Characterization of 30 MW$_{th}$ Circulating Fluidized Bed Boiler under Oxy-Combustion Conditions

$3^{rd}$ Oxyfuel Combustion Conference, September 10 – 13, 2013
Ponferrada, Spain

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Outline of presentation

- Introduction
- Development approach from small to large scale
- CFB boiler, test programs and fuels
- Research priorities
- Furnace heat transfer
- Process performance generally
- Summary of operational experiences
- Conclusions

Acknowledgement

The work leading to these results has been co-financed under the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 239188 and the EEPR09-CCS-COMPOSTILLA Project (European Union's European Energy Programme for Recovery).

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Introduction

- Prior to the CIUDEN CFB facility, Foster Wheeler has conducted several oxy combustion test campaigns at smaller pilot scale
  - VTT´s 100 kWth CFB test rig
  - CanmetEnergy´s 1 MWth oxy-CFB pilot plant
- Several feasibility studies to develop the Flexi-Burn CFB boiler concept
- The Oxy-CFB-300 Compostilla project to develop 300 MWe scale air/oxy flexible CFB boiler design has been a major driving force for vast R&D activities since 2010.
- CIUDEN 30 MWth Oxy-CFB pilot plant was commissioned in 2011-2012, and formed an important platform in testing activities
- Two EU projects, FP7 and EEPR funded, formed the frame for partnering and funding of this development.
Development approach from small to large scale

- **Bench scale** (0.6 m)
  - VTT pilot (0.1 MW<sub>th</sub>, 8 m)
- **M</m>OX</m>-CFB-300 (37 m)
- CIUDEN TDP (15 MW<sub>th</sub>, 20 m)
- CANMET pilot (1 MW<sub>th</sub>)
- **Lagisza 460 MWe (48 m)**

AIR /OXY differences

AIR: scale-up validation

OXY/ AIR
CIUDEN 30 MW$_\text{th}$ Oxy-CFB Boiler

- **1. Water tubes**
- **2. Cyclone**
- **3. Loop-seal**
  - a. Direct material recirculation
  - b. Intrex material recirculation
- **4. Intrex**
- **5. Heat recovery zone**
- **6. Convective evaporator**
- **7. Economizer**
Test programs at the CIUDEN Oxy-CFB Boiler

General objectives:

- Demonstrate air/oxy CFB combustion in large scale (Flexi-Burn CFB)
- Generate process data on various fuels for design verification and validation of models and design tools (1D and 3D CFB furnace models, 1D CFB dynamic model, emission models)
- Scale-up effects
- Gain operating experience in oxy combustion process and auxiliary equipment
- Demonstrate integrated operation of CFB and CPU
- Identify needs for future development
### Tested fuels

#### FLEXIBURN CFB

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Anthracite</th>
<th>Anthracite/ petcoke (70/30 w-%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proximate analysis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total moisture</td>
<td>w-% (a.r.)</td>
<td>5.41</td>
<td>4.77</td>
</tr>
<tr>
<td>Ash content (815°C)</td>
<td>w-%, d.s.</td>
<td>31.92</td>
<td>22.95</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>w-%, d.s.</td>
<td>6.05</td>
<td>7.03</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>w-%, d.s.</td>
<td>62.03</td>
<td>70.02</td>
</tr>
<tr>
<td><strong>Ultimate analysis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>w-%, d.s.</td>
<td>60.53</td>
<td>70.12</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>w-%, d.s.</td>
<td>1.83</td>
<td>2.20</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>w-%, d.s.</td>
<td>0.88</td>
<td>1.07</td>
</tr>
<tr>
<td>Sulphur</td>
<td>w-%, d.s.</td>
<td>1.01</td>
<td>2.17</td>
</tr>
<tr>
<td>Oxygen</td>
<td>w-%, d.s.</td>
<td>2.73</td>
<td>1.50</td>
</tr>
<tr>
<td><strong>Gross calorific value</strong></td>
<td>MJ/kg (d.s.)</td>
<td>22.98</td>
<td>26.49</td>
</tr>
<tr>
<td><strong>Net calorific value</strong></td>
<td>MJ/kg (d.s.)</td>
<td>22.58</td>
<td>26.02</td>
</tr>
</tbody>
</table>
Priorities in CFB process evaluations

- Knowledge on differences between air and oxy combustion
  - Extend validity of existing models for oxy-fuel combustion
  - Analysis of process data by using 1D CFB, 3D CFB and 1D Dynamic models
- Heat transfer in furnace and backpass (thermal design of large boiler)
- Combustion performance, unburned carbon in ash
- Emissions (SO2 & SO2 control by limestone, NOx & NOx control by SNCR, CO, NH3 slip) → Conclusions for the large scale design
- Effect of oxygen content in oxidant streams on process performance
- Limestone compounds in bed (related to sulphur capture mechanisms and bed behaviour in hot loop)
- Dynamic behaviour of the oxy-CFB process and validation of dynamic simulation model.
- Corrosion (esp. acid dew point in cold end), fouling, air ingress
- Operational aspects
- Performance of auxiliary equipment (any oxy combustion related issues)
Procedure for furnace heat transfer evaluation

