A new understanding of the combustion process in partial oxidation reformer

Xinyu Li

Institute of Clean Coal Technology
East China University of Science and Technology, Shanghai, China
1. Motivation

- Combustion process is vital to the long-period high efficiency operation of a POX reformer

- Information on the combustion process is very limited
  - Laminar flame studies
  - Simulations based on fast reaction assumption

  _Flames in hot recirculated gas may be totally different from the laminar flame_

- The combustion process was studied _in reformer conditions_ in this work
2. Model Description

- **Physical model**

  Jet in hot syngas coflow model

- **Numerical model**

  Eddy Dissipation Concept Model (no modification)
  - GRI-MECH 3.0
  - Radiation model: DO model

  Two common case for reformer burner design
  - Inverse diffusion flame (IDF) case
  - Normal diffusion flame (NDF) case

  Boundary conditions for IDF case

<table>
<thead>
<tr>
<th></th>
<th>Oxidant</th>
<th>Fuel</th>
<th>Coflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>300</td>
<td>300</td>
<td>1600</td>
</tr>
<tr>
<td>(K) Velocity</td>
<td>100</td>
<td>100</td>
<td>5.4</td>
</tr>
<tr>
<td>Species (mol)</td>
<td>100% O₂</td>
<td>100% CH₄</td>
<td>56%H₂+32%CO+12%H₂O</td>
</tr>
</tbody>
</table>
3. Simulation Results

3.1 Temperature profiles

Normal Diffusion Flame (NDF):
- flame located near burner
- Maximum temperature above 3000K

Inverse Diffusion Flame (IDF):
- located far downstream
- uniform temperature
- peak T of 1797K
3. Simulation Results

3.2 Flame structure analysis of IDF

\[ X_{\text{OH}} \text{(left contour)}, \quad X_{\text{CH}_2\text{O}} \text{(right contour)} \]
\[ X_{\text{O}_2} \text{(left lines)}, \quad T \text{(right lines)} \]

Two competitive processes

➢ Heating of the reactant mixture
➢ Dilution of \( \text{O}_2 \)

● Combustion occur in Zone C where \( \text{O}_2 \) mole fraction is lower than 10%.

● Low \( \text{O}_2 \) mole fraction leads to a low temperature increase.

● These features are similar to a MILD combustion process.

MILD: Moderate or intense low-oxygen dilution, flameless combustion
3. Simulation Results

3.3 Combustion mode analysis

Classification of combustion mode proposed by Antonio Cavaliere (2004)

For combustion process in a Well Stirred Reactor:

<table>
<thead>
<tr>
<th>Combustion mode</th>
<th>Inlet conditions</th>
<th>Working conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedback combustion</td>
<td>$T_{in} &lt; T_{si}$</td>
<td>$\Delta T &gt; T_{si}$</td>
</tr>
<tr>
<td>High temperature</td>
<td>$T_{in} &gt; T_{si}$</td>
<td>$\Delta T &gt; T_{si}$</td>
</tr>
<tr>
<td>Mild combustion</td>
<td>$T_{in} &gt; T_{si}$</td>
<td>$\Delta T &lt; T_{si}$</td>
</tr>
</tbody>
</table>

Applying this method to above CFD results:

Each computational cell is regarded as a WSR

$T$: Temperature of a cell obtained from CFD results

$T_{in}$: Temperature of a cell in frozen mixing conditions

$\Delta T = T - T_{in}$

$T_{si}$: Obtained from WSR calculations with mixture corresponding to the frozen mixing conditions
3. Simulation Results

3.3 Combustion mode analysis

All the data are located in the “No reaction” regime or “MILD combustion” regime.

The combustion mode of the IDF case is **MILD combustion**.
3. Simulation Results

3.4 Effect of coflow temperature on IDF

- Higher coflow temperature leads to higher peak temperature
- Combustion mode remain unchanged as the $T_{coflow}$ varies between 1300K-1700K.
3. Simulation Results

3.5 Effect of jet velocity on IDF

- Higher jet velocity means better mixing, so leads to lower peak temperature
- As the jet velocity varies in the range 40-100m/s, MILD mode remain unchanged.

Profiles along axis

Profiles at x=50d
3. Simulation Results

3.6 Effect of Pressure on IDF

- Higher pressure leads to early self-ignition, so higher flame temperature
- Maximum temperature is about 1900K, 200K higher than the normal pressure case
- Negative effect on MILD combustion
4. Results validation

4.1 Experimental setup

Experimental study of CH$_4$-O$_2$ flame in a bench-scale gasifier was conducted to validate these numerical findings.

- Preheated to 1473K before the experiment
- The endoscope can be moved up and down to capture the flame
- The thermocouples (type B) can be moved along the radial direction
### 4. Results validation

#### 4.2 Flame Images

- **IDF configuration**

<table>
<thead>
<tr>
<th></th>
<th>( \text{O}_2 )</th>
<th>( \text{CH}_4 )</th>
<th>( \text{O}_2/\text{CH}_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity( \text{m/s} )</td>
<td>Flow rate ( \text{L/min} )</td>
<td>Velocity( \text{m/s} )</td>
<td>Flow rate ( \text{L/min} )</td>
</tr>
<tr>
<td>80</td>
<td>34</td>
<td>80</td>
<td>49</td>
</tr>
</tbody>
</table>

- **NDF configuration**

<table>
<thead>
<tr>
<th></th>
<th>( \text{O}_2 )</th>
<th>( \text{CH}_4 )</th>
<th>( \text{O}_2/\text{CH}_4 )</th>
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<td>Velocity( \text{m/s} )</td>
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<td>Velocity( \text{m/s} )</td>
<td>Flow rate ( \text{L/min} )</td>
</tr>
<tr>
<td>39</td>
<td>24</td>
<td>80</td>
<td>33.93</td>
</tr>
</tbody>
</table>

- Consistent with the simulation results!
4. Results validation

4.3 Measured Temperature of IDF case

Axial Temperature profiles at different radial positions

<table>
<thead>
<tr>
<th>Radial position</th>
<th>Wall T</th>
<th>1#(150mm)</th>
<th>2#(350mm)</th>
<th>3#(450mm)</th>
<th>4#(550mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>r=0 mm</td>
<td>1323 K</td>
<td>1184 K</td>
<td>1380 K</td>
<td>1392 K</td>
<td>1385 K</td>
</tr>
<tr>
<td>r=25 mm</td>
<td>1349 K</td>
<td>1207 K</td>
<td>1413 K</td>
<td>1416 K</td>
<td>1405 K</td>
</tr>
<tr>
<td>r=50 mm</td>
<td>1366 K</td>
<td>1221 K</td>
<td>1445 K</td>
<td>1446 K</td>
<td>1438 K</td>
</tr>
</tbody>
</table>

r: distance from the axis

No thermocouple was burnt out!

- The combustion process in IDF configuration is MILD combustion.
5. Discussion

Advantages of establishing MILD combustion in POX reformer

- Protecting the burner, greatly prolongs the burner life
- Good stability
- Much less soot
- Uniform temperature, high efficiency
Summary

- The IDF in hot syngas environment is established in MILD combustion mode.

- The competitive processes between the heating of reactant and dilution of O\textsubscript{2} play a key role.

Outlook

- Stability of MILD combustion
  (different mixing design, preheat, higher pressure, etc.)
- More experimental study is needed
Thank you!

Xinyu Li, PhD candidate
Institute of Clean Coal Technology
East China University of Science and Technology,
No. 130 Meilong Road, Shanghai, China

E-mail: xinyu_lee@yeah.net