number on localized extinction and flame structure.

**Localized extinction:**
- Higher contents of O$_2$ on the rich side of the flame
- Fully burning probability was calculated

**Differential diffusion:**
- Significant level of differential diffusion in the near-field
- Farther downstream, minimized influence as reaction zone thickens

**CO levels:**
- Enhanced CO$_2$ + H → CO + OH reaction leading to high CO levels

**Next steps:**
- Make the whole set of results available
- Investigation of influence of O$_2$ content in oxidizer
Thank you for your attention!

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References:

