RIC Advanced Sensors & Controls FWP

Novel Sensors for Boilers

Dustin McIntyre, Dan Haynes, Joe Yip, Dan Hartzler, Chet Bhatt, Juddha Thapa, Nari Soundararajan, Yan Zhou, Swarom Kanitkar, Steve Richardson, Jennie Stoffa

Presenter: Benjamin Chorpening, Ph.D.
Technology Portfolio Lead
Benjamin.Chorpening@netl.doe.gov

Crosscutting Research and Advanced Energy Systems Annual Project Review Meeting, May 20, 2021
First a little about the Research & Innovation Center...
Research Focus by Site

Multiple Sites Operating as One Lab System

- Materials Performance
- Multi-environment Materials Characterization
- Alloy Development/Manufacture
- Geospatial Data Analysis

- Process Systems Engineering
- Decision Science
- Functional Materials
- Environmental Sciences
- Energy Systems Optimization

- Energy Conversion Devices
- Simulation-Based Engineering
- In-Situ Materials Characterization
- Supercomputer Infrastructure
- Diagnostics, Sensors, and Controls
### NETL Core Competencies

**Effective Resource Development** • **Efficient Energy Conversion** • **Environmental Sustainability**

<table>
<thead>
<tr>
<th>COMPUTATIONAL SCIENCE &amp; ENGINEERING</th>
<th>MATERIALS ENGINEERING &amp; MANUFACTURING</th>
<th>GEOLOGICAL &amp; ENVIRONMENTAL SYSTEMS</th>
<th>ENERGY CONVERSION ENGINEERING</th>
<th>STRATEGIC SYSTEMS ANALYSIS &amp; ENGINEERING</th>
<th>RESEARCH PLANNING &amp; DELIVERY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-Scale Modeling Atomistic to Device</td>
<td>Design, Synthesis, &amp; Performance</td>
<td>Reservoir Engineering</td>
<td>Design &amp; Validation</td>
<td>Multi-scale Modeling, Simulations &amp; Optimization</td>
<td>Business Management &amp; Agreements</td>
</tr>
<tr>
<td>Artificial Intelligence &amp; Machine Learning</td>
<td>Characterization</td>
<td>Geochemistry</td>
<td>Thermal Sciences</td>
<td>Advanced System Engineering</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

U.S. DEPARTMENT OF ENERGY

4
Technology Development Pathway

An Active Portfolio from Concept to Market Readiness

- **DISCOVERY**: Concept identified/proven at laboratory-scale
- **DEVELOPMENT**: Technology component validated/integrated
- **SYSTEM TESTING**: System performance confirmed at pilot-scale
- **DEMONSTRATION**: System demonstrated in operational environment
- **COMMERCIALIZATION**: Technology available for wide-scale market use

**TECHNOLOGY MATURATION**

- TRL 1-3: Fundamental Studies
- TRL 4-5: Technology component validated/integrated
- TRL 6-7: System performance confirmed at pilot-scale
- TRL 8: System demonstrated in operational environment
- TRL 9: Technology available for wide-scale market use

**Scale**

- Technology Confidence
- Investment
- Private Sector Cost Share

RIC projects
Changing Requirements for Fossil Energy Power

Increase Flexibility, Reduce CO₂ Emissions

Executive Order 14008 includes a goal of a carbon pollution-free electricity sector by 2035

How do we get there?

