Development of High Efficiency CFB Technology to Provide Flexible Air/Oxy Operation for Power Plant with CCS

FLEXI BURN CFB
WP4: Boiler design and performance

2\textsuperscript{nd} Project Workshop, 6\textsuperscript{th} February 2013, Ponferrada
WP4: Boiler design and performance

WP7: Coordination and dissemination

WP1: Comparison of air- and oxy-firing

WP2: Development of design tools

WP3: Demonstration tests at large pilot unit and commercial scale air fired unit

WP4: Boiler design and performance

WP6: Feasibility and readiness for the utilization of the technology within different regions in EU

WP5: Power plant integration, optimization and economics

Viable boiler design

Viable power plant

Supporting R&D work

Technology demonstration and background for the commercial scale design process
WP4 Main objectives and tasks

The main objective is to develop a feasible Flexi-Burn® CFB*) boiler design with optimized performance, cost and reliability.

Another objective is to increase the awareness of material issues related to the oxygen-firing process with extensive flue gas recycling.

• Task 4.1, Design and layout development for the selected cases (FWEOY, LUT)
  – Alternative boiler design configurations; optimization concerning combustion, emissions, water-steam circuit, dynamics, structures and costs
  – Location of heat surfaces and feed points of oxidant and fuel (mass and energy balances)
  – Performance predictions & 1D/3D calculation with the validated models

• Task 4.2, Materials of FLEXI BURN CFB power plant (VTT, FWEOY, ENDESA, EDP)
  – Most of the material research is carried out in other projects which results are transferred and utilized to guide the materials selection for the boiler (prevailing conditions and requirements, tube materials, cold end materials)

• Task 4.3, Development of FLEXI BURN CFB controls (FWEOY)
  – Control method development and strategy selection for boiler including auxiliary systems
  – Analysis of operation procedures and various operational situations

• Task 4.4. Vertical BENSON OT evaporator design and analysis for large scale FLEXI BURN CFB (FWEOY)
  – Optimization of evaporator design (tubing, headers, connecting piping, arrangement of star distributor and w/s separators)

*) "Flexi-Burn" is a trademark of Foster Wheeler AG, registered in the U.S., EU, Finland
Task 4.1: Design and layout development for the selected cases

Partners: FWEOY & LUT
Water-steam circuitry of the Flexi-Burn CFB boiler

Final concept taking into account design fuels, both operation modes, load range, dynamics and USC boiler tube material issues
Boiler concept, main features

• **Design basis**
  – Oxy-fuel combustion is considered as the primary operation mode of the boiler.
  – The water-steam cycle and boiler have been designed for maximum efficiency in oxy mode. Ultra-supercritical steam parameters with one reheat stage are applied.
  – 100 % MCR load is therefore defined for the oxy mode, while the maximum load in air mode has been set at 90 % MCR (gross) based on technical limitations and specified operating times in different modes.

• **There is no direct heat recovery from flue gases to oxidant (no RAPH or alike).**

• **Remaining flue gas heat is utilized in HP Eco and LP Eco.**

• **Bag filter unit enables low emissions and diverse fuel selection.**

• **Heat recovery system (HRS) with plastic HX tubes cools the flue gas further before CPU.**

• **Oxygen from ASU is preheated up to 170 °C with hot water and condensate from LP Eco.**

• **Fans with flexible air/RFG inlet are used in the primary and secondary oxidant systems.**

• **Oxidant is prepared in static mixers, which are separate for the primary, secondary and INTREX oxidant (PO, SO, IO) systems.**
Boiler concept, Flexi-Burn CFB furnace design

- Low mass flux BENSON once-through technology licensed by Siemens AG, Germany
- Furnace with gas tight membrane wall structure
- Heat surface setup shall fulfill the needs of SH and RH steam in both operating modes, within the load range.
- 4 parallel steam-cooled separators based on 3D modeling of the furnace (SH I)
- Enclosures of the COD and HRA form SH II.
- Tube bundles in HRA (SH III)
- SH IV tube bundles are placed in four parallel INTREX units fluidized with h-p oxidant.
- RH I located in HRA is provided with steam bypass for RH temperature control w/o sprays.
- Platen type panels hung from the top of the furnace act as RH II
- HP Economizer is connected in parallel with conventional feed water heaters.
- LP Economizer heats up condensate.

