Development Of Enabling Technologies For A Pressurized Dry Feed Oxy-coal Reactor

Project Review

DE-FE0029157

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Objective: Develop technologies and data that will enable design and operation of a pressurized oxy-coal combustor

$1.4M program ($1.1M DOE, $0.3M cost-share)

5-yr program (10/1/16 – 9/30/21)

Team

- Brigham Young University (Adams, Fry, Tree, students)
- Reaction Engineering International (REI)
- CPFD Software
Technology Deliverables

- 100 kW\textsubscript{th} 20-bar pressurized oxy-coal reactor
- Scalable pressurized dry coal feed system
- Scalable O\textsubscript{2}-CO\textsubscript{2}-coal burners/firing systems for diffusion flame and flameless combustion
- Measurement data
- Mechanistic process model to guide reactor scale-up and plant integration
POC System Overview

Coal Feed
CO₂ + Coal

Ash Tank
Molten slag collection

Gas Feed
O₂, CO₂, NG

Burner

OPTO 22
Control System

Burner Cap
Main Shell
Optical Ports
Blow off Diaphragm

Inlet/Outlet Water Streams
Bleed off Valve
Ball Valve
Control Valve
Heat Exchanger
Exit Nozzle

Cyclone Separator
Condensation Removal

Damper Inlet
Coal Feed Design Concept

- Modeled with Barracuda CFD software
- Fluidize coal in hopper for transport; add dilution CO$_2$ as needed
  - Sufficient coal flow and CO$_2$–to-coal ratio
  - Decoupling of fluidization and dilution flows
  - Flow sufficiently steady for burner operation
  - Sensitive to gas inlet design
- Piping system has roping
Fluidized Bed Design

Barracuda CFD Modeling of design concept

- CO₂ fluidizes coal in hopper
- Mixture transported to horizontal pipe
- Dilution CO₂ added in pipe

<table>
<thead>
<tr>
<th>Inlet A</th>
<th>Outlet C</th>
<th>Outlet E</th>
<th>Inlet B</th>
<th>Outlet D</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Fluidization Flow (g/s)</td>
<td>CO₂ Flow Through Vent (g/s)</td>
<td>CO₂ Flow Exiting Hopper (g/s)</td>
<td>CO₂ Dilution Flow (g/s)</td>
<td>Coal Flow at Exit (g/s)</td>
</tr>
<tr>
<td>0.384</td>
<td>0.034</td>
<td>0.350</td>
<td>3.350</td>
<td>5.757</td>
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<tr>
<td>0.500</td>
<td>0.150</td>
<td>0.350</td>
<td>3.234</td>
<td>5.712</td>
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<td>0.850</td>
<td>0.500</td>
<td>0.350</td>
<td>3.350</td>
<td>4.933</td>
</tr>
<tr>
<td>0.384</td>
<td>0.034</td>
<td>0.350</td>
<td>6.700</td>
<td>5.985</td>
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<tr>
<td>0.734</td>
<td>0.034</td>
<td>0.700</td>
<td>3.000</td>
<td>10.588</td>
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<tr>
<td>1.200</td>
<td>0.500</td>
<td>0.700</td>
<td>3.000</td>
<td>11.130</td>
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</tbody>
</table>
Bench-Scale Test Feeder

Bench-Scale Feed System

To load cell
Fluidization gas vent
Coal cell
Dilution gas inlet
Fluidization gas inlet
Flow exit and filter

Testing Validates Concept

Coal in Hopper (kg) vs. Time (s)

Coal Flow Rate (kg/hr) vs. Fluidization Flow Rate, E (kg/hr)
Full-Scale Coal Feeder

- ~13.6 kg/hr, 6 hrs
- Hydrostatic Testing to 34 bar
- Load-cells calibrated

Coal Load Valve
Vent CO₂
Load Cells
Fluidizing CO₂
To Reactor
Dilution CO₂
Distributor Plate
Feeder Controls
Flame Types