Fossil power plants
• Improve dispatchable power flexibility
• Integrate operation with energy storage
• Integrate with carbon capture

This will require development of
• Sensors to increase actionable plant information
• Optimized plant and grid control strategies
• Integrated system dynamic controls
• Sensors to assure environmental safety of carbon storage

ERCOT hourly electricity by fuel, Feb. 3-16, 2021, MWh. Source: Hitachi ABB Power Grids (Power Magazine, 2/19/2021)

Dispatchable power generation must flex better to coordinate with renewables to meet power demand while reducing CO₂ emissions.
<table>
<thead>
<tr>
<th>Sensors &amp; Instruments</th>
<th>Controls</th>
<th>Cybersecurity and Novel Concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High temperature optical fiber sensors</td>
<td>• Testing online system identification for detecting equipment problems</td>
<td>• VLC – Alternative to WiFi</td>
</tr>
<tr>
<td>• Crystalline fiber</td>
<td>• Cyber-physical systems as a hybrid power plant development acceleration tool</td>
<td>• Strengthening Cybersecurity with Fast Proxy Models in High Fidelity Digital Twins</td>
</tr>
<tr>
<td>• Sensing materials</td>
<td></td>
<td>• AI for screening and design of functional materials</td>
</tr>
<tr>
<td>• Interrogation</td>
<td></td>
<td>• Quantum sensors for fossil energy applications</td>
</tr>
<tr>
<td>• Real-time gas composition analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• LIBS for subterranean chemical sensing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• In-boiler temperature field measurements</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Ultrafast Laser Measurements for Power Generation (Task 48)

Dan Hartzler, Chet Bhatt, Nari Soundararajan, Dustin McIntyre, B. Chorpening
Project Objective and Approach

• Objective
Provide a laser based time domain measurement of species and temperature inside a boiler along a single line of sight

• Benefits
Extreme environment non-invasive non-contact measurement that can provide information on combustion and Thermodynamic processes that would potentially allow tuning of input parameters to improve operation and efficiency

• Challenges
Need a better understanding of the time domain scattering processes in the extreme environment and whether the Measurement can be adequately made with nanosecond or picosecond pulsed laser systems.

• Approach
• Ambient Measurements
  Measurements in lab air with available lasers and spectrometer/camera systems
• Gas Cell Measurements
  Measurements in low pressure optically accessible gas cell to determine calibration characteristics
• Tube Furnace Measurements
  Measurements in optically accessible high temperature gas cell with optical access to understand measurement Characteristics in a more relevant environmental conditions
Rotational Raman Scattering

Temperature sensitivity of pure RRS bands is in the:

- Stokes/anti-Stokes ratio (RIGHT)
- Relative intensities of the high and low frequency RRS bands (BELOW)

Hammann 2015 - “Temperature profiling of the atmospheric boundary layer with rotational Raman lidar during the HD(CP)^2 Observational Prototype Experiment

Seeger 1996 – "Experimental comparison of single-shot broadband vibrational and dual-broadband pure rotational coherent anti-Stokes Raman scattering in hot air"
Testing the Concept

The Raman measurement at room T/P using the 2’ long gas cell.
Laser: 532 nm @ ~100 mJ/pulse, beam diameter ~ 9mm
Detector window was set to 6 ns (6’ length) →
High resolution spectrometer setting used in order to resolve the N2 and O2 rotational bands (high res. = Low bandwidth)
  • Thus, the vibrational bands can’t be observed at the same time as the rotational bands

Air was diluted with nitrogen so that the O2 concentration = 21% and 12%
The cell was located about 5’ from the telescope as shown below, data was measured at two points corresponding to ~2-2.5’ and 7-7.5’ from the telescope
Ambient Temperature Testing

Description

- Dimensions: 71 mm (2.8") ID tube x 61 cm (24") long (2.41 L)
- Windows: ø 75 mm, Fused Silica, MgF2 AR coating (R < 1.5% @ 532 nm)
- Gasket sealed, gas tight (low pressures only)
Concentration Calibration

Silica Raman originates from the gas cell windows. It can be used to normalize the gas Raman signal.
Concentration Calibration

Raman spectrum of 39, 56, 73 and 90% Ar in air

Peaks
- ~535 nm – N2+O2 rotational
- ~543 nm – Silica
- 580 nm – O2 vibrational
- 608 nm – N2 vibrational
Next Steps for Laser Measurements