1. Furnace
2. INTREX
3. Solids separator
4. Cross-over duct (COD)
5. Heat recovery area, HRA (RH 1, SH3, Eco)
6. HP Eco and LP Eco
7. Flue gas to filter unit
### Flexi-Burn CFB furnace design vs. SC-OTU and OXY references

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>CIUDEN</th>
<th>Flexi-Burn 300</th>
<th>Lagisza</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Furnace dimensions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>m</td>
<td>20</td>
<td>37</td>
<td>48</td>
</tr>
<tr>
<td>Width</td>
<td>m</td>
<td>2.9</td>
<td>28</td>
<td>27.6</td>
</tr>
<tr>
<td>Depth</td>
<td>m</td>
<td>1.7</td>
<td>7</td>
<td>10.6</td>
</tr>
<tr>
<td>Number of separators</td>
<td>-</td>
<td>1</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td><strong>Thermal power</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxy mode (max.)</td>
<td>MW</td>
<td>30</td>
<td>708</td>
<td>--</td>
</tr>
<tr>
<td>Air mode</td>
<td>MW</td>
<td>14.5</td>
<td>647</td>
<td>966</td>
</tr>
<tr>
<td><strong>SH steam flow</strong></td>
<td>t/h</td>
<td>47.5</td>
<td>845</td>
<td>1300</td>
</tr>
<tr>
<td><strong>SH steam temperature</strong></td>
<td>°C</td>
<td>250(^1)</td>
<td>600</td>
<td>560</td>
</tr>
<tr>
<td><strong>SH steam pressure</strong></td>
<td>bar</td>
<td>30</td>
<td>279</td>
<td>275</td>
</tr>
<tr>
<td><strong>RH steam flow</strong></td>
<td>t/h</td>
<td>--</td>
<td>745</td>
<td>1101</td>
</tr>
<tr>
<td><strong>RH steam temperature</strong></td>
<td>°C</td>
<td>--</td>
<td>601</td>
<td>580</td>
</tr>
<tr>
<td><strong>RH steam pressure</strong></td>
<td>bar</td>
<td>--</td>
<td>56.5</td>
<td>50.3</td>
</tr>
<tr>
<td><strong>Feedwater temperature</strong></td>
<td>°C</td>
<td>170</td>
<td>290</td>
<td>290</td>
</tr>
</tbody>
</table>

**Notes:**
1) After spraying
2) Steam parameters in Lagisza at turbine inlet
Analysis of the final furnace configuration with 3D model

• The calculations of the final furnace design are in progress.
• In these examples, the fuel flow distribution has been modified to achieve more uniform temperature field:
• The following slides present example figures of air fired (90% load) and oxygen fired (100% load) cases.
Analysis of the final furnace configuration with 3D model

Temperature

Air, 90%          Oxy, 100%          Air, 90%          Oxy, 100%

Analysis of the final furnace configuration with 3D model

Oxygen

Air, 90%  Oxy, 100%  Air, 90%  Oxy, 100%
Analysis of the final furnace configuration with 3D model

Carbon monoxide

Air, 90%  Oxy, 100%

Air, 90%  Oxy, 100%
Analysis of the final furnace configuration with 3D model

Heat flux

- Air, 90%
- Oxy, 100%
- Air, 90%
- Oxy, 100%
Task 4.2, Materials of FLEXI BURN CFB power plant

Partners: VTT, FWEOY, ENDESA, EDP
Materials of FLEXI BURN CFB power plant

• VTT has carried out investigations on furnace wall and superheater materials
  – Preliminary conclusions on materials corrosion related to water-wall conditions in Oxy-fuel combustion (literature review and interpretation)
  – Thermodynamic calculations for superheater/reheater materials in oxy combustion conditions
  – Basic understanding of the corrosion mechanisms of materials is of extreme importance to take benefit of short-term material tests in the connection of full scale demonstration tests, etc.

• FWEOY has performed material studies to support the material selection for the Flexi-Burn CFB boiler
  – Main concerns relating to materials performance in oxygen-fired CFB boiler are increased CO₂ and H₂O content in the process when compared to air-fired CFB boiler.
  – Five different areas with different process conditions, and thus different requirements for materials, were recognized in an oxy-fuel CFB boiler:
    • Furnace membrane walls
    • Grid nozzles and wind box
    • INTREX superheater tubes
    • Convective superheater tubes
    • Recycled flue gas lines
Main concerns regarding the materials performance were:

- Porous oxide formation caused by increased $\text{H}_2\text{O}$ (and $\text{CO}_2$) content
- Carburisation caused by high $\text{CO}_2$ content and carbon-rich deposits
- Higher $\text{SO}_2$ and $\text{HCl}$ content in combustion gases

A plan to address the issues was developed

- Materials testing in laboratory conditions
- Process studies (thermodynamic process calculations) to understand the impact of process conditions prevailing in particular process area on process behavior and/or materials
- Field tests with corrosion, fouling and acid dew point probes at TDP
- Study of oxygen safety in oxidant systems

Process studies, laboratory corrosion tests and field tests were performed for typical materials that are used in each section.
Materials of FLEXI BURN CFB power plant

• Conclusions highlighting the guidelines for material selection were drawn.

