Gasification of Biomass with In-Situ CO$_2$ Capture and Separation in a 200 kW$_{th}$ Pilot Plant

N. Armbrust, D. Schweitzer, A. Gredinger, M. Beirow, T. Beisheim N. Poboss, C. Hawthorne, H. Dieter, G. Scheffknecht

**Fluidized bed gasification infrastructure**

**Fluidized Bed Gasification**
- Air gasification
- Steam gasification
- Steam/Oxygen gasification
- Sorption enhanced reforming (SER)
- Two stage SER gasification

**Fuels**
- Biomass
- Waste
- Lignite

**Measurement techniques**
- Tar: wet chemical acc. tar protocol
- Non-condensable gases: online
- Non-condensable HC: GC
- H₂S, HCl: wet chemical
- Online Tar analysis

**20 kW th DFB Pilot Facility**

**5 kW th electrically heated FB batch System**

**200 kW th DFB System**
The Sorption Enhanced Reforming (SER) process

**Gasifier**
- Water Gas – Shift: \( CO + H_2O \leftrightarrow CO_2 + H_2 \)
- Insitu CO\(_2\) - capture: \( CO_2 + CaO \leftrightarrow CaCO_3 \)
- Gasification temperature: 650°C - 725°C

**Regenerator**
- Regeneration: \( CaCO_3 \leftrightarrow CO_2 + CaO \)
- Char combustion: \( C + O_2 \leftrightarrow CO_2 \)
- Regenerator temperature: 850°C – 900°C

**Solid flow**
- CaO
- CaCO\(_3\)
- Char

**Enthalpy flow**

**H\(_2\) – rich product gas**

**CO\(_2\) – rich flue gas**

**Biomass**
**Waste**
**Lignite**
**Steam**

**CO\(_2\) recycle**

**O\(_2\)**
Equilibrium Reaktion: \( \text{CaO} + \text{CO}_2 \leftrightarrow \text{CaCO}_3 \)

**CO\(_2\) Capture (Carbonation)**

\[
\text{CaO} + \text{CO}_2 \rightarrow \text{CaCO}_3
\]

**Calcination**

\[
\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2
\]

Oxyfuel Flue Gas \(\text{CO}_2\) Concentration

Outlet \(\text{CO}_2\) Conc. for 90\% Capture

Max \(T_{\text{Carbonator}}\)

Min \(T_{\text{Regenerator}}\)
200 kW\textsubscript{th} SER DFB Gasification Pilot Plant

<table>
<thead>
<tr>
<th>Gasifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Int. Diameter</td>
</tr>
<tr>
<td>Height</td>
</tr>
<tr>
<td>Gas velocity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Regenerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Int. Diameter</td>
</tr>
<tr>
<td>Height</td>
</tr>
<tr>
<td>Gas velocity</td>
</tr>
</tbody>
</table>

200 kW\textsubscript{th} Dual Fluidized Bed Gasifier
200 kW_\text{th} \text{ SER DFB Gasification Pilot Plant}

- Feedstock & limestone dosing unit
- Cyclone
- Steam generator
- Preheater
- Quench
- Product gas flare
- Induced draft fan
- Baghouse filter
- Purge

**Gasifier**

**Regenerator**
Stable conditions above 17h continuously gasification

- Product gas composition is sensitive to temperature change
- Product gas lower heating value varies with the gas composition

**Experimental operation: Gas composition Gasifier**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Stable conditions above 17h continuously gasification
- Product gas composition is sensitive to temperature change
- Product gas lower heating value varies with the gas composition
Increasing gasification temperature results in:

- Decreasing H₂, CH₄, CₓHᵧ concentrations
- Increasing CO₂ and CO concentrations due to the CO₂/CaO equilibrium
- Decreasing LHV

The SER operation window takes place between 600°C to 700°C resulting in the maximum H₂.
Increasing gasification temperature results in
- Increasing Gas Yield
- Increasing Cold Gas Efficiency
Increase of conversion: two-stage gasification

Advantages of the process:
- high biomass conversion in the gasifier
- low tar concentration
- high hydrogen yield and concentration (> 80%)
- high flexibility of the product gas composition

CO₂ - capture
CO₂ + CaO ⇌ CaCO₃

Water-gas shift
CO + H₂O ⇌ CO₂ + H₂
Oxy-fuel regenerator performance

- Successful oxy-fuel regeneration with flue gas recycle
- Full calcination of sorbent
- Calciner CO₂ outlet concentrations above 95 vol.-%,dry (without purge gas)
- Excess O₂ outlet concentrations below 3 vol.-%,dry
- Inlet O₂ concentrations above 50 vol.-%,dry without temperature peaks in the riser
Long-term experiment: Grain size distribution of the bed material

Cumulative particle size of raw limestone and bed material after many hours of operation.