EY20 Progress Highlights

• Safety analysis performed and infrastructure installed
• Installation of tube furnace in to B25 212
• Initial measurements in unheated seal tube completed successfully

Upcoming Milestones

• Optical testing in tube furnace with various gas concentrations and elevated temperature
• Installation of telescope optics equipment in lab for validation and signal enhancement

Technical Challenges and COVID Impacts

• Vendor issues have caused delays with fabrication efforts
• Time resolution limitations of existing laser and spectrometer
Goal: To understand boiler temperature to optimize thermal performance

- Accurate temperature data will validate combustion models for more efficient designs
- Aid in improving operation and reducing damage to the boiler from localized hot spots at part load conditions

Approach:
Design and develop green light emitting pyrotechnic particles with 2 protective layers that are shed from thermal stresses due to heating and cooling
Key Results and Highlights

- **Development of the reactive core**
  - Examined over 30 mixtures of green light emitting formulations and identified key components for metallic fuel, oxidizer, binder, and colorant
  - 5 compositions have been selected as candidates for further study to be refined and optimized for coating
  - Compositions selected can be tuned by the type of components or their amount to facilitated granulation and coating while minimizing impact to green light emission.

- **Granulation of the reactive core**
  - Developed a procedure to generate the desired size of granules (420 µm < size < 840 µm)
  - Working to improve method since yield is low (<10%) and a secondary treatment is needed to smooth into spherical shape for coating
Particle Coating Progress

Key Results, and Highlights

- Coating of the fine granulated core materials
  - A representative particle made with core Mg and multilayer ZrO$_2$/Al$_2$O$_3$ coatings showed to protect metal from oxidation at elevated temperatures (>600°C).
  - Developed method to normalize pyrotechnic surface with phosphates to improve adhesion of ZrO$_2$ middle layer
  - Demonstrated coating of multiple layers onto fine pyrotechnic particles
  - Continuing work will focus on improving adhesion and uniformity of the layers to improve thermal protection
- Fluidized spouted bed under development to enable more uniform coating of the small particles
- Modeling of the reactive particle
  - Constructing an analytical model for multi-layered composite particles with pyrotechnic core to predict optimized thickness, and breakage time curves during thermal shock in a simulated boiler environment
Progress and Challenges

Challenges

Identifying best green light emitting compositions

- Oxidant: KClO₄
- Fuel: Sn/Co/Mg
- Colorant: Ba(NO₃)₂, BaCl₂.2H₂O
- Binder: Ethyl Cellulose/Shellac
- Chlorine source: PVC/Parlon

Challenges:
- Highly heterogeneous system
- As high as 5/6 components with varying properties

Granulation of best composition

- (-20 +40 mesh, 420 – 840 μm)
- Best results so far:
  - Ethyl Cellulose (5w%), Ethanol (75wt%), Water (20wt%)
  - Instrument: High shear mixer

Challenges:
- Granules are not smooth (requires additional steps – ex. tumbling)
- Complexity of binder/solvent involvement in multiple stages
- Homogeneity in granules at the desired scale (400-800 μm)

Tumbling

Coating 1st layer (ZrO₂)
- Binder: Boehmite/E.C.
- Solvent: Ethanol

Coating 2nd layer (Al₂O₃)
- Binder: Boehmite/E.C.
- Solvent: Ethanol

Challenges:
- Coating single particles without avoiding contact
- Static – very small particles
- Possibility of redissolution of binder compromising granule integrity
Temperature Measurement via Reactive Particles Milestones

- Completion of 4 green light emitting components
- Complete construction or modification of laboratory scale reactor
- Initiate trial testing testing of coated pyrotechnic materials
- Particles manufactured and tested which display desired general shedding behavior pattern
- Complete construction or modification of laboratory scale reactor
- Completion design of laboratory reactor
- Complete design of spouted bed coater
- Complete design of spouted bed coater
- Complete construction of spouted bed coater
- Demonstrates coating of single ceramic layer onto pyrotechnic particles using spouted bed coater
- Particles manufactured and tested with **two** distinct temperature responses and spectral signatures