- **Diffusion flame**
  - Coal concentrated in center
  - Currently installed

- **Flameless combustion**
  - Coal distributed at inlet
  - Future design

- **Design approach**
  - Previous oxy-coal burner design and testing experience
  - CFD modeling of reactor combustion and heat flux
Burner Concepts

- Baseline Design
  - Coal conveyed with $\text{CO}_2$ in primary (~1:1)
  - Mixed $\text{O}_2$ and $\text{CO}_2$ in secondary annulus
  - Mixed $\text{O}_2$ and $\text{CO}_2$ in tertiary lances
  - $\text{CO}_2$ for temperature and momentum control

<table>
<thead>
<tr>
<th>Case</th>
<th>CO$_2$/Coal Ratio</th>
<th>%O$_2$ Non-Coal Feed</th>
<th>Coal Vel. (m/s)</th>
<th>Inner O$_2$ Vel. (m/s)</th>
<th>Outer O$_2$ Vel. (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>1.8:1</td>
<td>20</td>
<td>5.3</td>
<td>1.03</td>
<td>10.5</td>
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<tr>
<td>Case 2</td>
<td>8.0:1</td>
<td>20</td>
<td>0.51</td>
<td>0.5</td>
<td>0.54</td>
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<td>Case 3</td>
<td>4.2:1</td>
<td>10.4</td>
<td>5.0</td>
<td>5.2</td>
<td>5.3</td>
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</tbody>
</table>

Simulations from Reaction Engineering International
Burner Design

Connections From MFCs to Burner

Burner Installed

Burner Testing
PCHT Model

- Fast-running physics-based model
- Design screening, scale-up, plant integration
- Jet mixing, particle transport, reactions, radiative heat transfer
- Use adaptive dimensionality
  - Use 3D only where necessary
  - Biggest challenge is radiation
- Compare to reactor test data
- Model reactor scale-up, compare to CFD results
Calculation Speed-ups

Moving from fully 3D to 3D/axi-symmetric/1D dimensionality reduces computational time with minimal loss in accuracy.

Radiation Calculations
- Median difference in incident wall flux < 1% for all meshes
- 274% speed-up
- 273% speed-up
- 270% speed-up

Flow Calculations
- Average difference in axial velocity < 3%
- 396% speed-up

Presentation by BYU Engineering
POC Reactor Design

Four Refractory-Lined Sections

1) Top Section - Dome cap, houses Burner
2) Burner - Transports primary, secondary and tertiary flows into reactor
3) Main Section - 1.8 m combustion zone with optical access ports and embedded wall TC
4) Bottom Section - Slag collection and exhaust nozzle for flue gases

Total reactor weight ~ 6 tons
• Sapphire window assemblies have been machined and installed to allow optical measurements to be taken with reactor pressures at 20 bar
• These have been hydrostatic tested to 34 bar
• Integrated into assembly design
  • Purge system
  • Mounts for optical devices (radiometer, laser, passive FTIR)
Heat Flux

Multi-depth Thermocouples

- Five Sets (along reactor axis) are installed and operating nominally
- Provide both inside refractory surface temperature and total heat flux
- System is ready for testing

Narrow Angle Radiometer (NAR)

- Prototype is completed along with extensive calibration and uncertainty analysis on a black body radiator
- 4 more devices are under construction
  - Electronics complete
  - Mechanical components expected next week
- One of these will be evaluated against Chalmers and University of Utah NARs (published results)

Assuming surface or gas viewed through the aperture is diffuse and uniform in temperature and emissivity and Stefan-Boltzmann law applies

\[ q_{A-L} = \omega_{L-A} A \cos \theta_A I_A \]
\[ \omega_{L-A} = \frac{A \cos \theta_I}{r^2} \]
\[ I_A = \frac{e_A \sigma}{\pi} T_A^4 \]

for this configuration these reduce to:

\[ q_{A-L} = \frac{A e_A \sigma}{r^2 \pi} T_A^4 \] which applies to both aperture and lens
Temperature and Soot

