UK-US Collaboration in Fossil Energy Technology

Task 3: Gas turbines fired on syngas and other fuel gases

14 May, 2009
Pittsburgh
Overview

- Partners
- Background
- Objectives
- Work program
- Results / achievements
- Benefits of collaboration
- Future activities

UK:
Alstom Power Ltd
Cranfield University*
Siemens Industrial Turbomachinery Ltd

US:
Oak Ridge National Laboratory
Siemens Energy Inc*

*Task Leaders
### Advanced Turbine Operating Conditions

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Combustor Exhaust Temp, °F (°C)</strong></td>
<td><del>+2700 (</del>+1480)</td>
<td><del>+2700 (</del>+1480)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Turbine Inlet Temp, °F (°C)</strong></td>
<td><del>-2600 (</del>-1370)</td>
<td><del>-2600 (</del>-1425)</td>
<td><del>-1150 (</del>-620)</td>
<td><del>-1400 (</del>-760) (HP) <del>-3200 (</del>-1760) (IP)</td>
</tr>
<tr>
<td><strong>Turbine Exhaust Temp, °F (°C)</strong></td>
<td><del>-1100 (</del>-595)</td>
<td><del>-1100 (</del>-595)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Turbine Inlet Pressure, psig</strong></td>
<td>~-265</td>
<td>~-300</td>
<td>~-450</td>
<td>~-1500 (HP) ~-625 (IP)</td>
</tr>
<tr>
<td><strong>Combustor Exhaust Composition, %</strong></td>
<td>CO₂ (9.27) H₂O (8.5) N₂ (72.2) Ar (0.8) O₂ (8.6)</td>
<td>CO₂ (1.4) H₂O (17.3) N₂ (72.2) Ar (0.9) O₂ (8.2)</td>
<td>H₂O (82) CO₂ (17) O₂ (0.1) N₂ (1.1) Ar (1)</td>
<td>H₂O (75-90) CO₂ (25-10) O₂ N₂ Ar (1-1.7)</td>
</tr>
</tbody>
</table>

**Background – Novel Environments**

Current engines with fuel flexibility (Crude oil, Diesel, Dirty contaminants)
Background – Target Areas

IGCC Plant

- Improved Efficiency
- Fuel Flexibility
- NG, Syngas, H₂
- Low Emissions
- Reduction in Plant Cost$/KW
- CO₂ Sequestration Ready

Program Development and Major Activities are Driven by Plant Level Goals

Compressor
- Increased PR
- Efficiency Improvement

Combustor
- Fuel flexible
- Low Nox
- Increased Temperature

Turbine
- Increased inlet temperature
- Improved efficiency
- Reduced in cooling and leakage

Exhaust Temperature
- Increase for maximized combined cycle performance.

Power Output
- Increased to lower $/KW

Improved Coatings
- High temperature capability
- Reduction in thermal conductivity
Task focused on:
- changes expected in the future fuel gases
- impact on hot gas path components in the power turbine
  - blades, vanes and combustor cans
  - enhanced corrosion, erosion and deposition
  - reduced component lifetimes
  - reduced viability of gas turbines
- correct selection of advanced materials
  - corrosion resistant coatings
  - thermal barrier coatings (TBCs)
  - route to counter higher levels of contaminants
Alloy degradation depends on gas composition.

A set of boundary conditions needs to be established for each working fluid.

An evaluation into the effect of corrosion species and degradation mechanisms is ongoing.
Deposition of molten reactants from the ash creates the aggressive environment. Molten salts cause initial rapid hot corrosion via fluxing reactions between planar interlamellar porosity resulting in debonding of the surface lenticular splats.

Formation of red deposit on the blade, deposit formation similar to the one observed due to Fly Ash.

Post combustion concentration vary from above concentrations.
Fuel Compositions for Varied Coal/Biomass Feedstocks

Varied concentration of contaminants can result in varied materials behavior.
Fate of Gasified Fuel Particle

- GASIFIED FUEL PARTICLE
  - reaction
  - vaporisation
  - no response
  - less volatile

- VAPOUR
  - condensation
  - more volatile
  - vaporisation

- CHLORIDES, ELEMENTS, SULPHIDES, HYDROXIDES, OXIDES, etc
  - reaction
  - condensation/reaction
  - deposition