**Milestones**

- Q1/20
- Q2/20
- Q3/20
- Q4/20
- Q1/21
- Q2/21
- Q3/21
- Q4/21
- Q1/22
- Q2/22
- Q3/22
- Q4/22

**Status:**
- **Completed**
- **In progress**
- **Not initiated**
Multipoint Boiler Tube Temperature Monitoring (Task 32)

Juddha Thapa, Jared Charley, Benjamin Chorpening

**Measure temperatures from every tube**
- Expected spatial resolution 1 inch (200 ft long)
- Identify local hot spots on tube wall
- Spot maldistribution of steam flow at low power
- Gold-coated silica fiber possible: <1200°F (650°C), air
Distributed Temperature Sensing

Measuring temperature at multiple points along the optical fiber

e.g., Variable temperature zone and mm, cm or more sensor spacing

Optical Fiber

Luna OBR 4600

Rayleigh Scattering

Gold-coated fiber
Singlemode, up to 700°C

OFDR: high resolution and distributed temperature measurements
Plate Heater Apparatus in the Laboratory

- For testing distributed temperature measurement up to 700°C
- Electrically heated steel plates, 5 cm (2 inches) wide
- Thermocouples for temperature comparison, 2 on each plate near fiber
- Also for testing optical fiber installation approaches
Gold-coated Fiber Inside SS Tubing

Gold-coated fiber is flexible and fragile

Inserting 125µm diameter, flexible gold-coated fiber inside the 1/8\textsuperscript{th} inch SS tubing is difficult

Put it inside the stainless steel tubing to protect.

Insert Teflon tubing inside the SS tubing, use it to pull the fiber into the tube

Minimum bend radius of about 1.5 inches at 3 locations
Gold-Coated Fiber Test

Length of the gold fiber=5m

First cycle
Sensing Range (m)=5.000
Gage Length (cm)=1.000
Sensor Spacing (cm)=0.500
Temperature Calibration

Temperature reported by Luna software has larger difference to that of measured temperatures

Generate a temperature calibration equation and post process the data. LabView program has been written to post process the temperature data.

Calculated temperatures (red circles)

Temperatures reported by Luna device (blue circles)
Set temperature 650°C

Spectral shift along the length of the gold-coated fiber from: 19°C to 600°C.
Temperatures inside the graph are the set values.

Temperature Calibration

Where $T$ is temperature in °C and $SS$ is the spectral shift in GHz

Difference between the calculated and measured temperatures less than 8°C
After postprocessing, Error > ±10°C at higher temperatures (500 and 600°C)

Spikes result of bad data points
After adjustments

- Increased gauge length
- Annealed the gold-coated fiber up to 600°C

RT = 22°C

The gold-coated fiber could be used for the distributed high temperature measurements in the boiler tube environment.

After Postprocessing, Error < ±10°C vs thermocouples
Status and Future Work

- Lab-bench testing successful
  - Adjusted measurement settings
  - Anneal fiber
  - Temperature accuracy and resolution checked
- Dry run of installation and testing in NETL laboratory to prepare for pilot-scale test at UNDEERC
  - Installation of the gold-coated fiber into a 1/8 inch stainless steel tube for protection
  - Included mechanical connection to a 30 meter section of ordinary silica fiber (lead-in)
  - Tested through several temperature cycles up to 600°C using the plate heater apparatus
  - Custom postprocessing of data necessary to obtain accurate temperature readings across the temperature range (within 10°C)
- Pilot scale test put on hold in March 2020 due to COVID-19, expected to move forward in 2021
- Power plant field test

2-inch wide heated bars approximate boiler tubes
Questions

Benjamin.Chorpening@netl.doe.gov

This work was funded by the Crosscutting Research Sensors & Controls Program, through FWP-1022427.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.