OPTIMELT™ Heat Recovery Technology

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43rd ASEAN Glass Conference
October 14 – 17, 2019
Cebu, Philippines
Benefits of OPTIMELT

- Reduces energy consumption and CO$_2$ emissions
  - 20% vs oxy-fuel
  - 30% vs air-regen
  - 50% vs recuperative
- Reduces air pollutants to level of oxy-fuel
  - Achieves 80% NOx reduction vs conventional oxy-fuel burners
- Meets stringent quality specifications
- Reduces foam relative to oxy-fuel
- Smaller regenerators relative to air-regen
- Minimal deposits on walls, checkers
- Can increase pull rate
  - Smoother crown temperature profile
- Can maintain pull rate while reducing level of electric boost

![Graph showing NOx emissions and O$_2$ levels](image)

*Oxy-fuel: Apr-Jun
OPTIMELT: Feb-Apr
OPTIMELT: Jun-Aug*
How OPTIMELT Technology Works

- Reforming of natural gas in regenerators
  - Recovers twice as much heat from flue gas of oxy-fuel furnaces as preheating oxygen/fuel
  - High efficiency non-catalytic reforming process
  - Recycled flue gas with CO₂ and water vapor is used for endothermic CH₄ reforming
  - Regenerators roughly 1/3rd the size of air-fired regenerators

- Hot syngas is burned with oxygen in the furnace
OPTIMELT™ Process
Development Path

CFD Modeling (2013 to today)

Pilot Scale Tests (2012)

Bench Scale Tests (2011)

Pilot Test for Syngas Flame (2013)

Container Glass

50 t/d (2014)
Commercial Demonstration

High Quality Tableware

(2017)
Status of Pavisa Furnace 13 Demonstration Project

- Specialty glass and crystal products for wine, liquor, food, cosmetic, and pharmaceutical industries
- OPTIMELT Installation
  - 50 t/d oxy-fuel container furnace retrofitted with OPTIMELT system in 2014
  - In commercial operation since September 2014, system owned and operated by Pavisa
- Results
  - Glass pull rate and quality 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 small 50tpd furnace
  - No fundamental technology issues identified
- Operation temporarily stopped due to TCR port damage in September 2017 earthquake
  - System will be fixed in December 2019 and re-started
  - Refractory testing with samples in regenerators will continue
Pavisa Regenerator Condition

- Condition of Left Regenerator after cleaning of spalled material
- Checker channels free from deposits
Libbey Leerdam Transition Towards Increased Sustainability

- **Libbey’s Goals**
  - Best-in-class furnace technology to reduce energy consumption and lower emissions
  - Support of Libbey’s sustainability strategy and alignment with European carbon reduction roadmap
  - Positioning Leerdam location for the sustainable production of premium tableware products

- New feeder system to connect to existing glass machines
- On-site VPSA oxygen supply with liquid oxygen backup
- 2 Oxy-fuel burner skids with 6 OPTIFIRE JL-Burners
- Associated safety, equipment and control upgrades
- Side-fired oxy-fuel furnace with two end-port TCR
- Cycle time typically 20-30 min
- Oxy-fuel system always on stand-by
Furnace L1 at Libbey Leerdam

- **Oxy-Fuel Port Neck**
- **OPTIMELT Port Necks**
- **Right/Left Regenerator**
- **OPTIMELT Flue Gas Skid**
- **Downcomer for Flue Gas**
- **3 OPTIFIRE JL Oxy-fuel Burners**
Installation
Syngas Flame –
Time Lapse of 20min Cycle

Oxy-fuel flames nearly invisible in IR camera image
- Oxy-fuel model shows a glass surface with large temperature differences: range from 1420°C to 1500°C
- OPTIMELT glass surface temperatures are more uniform: range from 1440°C to 1490°C
- CFD model results are close to measured crown temperature trend
Port Necks, Regenerator and RFG Ducts inspected after 10 months of service
Very little deposits on walls and checkers
Checker passages completely free
Clean checkers confirm Pavisa experience

Right Regenerator Crown

Right Regenerator Checker Top

Right Regenerator Bottom
L1 Emissions Results

**NOx L1 kg/ton**

- Recuperator: 1.60
- Oxy-fuel: 0.40
- OPTIMELT: 0.38
- Goal: 0.90

**SOx L1 kg/ton**

- Recuperator: 0.94
- Oxy-fuel: 0.23
- OPTIMELT: 0.19
- Goal: 0.50
L1 Glass Quality Results

**QUALITY seeds/gram**

- **Recuperator**: 0.035
- **Oxy-fuel**: 0.010
- **OPTIMELT**: 0.020
- **Goal**: 0.030

**COLOR**

- **Recuperator**: 7
- **Oxy-fuel**: 9
- **OPTIMELT**: 9
- **Goal**: 8

Relative scale (higher is better)
L1 Energy Efficiency

Normalized to 50% Cullet, 25°C ambient temperature
Oxy-fuel: 14 Apr - 29 May 2018
OPTIMELT: 8 Aug - 5 Sep 2018

Normalized Fuel Consumption [GJ/t] vs Furnace Production

~13%
OPTIMELT Savings

- OPTIMELT recovers flue gas heat
- Leerdam L1 furnace is conservatively sized and typically operating at 80% capacity resulting in lower flue gas temperatures at the TCR inlet
- Correct balance for furnace pressure is important
  - Minimize air inleakage under TCR operation
  - Minimize direct hot flue gas leakage from furnace to flue gas system bypassing the regenerators

<table>
<thead>
<tr>
<th>Factor</th>
<th>Effect on Savings</th>
<th>Comment</th>
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<tr>
<td>Furnace size</td>
<td>larger</td>
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<tr>
<td>Pull rate</td>
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<td>higher</td>
</tr>
<tr>
<td>Cullet rate</td>
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<tr>
<td>Insulation quality</td>
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<tr>
<td>Flue gas temperature</td>
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<tr>
<td>Electric boost</td>
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<td>lower</td>
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</tbody>
</table>

LIFE15 CCM/NL/000121 - LIFE OPTIMELT
OPTIMELT Savings for 350 t/d Container Furnace (no electric boost)

Effects of Cullet % at Year 6

Effects of Furnace Aging

(50% cullet)

Significant energy savings vs air-regen and oxy-fuel
Thank You for your Attention…

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