• Material selections for the ducts and pressure parts have been adapted to the guidelines.
  – Pressure part material selection based on steam conditions appears valid.
  – In flue gas and oxidant ducts, avoiding low surface temperatures is important (besides material selection). Air in-leakage or lack of insulation can cause cold spots in flue gas ducts.
  – According to thermodynamic calculations, limestone injection is an effective measure against acid dew point issues.
  – Probe tests support these findings.
Task 4.3, Development of FLEXI BURN CFB controls

Partners: FWEOY
Development and testing of FLEXI BURN CFB controls

- Two major steps in the development of control strategy:
  1) Understanding the (steady-state and dynamic) behavior of the plant, i.e. modeling
  2) The control concept development
- Integration to the ASU and the CPU units is considered only as (mass and energy) input/output flows.
- The major issue in modeling is to discover the properties of oxy-firing mode and the principle differences between the operations of air- and oxy-combustion.
- Tests for validation of the new boiler model – such as reactivity tests and load changes in oxy and air modes – have been carried out at VTT (~0.1 MW) and CIUDEN (~15 MW).
- Results of simulation studies done under WP 2 have been utilized in development of control concept for the Flexi-Burn CFB boiler.
- Various dynamic tests have been carried out in Apros simulation environment, such as load ramps, load step changes, switch between the air and oxy combustion mode, and thermal inertia test.
Control concept of USC OTU Flexi-Burn CFB boiler

• Main controls of the boiler:
  • The operator can select the boiler load control mode from steam pressure control or steam flow control.
  • The boiler master controller will control fuel, feedwater and air/oxygen/oxidant flow through appropriate masters to meet pressure/mass flow set point value.
  • Boiler master controller output is forwarded to ASU and CPU master controllers.
Control concept of USC OTU Flexi-Burn CFB boiler

• **Fuel and feedwater master controllers:**
  • The fuel master's objective is to match the heating value compensated solid fuel flow to the solid fuel firing demand as dictated by the boiler master.
  • In balance control the feedwater flow is calculated to ensure stable steam temperature after final superheating stage.

• **Oxygen and oxidant control:**
  • The combustion oxidant master provides a single point control for the total oxygen flow.
  • The total oxygen volume flow depends on the boiler master output demand and fuel specific oxygen/power parameter. Total oxygen is divided for different oxidants.
  • Oxygen and RFG flows to PO and SO mixers are controlled independently. $O_2$ content of each oxidant stream is controlled by corresponding RFG flow (fan with speed control).
  • The operator can adjust oxidant $O_2$ setpoints. It is a feasible method for adjusting furnace temperatures, unavailable in normal air firing.

• **ASU – boiler interface and boiler – CPU interface controls:**
  • ”ASU follows”; ”CPU follows” is the basic approach.
  • ASU keeps pressure in the GOX duct at setpoint, utilizing buffers when needed.
  • CPU adjusts the pressure at its inlet, i.e. at boiler – CPU interface.
Task 4.4, Vertical BENSON OT evaporator design and analysis for large scale FLEXI BURN CFB

Partners: FWEOY
Vertical BENSON OT Evaporator design and analysis for large scale FLEXI BURN CFB (FWEOY)

• SIEMENS has carried out thermohydraulic analysis of the evaporator
  – Two tube sizes were compared regarding tube cooling and static and dynamic stability.

• Main target of this stage of investigation was to obtain a comprehensive picture of the evaporator characteristic, in order to get a basis for the determination of the final tube design. In this context the following investigations have been performed:
  – Detailed investigations of evaporator thermo-hydraulic behavior at steady state conditions for different load case (40 – 100 % MCR) specifications
  – Investigation of evaporator static and dynamic stability
  – Tube cooling analysis (investigation of inner heat transfer and tube wall temperatures)
  – Thermal stress investigation

• Summary of results:
  – Studied tubes proved feasible, with different ranking regarding tube cooling and dynamic stability.
  – Selection can be based on other criteria such as structural issues.
WP4 Summary and outlook

- Different design alternatives of Flexi-Burn CFB boiler have been investigated in order to find the optimal configuration for CFB hot loop, HRA, water and gas preheating
  - FWEOY’s 1D CFB model & thermal performance design and calculation software, 3D CFB model, layout engineering
  - Boiler design information has been provided for WP5.
- Material related issues have been identified and studies carried out by laboratory testing, thermodynamic process calculations and field tests. Results have been implemented in boiler design.
  - Conventional boiler materials appear applicable also for oxy-fuel CFB boilers.
  - Attention needs to be paid to design of low temperature sections.
- 1D dynamic model extended for oxycombustion CFB furnace was implemented in FWEOY’s dynamic simulation tools in Apros simulation environment.
- Control concept for the CFB hot loop and boiler has been developed.
- SIEMENS has carried out thermohydraulic analysis for the determination of tube size of the Flexi-Burn CFB evaporator.
- Developed Flexi-Burn CFB boiler design has been evaluated against the results obtained in the CIUDEN TDP tests. No significant design changes seem necessary.
- Adjustment of operating parameters for optimal performance can be done with the design tools validated with test data. This concerns e.g. furnace temperatures and oxidant injections.
  - 1D CFB model & thermal performance design and calculation software
  - 3D modeling – checking of the final design
  - Dynamic simulations
- Cofiring of biomass (wood pellets) with anthracite seems feasible also in oxycombustion.
Thank You

**Acknowledgements:**
The research leading to these results has received funding from the European Community’s Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 239188.