Advanced Heat Recovery for Oxy-Fuel Fired Glass Furnaces with OPTIMELT™ PLUS Technology

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Reforming of Natural Gas in regenerators recovers significant heat in the flue gas of oxy-fuel furnaces
  – Regenerative system takes advantage of high operating temperatures
  – High efficiency non-catalytic reforming process
  – Recycled flue gas with CO₂ and water vapor is used for endothermic CH₄ reforming to CO and Hydrogen (syngas)

Hot syngas is burned with oxygen in the furnace

Regenerators roughly 1/3 the size of air-fired regenerators

OPTIMEILT advantages
  – Reduced energy consumption (~20% vs oxy-fuel)
  – Reduced CO₂ emissions
  – Reduced air pollutants to the level of oxy-fuel performance (NOx, SOx, CO, etc.)

Extensive Development program started 2011
  – Demonstration at Pavisa and commercialization of OPTIMEILT TCR
  – Introduction of combination with oxygen preheating: OPTIMEILT Plus
Optimelt System at Pavisa

- Side-fired oxy-fuel furnace converted to end-port TCR
- Oxy-fuel system on stand-by as backup
Status Pavisa Furnace 13

- **Operation**
  - System in automatic and continuous operation since September 2014
    - System turned over to Pavisa, formal acceptance by Pavisa
    - Reliable operation (99.7% availability May/June excluding power failures)
  - Glass pull rate and quality continue to be within Pavisa requirements
  - Emissions in the range of emissions for Low NOx glass oxy-fuel burners
  - Energy reduction 15 to 18% - in line with expectations for 50tpd furnace
  - No fundamental TCR technology issues identified

- **Wide Flame Burner Gen III for OPTIMELT tested in Furnace 13**
  - New cooling concept to allow idle burners for future commercial projects
  - Tested successfully two months, temperatures are within material limits

- **End-firing of Oxy-fuel Combustion System as an alternative to the side-fired oxy-fuel burners installed in May**

- **Refractory testing in regenerators continues**

Pavisa continues to support ongoing OPTIMELT development
Regenerator and Checker Performance

- Summer Inspection: Checker in very good condition after 22 months
  - Passages free of deposits
  - No signs of corrosion
  - Light deposits at bottom, easy to clean
- Port neck and regenerator top refractory was not the right choice for application
  - Nepheline spalling of material in hottest zone
  - Better material identified, replacement 2016
- Lower regenerator walls and rider arches in very good condition
- Dampers, ducts and fan deposits
  - Cleaning no problem, no operational impact

Very encouraging results, valuable information for scale-up
Refractory Test Program Continues

- Refractory selection program tests are ongoing
- Test Rounds:
  - 1 completed: 8 months
  - 2 completed: 1 month (quick screening test for exclusion of refractories)
  - 3 currently ongoing for ~9 months
  - 4 in preparation
- Round 1 and 2 results were used in the selection of the refractory for next commercial project
  - Observed corrosion patterns typical for glass furnace conditions
  - SiO2 reduction by H2 /CO/C in syngas was not observed
  - Selection not a straightforward scientific process, actual testing is important
    - Very high alumina and Magnesia samples promising
    - Fused-cast AZS refractories superior to bonded material
  - Surprising differences in same classes or material due to details in composition and manufacturing matter

Technology Development guided by Pavisa Refractory Exposure Tests
OPTIMELT Status Leerdam 1

- Installation on tableware furnace
  - Praxair VPSA oxygen supply with liquid oxygen backup
  - Libbey Motivation: fuel and oxygen savings, emissions, sustainability
- Partial Project funding by EU (LIFE Grant LIFE15 CCM-NL-000121)
- Engineering and Design phase nearly complete
  - Sorg: Furnace, Regenerators and Oxy-fuel system
  - Praxair: OPTIMELT system and JL Oxy-fuel Burners
- Procurement underway
  - EU fabrication requirement
- Construction and startup 2017
OPTIMELT™ PLUS Technology
OPTIMELT™ Plus Technology

- High efficiency non-catalytic reforming process (OPTIMELT) coupled with regenerative oxygen preheating (Plus)
- Recycled flue gas with CO\textsubscript{2} and water vapor is used for CH\textsubscript{4} reforming
- Regenerative system allows high operating temperatures/reforming rate

Hot Syngas
\[ \sim 1200\, ^\circ\text{C} \sim 2200\, ^\circ\text{F} \]

Regenerative system allows high operating temperatures/reforming rate

Regenerative reforming reactions
\[ \text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 \quad 2060 \text{ kcal/Nm}^3 \quad \text{CH}_4 \quad (215 \text{ Btu/scf-CH}_4) \]
\[ \text{CH}_4 + \text{CO}_2 \rightarrow 2\text{CO} + 2\text{H}_2 \quad 2630 \text{ kcal/Nm}^3 \quad \text{CH}_4 \quad (275 \text{ Btu/scf-CH}_4) \]
OPTIMELT Plus Benefit