- PARTICULATES
  - entrainment
  - particulate removal

- ASH AND SLAG
  - residue withdrawal

- SOLID GASIFICATION RESIDUES
  - disposal/utilisation

- FLUE GASES
  - dust
  - vapour
  - stack
### Volatility of Trace Species in Gasification

<table>
<thead>
<tr>
<th>Increasing Volatility</th>
<th>Element</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hg, Sb, Se (As, V, B)</td>
</tr>
<tr>
<td></td>
<td>Cd, Pb, Sn, Zn (As, B)</td>
</tr>
<tr>
<td></td>
<td>Co, Cu, K, Mn, Mo, Na</td>
</tr>
<tr>
<td></td>
<td>As, Ba, Be</td>
</tr>
<tr>
<td></td>
<td>Ca (V, As, B)</td>
</tr>
</tbody>
</table>

( ) sensitive to air vs oxygen gasification

#### Effect of Hot Gas Filtration on Alkali Levels in Gasification Gases

![Graph showing the effect of hot gas filtration on alkali levels in gasification gases](image_url)
Gas Contaminant Levels in Combusted Gasifier-derived Fuel Gases

![Diagram showing gas contaminant levels in different systems.](Image)

- **Biomass-fired systems**
- **Biomass-coal co-fired systems**
- **Coal-fired systems**

<table>
<thead>
<tr>
<th>System Type</th>
<th>SOX (vpm at 1 bar)</th>
<th>HCl (vpm at 1 bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal-fired systems</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Biomass-fired systems</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Biomass-coal co-fired systems</td>
<td>1000</td>
<td>10000</td>
</tr>
</tbody>
</table>

- **Hot gas stream**
- Volatile K compounds, SOX, HCl

- **Cooler metal surface**
- $K_2SO_4$

Dewpoint Temperature (°C) vs. [K] (ppb-wt)

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IGCC Materials Behavior – 3
Bond coat Behavior in Combusted Environments

Need to investigate the kinetics of mixed oxide formation as TGO.
Task 3: Objectives

• To quantify the major effects of low calorie value (LCV) fuels, including coal, biomass and waste derived syngas, on gas turbine materials to support component design and life prediction.

• To characterize the range of fuel gas atmospheres anticipated in coal and biomass gasification systems.

• To model the range of gases and expose selected alloy/coating combinations to burner rig testing and determine deposition rates and the erosion/corrosion resistance of state-of-the-art material systems over the appropriate temperature range.

• To identify the fuel/operating conditions and the candidate alloy and coating combinations which are most appropriate to the gas turbine power generating systems under consideration.
Task 3: Major Deliverables

- Characterization maps showing the range of gas turbine atmospheres likely to result from the gasification of various coal, biomass and waste sources.

- Quantification and ranking of critical alloys and coatings in terms of their erosion and corrosion resistance and the provision of data on selected alloys and alloy/coating combinations exposed under burner rig test conditions in a range of simulated industrial gas turbine syngas atmospheres (in progress).

- Definition of fuel/operating combinations leading to service problems, consideration of avoidance strategies and the development of lifing procedures (Phase 2).
Task 3: Test Conditions

Burner rig tests based on:
- Diesel fired (Alstom Power, UK);
  - equivalent to 4 ppm Na, 4 ppm K, 1 wt% S in liquid fuel
- IGCC derived syngas plus coal-ash loading (Siemens, USA)
- H₂ enriched IGCC derived syngas plus coal-ash loading (Siemens, USA)
- Pyrolysis based fuel gas (Siemens, UK)

Burner rig test conditions defined in terms of inputs to rig or targets in exposure section, remembering:
- Natural gas fired
- Atmospheric pressure (need to compensate for difference to maintain dewpoints)
- Add contaminants to combustion chamber
# Burner rig – Test Conditions

<table>
<thead>
<tr>
<th>Parameter to set</th>
<th>Units</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UK / US</strong></td>
<td></td>
<td>UK</td>
<td>US</td>
<td>US</td>
<td>UK</td>
</tr>
<tr>
<td>Gas temperature at entry to exp. section</td>
<td>°C</td>
<td>1180</td>
<td>1180</td>
<td>1250</td>
<td>1180</td>
</tr>
<tr>
<td>Gas velocity</td>
<td>m/s</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Dust (type)</td>
<td></td>
<td>-</td>
<td>pf fly ash (sieved)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dust loading</td>
<td>ppm or mg/h</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SO\textsubscript{X}</td>
<td>vppm</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>HCl</td>
<td>vppm</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H\textsubscript{2}O</td>
<td>% vol</td>
<td>8.7</td>
<td>8.7</td>
<td>~20</td>
<td>9.7</td>
</tr>
<tr>
<td>Na</td>
<td>ppb or mg/h</td>
<td>125 ppb</td>
<td>125 ppb</td>
<td>125 ppb</td>
<td>80</td>
</tr>
<tr>
<td>K</td>
<td>ppb or mg/h</td>
<td>125 ppb</td>
<td>125 ppb</td>
<td>125 ppb</td>
<td>80</td>
</tr>
</tbody>
</table>
24 materials systems selected

