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_{th} 20-bar pressurized oxy-coal reactor
- Scalable pressurized dry coal feed system
- Scalable O_2-CO_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**
\[ \text{CO}_2 + \text{Coal} \]

**Ash Tank**
Molten slag collection

**Gas Feed**
\[ \text{O}_2, \text{CO}_2, \text{NG} \]

**Burner**

**OPTO 22 Control System**
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

![Diagram of Coal Feed Design Concept]

- Vent CO\(_2\)
- Fluidized coal
- CO\(_2\) + coal
- Fluidizing CO\(_2\)
- Dilution CO\(_2\)
- To reactor
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>
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</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>
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<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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<td>0.500</td>
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<td>3.234</td>
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<td>3.350</td>
<td>4.933</td>
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<td>0.384</td>
<td>0.034</td>
<td>0.350</td>
<td>6.700</td>
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<td>1.200</td>
<td>0.500</td>
<td>0.700</td>
<td>3.000</td>
<td>11.130</td>
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</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
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 CO₂ in primary (~1:1)
- Mixed O₂ and CO₂ in secondary annulus
- Mixed O₂ and CO₂ in tertiary lances
- CO₂ for temperature and momentum control

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
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<tbody>
<tr>
<td>CO₂/Coal Ratio</td>
<td>1.8:1</td>
<td>8.0:1</td>
<td>4.2:1</td>
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<tr>
<td>%O₂ Non-Coal Feed</td>
<td>20</td>
<td>20</td>
<td>10.4</td>
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<tr>
<td>Coal Vel. (m/s)</td>
<td>5.3</td>
<td>0.51</td>
<td>5.0</td>
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<tr>
<td>Inner O₂ Vel. (m/s)</td>
<td>1.03</td>
<td>0.5</td>
<td>5.2</td>
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<td>Outer O₂ Vel. (m/s)</td>
<td>10.5</td>
<td>0.54</td>
<td>5.3</td>
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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
Moving from fully 3D to 3D/axi-symmetric/1D dimensionality reduces computational time with minimal loss in accuracy.

Schematic of intensity rays for fully 3D vs 3D/axi-symmetric Single Weighted Ray (SWR) technique.

Median difference in incident wall flux < 1% for all meshes.
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
POC Reactor

- Main Shell
- Heat Exchanger
- Emergency Pressure Relief Valve
- Cooling Spray
Reactor Optical Access

- 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

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

for this configuration these reduce to:

\[ q_{A-L} = \frac{A_L A_A}{r^2} \frac{e_A \sigma}{\pi} T_A^4 \]

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 fabricated for outside mounting of optical collection probe.
- Purge system has been installed.
- System is ready for testing.
- If purging does not work, a design and fabrication for internal installation will be necessary.
Reactor Status

- **Completed:**
  - Main reactor with diffusion burner system
    - Pressurized air, NG, O$_2$ and CO$_2$
  - Pressurized coal feed system
  - Flue gas cooling / clean-up system
  - Control system
  - HAZOP review and updates
  - Pressure burst test
  - Refractory cure

- **Immediate Next Steps:**
  - Pressurized natural gas combustion tests
  - Pressurized coal combustion tests
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
Shakedown Test Results

Inner B Thermocouple Temperature

Outer B Thermocouple Temperature

Wetted Refractory Surface Temperature (Calculated)
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
Summary

• A 100 kW$_{th}$ 20-bar pressurized oxy-coal reactor has been installed at BYU with corresponding systems
  • Pressurized dry pulverized coal feed system
  • O$_2$-CO$_2$-coal burner firing system

• Extensive safety study and certifications have been performed and passed

• System shakedown testing has been performed

• Diagnostic equipment has been developed and installed
  • heat flux, radiation, gas temperature, solids measurement

• We are ready to begin pressurized oxy-coal combustion experiments
# Milestones

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<td>DOE-NETL Kickoff Meeting (Task 1.2)</td>
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* Adjusted schedule after project extension

I’m guessing on Tasks 3.2 and 5.1. Update them as you wish.
Acknowledgment: "This material is based upon work supported by the Department of Energy under Award Number DE-FE0029157." Program Manager Steve Markovich.

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