- OPTIMELT Plus improves the heat recovery by another 5% in comparison to OPTIMELT
  - Example heat and mass balance comparison of the two heat recovery technologies below
  - 240 t/d container furnace with 1 MW electric boost and 30% cullet ratio

<table>
<thead>
<tr>
<th></th>
<th>Oxy-fuel baseline</th>
<th>OPTIMELT TCR</th>
<th>OPTIMELT Plus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel Input</strong></td>
<td>GJ/t</td>
<td>4.0</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>MMBtu/ton</td>
<td>3.8</td>
<td>3.0</td>
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<tr>
<td><strong>Fuel Savings</strong></td>
<td>%</td>
<td>base</td>
<td>21.3</td>
</tr>
<tr>
<td><strong>Flue Gas Temperature</strong></td>
<td>°C</td>
<td>1500</td>
<td>650</td>
</tr>
<tr>
<td></td>
<td>°F</td>
<td>2700</td>
<td>1200</td>
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</table>
Oxygen preheating to ~1200°C with second set of regenerators
Total checker volume less than OPTIMELT
Concept engineering and costing complete for 240tpd furnace

Front: TCR Syngas Regenerators
Back: Oxygen Regenerators
Flame is formed at the interface of hot syngas with hot oxygen
- Technology to shape flame similar to OPTIMELT TCR
- No overheating of ports, walls or crown
- Flame can be positioned in furnace to achieve desired heat transfer
- Combustion technology prevents large area of unburned fuel in the furnace
Options for Heat Recovery

- OPTIMELT TCR flue gas leaves regenerators at ~650°C (1200°F)
- Technology can be combined with many heat recovery options
  - Regenerative oxygen preheat: OPTIMELT Plus
  - Integrated batch/cullet or cullet preheating
    - No air dilution required due to lower temperature of flue gas
    - Requirement to remove the organic fume/odor from the flue gas after a cullet preheater
  - Additional heat recovery options from flue gas
    - Boiler and turbine (ORC)
    - Steam boiler to generate reforming steam for TCR
    - Recuperative oxygen preheat to ~500°C

- Regenerative oxygen preheating
  - Stand-alone preheater to ~1200°C
  - Combination with batch/cullet preheating
Examples of Heat Recovery Options

TCR Heat recovery (~20% fuel savings vs. oxy-fuel baseline)

TCR - Cullet preheater heat recovery

TCR - Boiler heat recovery (Steam injection without FGR)
## Fuel Savings of Heat Recovery Options

Results of heat and mass balances (300tpd container furnace at 50% cullet)

<table>
<thead>
<tr>
<th>Case</th>
<th>Heat Recovery System</th>
<th>Fuel Savings (%)</th>
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<tbody>
<tr>
<td>1</td>
<td>Oxy-fuel</td>
<td>baseline</td>
</tr>
<tr>
<td>2</td>
<td>OPTIMEELT Thermochemical Regenerator (TCR)</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>OPTIMEELT Plus (TCR with O2 Regenerator)</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>OPTIMEELT TCR with Cullet PH</td>
<td>29</td>
</tr>
<tr>
<td>5</td>
<td>Oxygen Regenerator (100% O₂ purity, PH to 1200°C)</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>Oxygen Regenerator with Cullet PH</td>
<td>22</td>
</tr>
<tr>
<td>7</td>
<td>Oxygen Regenerator with Batch/Cullet PH</td>
<td>28</td>
</tr>
</tbody>
</table>

- Efficient heat recovery with OPTIMEELT lowers level of available heat
- Further heat recovery feasible (some options with diminishing returns)
- Integration issues and environmental impact must be considered

Additional CAPEX must be balanced against incremental heat recovery
Summary

- Praxair’s OPTIMELT™ Thermochemical Regenerator (TCR)
  - High reduction of fuel consumption
    (container furnace: ~20% vs oxy-fuel, ~30% vs. air-regenerative)
  - Reduces CO₂ emissions
  - Reduces air pollutants to the level of oxy-fuel performance
    (NOx, SOx, CO, etc.)

- Pavisa System in automatic and continuous operation

- Two commercial size projects in engineering phase
  - Libbey L1: end-fired tableware furnace with side-fired oxy-burners
  - Customer 2: 240 tpd end-fired container furnace (flint glass) with end-fired oxy-burners

- OPTIMELT™ Plus – a novel technology that maximizes heat recovery without large equipment addition
Thank You for your Attention!

Please stop by at our booth at the Hilton!
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