12 UK
12 US

**Base alloys (UK+US)**
- CMSX4
- IN738LC
- Haynes 230
- MarM247
- IN939
- CM247LC
- Hastelloy X
- PWA1483

**Coatings (UK+US)**
- Corrosion resistant or bond coatings
  - HVOF ‘LCO22’
  - EB MCrAIY (PWP 286)
  - HVOF SV21
  - APS SL30
  - CERAL 10
  - Amdry 995
  - 2464
  - 2231
  - 2453
- Thermal barrier coatings (TBCs)
  - EB-PVD
  - APS
  - Porous APS
Cranfield Burner Rig: Diesel Oil + Contaminants

Bond coated HastX

Alloy (CM)247LC

IN939

Nominal inlet gas temperature = 1180 °C
Nominal outlet gas temperature = 930 °C
Nominal external probe temperature = 950 °C

Diesel Oil
nominal contaminant levels
125 ppb Na (weight)
125 ppb K (weight)
625 ppm SO2 (weight)
Water content 11.3% vol.

Probe temperatures measured at the mid-point. 60-70°C variation along probe length.
Preliminary Results Confirm the Need for an Increased Integrity of Coated Substrates

Uncoated substrate

Overlay coated substrate

Bond coat & TBC coated substrate

Less severe damage of coated specimens compared to bare alloys
Materials Comparison: 1000 hrs / $T_{\text{metal}}$ 750 °C

<table>
<thead>
<tr>
<th>Diesel oil w impurities</th>
<th>Syngas w impurities + Dust</th>
<th>High H2 w impurities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bond coated IN939</td>
<td>Bond coated IN939</td>
<td>Bond coated IN939</td>
</tr>
<tr>
<td>Bond coated (CM)247LC</td>
<td>Bond coated (CM)247LC</td>
<td>Bond coated (CM)247LC</td>
</tr>
<tr>
<td>Bond coated PWA1483</td>
<td>Bond coated PWA1483</td>
<td>Bond coated PWA1483</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Corrosion / erosion</td>
<td>Corrosion &amp; moisture</td>
</tr>
</tbody>
</table>
Alloy Performance Comparison

\[(T_{\text{gas}} = 1180 \, ^\circ\text{C} / T_{\text{metal}} = 950 \, ^\circ\text{C})\]

**IN939 (Diesel oil)**
1000 h (Test 1)

**IN939 (Syngas)**
1000 h (Test 2)

Increased oxide thickness and depth of degradation in IGCC environments

Adhered scale

Eroded scale
Ongoing Work

• Complete the characterization to test samples from burner rig test 3 (high hydrogen) and 4 (biomass) to determine extent of damage compared to first two tests.

• Quantification and ranking of critical alloys and coatings in terms of their corrosion resistance exposed under burner rig test conditions in a range of simulated industrial gas turbine syngas atmospheres.

• Definition of fuel/operating combinations leading to service problems, consideration of avoidance strategies and the development of lifing procedures.

Increase confidence in materials data in multi-fuel operation, specifically driven by the engine requirements.
Potential Activities

- Evaluation of material performance under multiple drive gas conditions to evaluate impact of fuel flexibility.
- Determining the degradation of state-of-the-art materials/coatings under such IGCC/CCS operating conditions – covering oxidation, corrosion, erosion, thermal cycling (including interactions with mechanical properties).
- Provide novel concepts for better oxidation/corrosion resistance alloys and coatings.
- Development and validation of life prediction methods and extrapolation to high pressure/high velocity environments.
- Assessment of current limitations of the Cranfield burner rig to test high temperature/high velocity conditions for IGCC/CCS environments - potential to upgrade the rig capability for testing DOE 2010 goals (T_{gas} combustor exhaust ~1500 °C) with corrosive and ash loading for simulation of IGCC/CCS environments.