Two-color Laser Extinction (Soot and Ash)
- A table has been designed and fabricated to mount the laser on one side of the reactor and integrating sphere on the opposite side of the reactor
- Curtain holders have been installed to protect users from stray laser light
- **System is ready for testing** – awaiting pressurized flame conditions

Optical Pyrometer / Passive FTIR
- A holder has been designed and installed for outside mounting of optical probe
- Purge system has been installed
- **System is ready for testing**
• OPTO 22 control
• 115 control points
• Integrated safety protocols
  • Interlocks
  • Logical decision points
• Historical data logs
Reactor Status

- **Completed:**
  - Main reactor with diffusion burner system
    - Pressurized air, NG, O₂ and CO₂
  - Pressurized coal feed system
  - Flue gas cooling / clean-up system
  - Control system
  - HAZOP review and updates
  - Pressure burst test
  - Refractory cure
  - Shake down
  - Natural Gas Combustion

- **Immediate Next Steps:**
  - Pressurized coal combustion tests
• A Hazard and Operability Study was performed in June of 2019

• Participants in the study included:
  • College of Engineering Safety Personnel
  • College of Engineering Lab Managers
  • BYU Risk Management
  • Project Professors and Graduate Students
  • Invited Engineers from Industry with Similar Processes

• 76 Action Items were generated in this study that included:
  • Hardware Reconfigurations
  • Interlock Installation
  • Control Logic Modifications
  • Standard Operating Procedure Modifications

• All action items have been addressed and tested

• State Pressure Vessel Inspection has been passed and Operating Permit Obtained
• The purpose of these tests is to verify that the equipment as installed was capable of:
  • Spanning the range of expected operating conditions
  • Stabilize a natural gas flame at atmospheric pressure
  • Identify any problems with equipment configuration

• Data presented on this slide are concerned with firing rate and flame stability

• Data presented on the next slide demonstrate the functionality of the multi-depth thermocouples

Equivalence ratio near 1/ analyzer
Shakedown Test Results

Inner B Thermocouple Temperature

Wetted Refractory Surface Temperature (Calculated)

Outer B Thermocouple Temperature
## Targeted Operating Conditions

### Burner Configuration

- A – $O_2$ ports (8)
- B – $O_2$ & $CO_2$ anulus
- C – natural gas anulus
- D – coal & $CO_2$ port

### Geometry and Firing Conditions

<table>
<thead>
<tr>
<th>Label</th>
<th>Port or Anulus</th>
<th>ID (mm)</th>
<th>OD (mm)</th>
<th>Coal (kg/h)</th>
<th>$CO_2$ (kg/h)</th>
<th>$O_2$ (kg/h)</th>
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<tbody>
<tr>
<td>A</td>
<td>$O_2$ ports</td>
<td>3.8608</td>
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<td>0</td>
<td>37.2</td>
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<tr>
<td>B</td>
<td>$O_2$ &amp; $CO_2$ anulus</td>
<td>28.448</td>
<td>31.75</td>
<td>0</td>
<td>55</td>
<td>27</td>
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<tr>
<td>C</td>
<td>natural gas anulus</td>
<td>8.509</td>
<td>9.525</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>D</td>
<td>Coal &amp; $CO_2$ port</td>
<td>NA</td>
<td>6.35</td>
<td>13.6</td>
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<td>0</td>
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</tbody>
</table>

Similar to Case 3
From CFD Modeling
Attempt #1

- All systems functioned nominally
- Coal was only introduced into reactor in two plugs
- Postmortem analysis indicated that students used coal that had sat in a drum over a high humidity weekend (It was agglomerated)
- Next attempt will occur during the week of May 10th.
### Milestones

<table>
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<tr>
<th>Year 1 - Milestone and Related Task</th>
<th>Scheduled Completion</th>
<th>Actual Completion</th>
<th>Percent Completed</th>
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<td>DOE-NETL Kickoff Meeting (Task 1.2)</td>
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<td>Coal Feed System Construction (Task 3.2)</td>
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<tr>
<td>Reactor Test Data Modeling (6.2)</td>
<td>9/30/21*</td>
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* Adjusted schedule after project extension
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