- At steady-state conditions, the median particle size decreased about 100µm from its raw limestone value of around 450µm to 350µm.
- The maximum measured attrition rate is approximately 3 wt.-% bed loss / hour.
Application: Heat, Power, Fuels, Chemicals, H₂, Cement

**Synthesis**

**Heat**, **Power**, **Fuels**, **Chemicals**, **H₂**, **Cement**

---

**Regenerator**

**Gasifier**

Fuel

Limestone (CaCO₃)

CaO

CaCO₃

Char

**H₂-rich**

Gas

**Gas Conditioning**

**Synthesis**

**Fuel Cells**

Gas engine

Power

Hydrogen

Fuels

Chemicals

Storage

Cement production

CO₂-rich Gas

CaO

(+CaSO₄)

Purge

---
R&D SER Process Roadmap

DFB-Cold Model and Process Simulation:
Fundamental CO₂ capture research

Semi batch experiments
- Electr. heated facility
- SER-basic research

Process Characterisation
- Electr. heated 10 kW<sub>th</sub> facility
- Investigation of the effect of different process parameter

Process Demonstration:
Realistic Process Conditions
• No external heating

Commerical Plant

200 kW<sub>th</sub> - Pilot Plant
Process Demonstration
Development

20 kW<sub>th</sub> - DFB Facility
Labscale
Process Simulation

Process Idea

Staged gasification
FID Online Tar Analyzer

- Developed by IFK and industry partner Ratfisch Analysensysteme GmbH
  - www.ratfisch.de
- Commercially available 2015
- Robust system for plant environment
- Gasifier equipment monitoring possible

- Influence of gasification conditions on tar concentrations directly visible
- Semi-continuous measurements (60 second steps)
- Simplified detection of optimal gasifier / gas cleaning equipment operation point possible

![Graph showing tar concentration and gasification temperature over time]
Conclusion

- SER is a flexible process for different applications
- Process demonstrated at a 200 kW\textsubscript{th} DFB pilot facility over multiple days
- In Situ CO\textsubscript{2} capture enables decarbonisation of gasification
- High H\textsubscript{2} concentrations of up to 75 vol.-%
- Product gas lower heating values up to 15 MJ/m\textsuperscript{3}\textsubscript{STP}
- Low tar formation due to catalytic effect of CaO
- CaO bed material increases ash melting points
- Sulfur capture by CaO enables low sulfur concentration in CO\textsubscript{2} and product gas
- Online tar analyzer available 2015
Thank you for your attention

The authors gratefully acknowledge the financial support from the funding organizations: Design, construction, and operation of the pilot plant was conducted as part of a project funded jointly by Alstom Power and EnBW Kraftwerke AG together with the German state of Baden-Württemberg.

Contact welcome:
Heiko Dieter
Institute of Combustion and Power Plant Technology
University of Stuttgart
heiko.dieter@ifk.uni-stuttgart.de
www.ifk.uni-stuttgart.de
### Experimental

<table>
<thead>
<tr>
<th></th>
<th>Temperature</th>
<th>S/C-Ratio</th>
<th>WHSV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[°C]</td>
<td>[mol(<em>{H_2O}/mol</em>{C})]</td>
<td>[kg(<em>{Fuel}\text{h}^{-1}/kg</em>{CaO})]</td>
</tr>
<tr>
<td><strong>Long-term experiment</strong></td>
<td>constant approx. 650</td>
<td>constant approx. 2</td>
<td>constant approx. 0,5</td>
</tr>
<tr>
<td><strong>Temperature variation</strong></td>
<td>varied 600 - 750</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>S/C-Variation</strong></td>
<td>constant approx. 675</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>WHSV-Variation</strong></td>
<td>constant approx. 675</td>
<td>constant approx. 2</td>
<td>low– high</td>
</tr>
</tbody>
</table>

Experiments were conducted with wood wood pellets European standard for quality (EN 14961-2).
### Comparison: 20 kW\textsubscript{th} and 200kW\textsubscript{th} DFB Facility

<table>
<thead>
<tr>
<th></th>
<th>20 kW\textsubscript{th} DFB</th>
<th>200 kW\textsubscript{th} DFB</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2</td>
<td>Vol.-%</td>
<td>73,1</td>
</tr>
<tr>
<td>CO2</td>
<td>Vol.-%</td>
<td>5,5</td>
</tr>
<tr>
<td>CO</td>
<td>Vol.-%</td>
<td>6,8</td>
</tr>
<tr>
<td>CH4</td>
<td>Vol.-%</td>
<td>11,1</td>
</tr>
<tr>
<td>C\textsubscript{x}H\textsubscript{y}</td>
<td>Vol.-%</td>
<td>3,5</td>
</tr>
<tr>
<td>LHV</td>
<td>[MJ/m\textsuperscript{3}\textsubscript{STP}]</td>
<td>14,7</td>
</tr>
<tr>
<td>CGE</td>
<td>[%]</td>
<td>55-60</td>
</tr>
<tr>
<td>Temp (Gasif.)</td>
<td>[°C]</td>
<td>650</td>
</tr>
<tr>
<td>Temp (Reg.)</td>
<td>[°C]</td>
<td>875</td>
</tr>
</tbody>
</table>

⇒ Good agreement between the gas composition and calorific value of the product gas for both facilities

⇒ A higher Cold Gas Efficiency (CGE) can be observed in the 200 kW DFB, due to the higher gas yield.
Long-term experiment

Goal of the long-term experiment

- Collect basic gasification datas under SER – conditions
  - Gas composition
  - Gas yield
  - Tar yield
  - Sorbens deactivation
  - Comparison with previous experiments conducted in a lab scale
- Investigation of the hydrodynamic behaviour of the test facility
  - Operate the circulation rate in a robust manner
  - Control the gasification temperature
  - Investigate the attrition behaviour of the bed material
  - Identification of the makeup and purge rate of the bedmaterial
Goal of the temperature variation experiment

- Identification of the optimum gasification temperature for:
  - Maximum product gas yield and hydrogen concentration
  - Optimum gas composition for ongoing gas conditioning (e.g. methanation)
  - Minimum tar concentration
- Investigation of the hydrodynamic behaviour of the test facility
  - Adjust and control the gasifier temperature
200 kW_{th} SER DFB Gasification Pilot Plant