- Furnace vertical temperature, pressure and oxygen profiles
- Detailed analysis of solids composition and mass balance
- Solids density profile correlations
- Comparison of solids behaviour in air and oxy combustion
- Back calculations to verify the model accuracy with the test data
- If necessary, tune the model parameters to get the best fit with the test data
- Combustion profile
- Heat release profile
- Validation of 3D CFB model by CIUDEN CFB data
- Comparison of heat transfer in air and oxy combustion
Measurements for heat transfer analysis

- Measured furnace vertical temperature, pressure and oxygen profiles
- Fuel and limestone flow
- Ash weighing for determination of distribution between fly and bottom ash
- Solids sampling for their physical and chemical characterization
- Furnace profile measurements for solids and gas
- Heat flux measurements (integrated in membrane walls at three elevations) for direct monitoring of heat transfer (air vs. oxy)

Heat flux sensors for direct heat transfer measurement

Chordal termocouple
Verification of 1D CFB model by back calculations

**Examples**

- Particle convection is the primary mechanism of heat transfer in CFB furnace
- Solids material balance and solids density profile are key factors in particle convection.
- Correlation was developed for the CIUDEN CFB including
  - Fluidization velocities,
  - Furnace PSD and
  - Bed inventory (mass) in furnace
- Correlation predicts solids densities of both combustion modes well
Modeling of heat transfer

• Heatflux sensors installed at different elevation in furnace
  ➔ Direct comparison of heat flux locally between air and oxy combustion

• Correlating heat transfer coefficient with key process parameters: solids density, temperature

• Tuning the parameters for all test data with different fuels.
  ➔ Tool to compare heat transfer in air and oxy combustion mode in the CIUDEN CFB.
Comparison of furnace temperature in air and oxy combustion test points with near similar operating conditions

- The temperature level in oxygen-fired case is slightly higher due to higher fuel input.
The heat transfer panels are located at different walls. Other surfaces are refractory lined.

The heat flux in oxygen-fired case is slightly higher due to higher furnace temperature.
<table>
<thead>
<tr>
<th>Oxy compared w/ air combustion¹</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace temperature</td>
<td>Equal</td>
</tr>
<tr>
<td></td>
<td>Oxidant O₂ level can be used for temperature control in oxy → adds up flexibility in oxy control over the load range</td>
</tr>
<tr>
<td>Solids density profile</td>
<td>Equal</td>
</tr>
<tr>
<td></td>
<td>With same fuel/limestone particle size</td>
</tr>
<tr>
<td>Furnace heat transfer</td>
<td>Equal</td>
</tr>
<tr>
<td></td>
<td>Furnace temperature, solids density profile and feed material characteristics are the primary variables.</td>
</tr>
<tr>
<td>Unburned carbon in ashes</td>
<td>Equal</td>
</tr>
<tr>
<td></td>
<td>Generally higher at low load and lower in high load oxy operation</td>
</tr>
<tr>
<td>CO emission</td>
<td>Slightly higher</td>
</tr>
<tr>
<td>SO₂ capture by limestone</td>
<td>Higher</td>
</tr>
<tr>
<td></td>
<td>Higher in oxy combustion due to higher SO₂ concentration</td>
</tr>
<tr>
<td></td>
<td>Retention is reduced at low temperature/load due to direct sulphation mode (i.e. below calcination temperature)</td>
</tr>
<tr>
<td>NOₓ emission</td>
<td>Equal / lower</td>
</tr>
<tr>
<td></td>
<td>Lower at high load/high temperature</td>
</tr>
<tr>
<td>N₂O emission</td>
<td>Higher/Equal</td>
</tr>
<tr>
<td></td>
<td>Fuel dependent, similar temperature dependence as in air combustion</td>
</tr>
</tbody>
</table>

¹ Conclusions and remarks are valid for ppm’s. When expressed as mg/MJ, all are lower in oxy combustion.
Summary of operational findings

- Boiler operation and performance generally not outstandingly different (oxy vs. air)
- Furnace control with oxidant O2 demonstrated; ~similar oxidants used as in planned OXY-CFB-300 boiler concept
- Switches between the operating modes (air&oxy) can be done smoothly by automated sequence. No process technical issues originating from the oxy combustion conditions have been experienced.
- Correct PSD (crushing) of anthracite is important due to hard ash.
- Optimal furnace operating parameters (e.g. temp.) with the design fuel were determined
- No clear re-carbonization issues encountered, however conditions in fluid bed heat exchanger (INTREX™) were not fully representative (low solids outlet T)
- No significant fouling has been observed. Neither any corrosion issues were observed in the CFB hot loop and heat recovery area.
- Acid dew point issues avoidable through limestone feeding, control of surface temperatures and elimination of leaks (important also for flue gas CO2). Test duration was obviously too short to experience boiler tube degradation.
Conclusions

• An extensive process database was accumulated during the boiler commissioning and two test projects at the CIUDEN Oxy-CFB boiler in 2011-2012.
• Major focus in data evaluation and modeling activities was to understand the impact of oxy combustion condition on combustion, emissions and heat transfer.
• An important result was that with the same operating parameters, furnace heat transfer appears to be at the same level as of air combustion.
• The tests confirmed the previous findings from smaller scale pilots that there is no major difference in process operation compared to air combustion.
• Valuable experience on operation of the oxyfuel CFB process was gained.

⇒ OXY-CFB-300 boiler design verification
Thank you

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