Intensifying CO$_2$ removal

using sorption-enhanced reactions

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Sorption-Enhanced Water-Gas Shift - SEWGS

- Technology
  - High carbon capture ratio with unique low steam use
  - Able to operate under sour conditions and to remove H₂S as well as CO₂
  - SEWGS technology builds further on the vast industrial experience with PSA systems.
  - Combination of several process steps into one (process intensification)
  - Highest efficiencies
  - Platform technology for syngas treatment

- Most cost effective CCS solution in IGCC and BFG
  - For IGCC, costs per ton CO₂ avoided estimated to be 35% lower than state of the art i.e. 23 €/ton
What problem are we trying to solve?

• Many chemical reactions are thermodynamically limited in conversion

• Consequences:
  – Multiple passes
    – i.e. large recycles
  – Multiple reactors
    – Heat management
  – Need to separate products from reactants
    – Expensive distillation / cold box technology

→ Sorption-enhanced reaction/catalysis lessens impact of thermodynamic limitation

Sorption-Enhanced Water-Gas Shift (SEWGS)

- Initial targeted application Carbon Capture and Sequestration (CCS)
- Power production with CO$_2$ capture

\[ \text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2 \quad \Delta \text{H} = -41 \text{ kJ/mol} \]

Practical Reaction Conditions

- Two stage conversion of CO
  - 12% $\rightarrow$ 3% $\rightarrow$ 0.5%
  - 350-400°C $\rightarrow$ 180-250°C
  - 20-30 bar

In situ removal of carbon dioxide
Pre-combustion capture

- Current plants would use optimised shift followed by physical solvent separation process
Pre-combustion capture

- Combine shift and separation greatly reduces the number of temperature steps in the overall process
The Intensification Step

- Combines the Water-Gas-Shift reaction with sorbent material to simultaneously produce $H_2$ at high temperature whilst also capturing $CO_2$

$CO + H_2O \rightleftharpoons CO_2 + H_2$

$\Rightarrow$ Carbonate Formation $\Rightarrow$

$H_2$ $\Rightarrow$ $H_2O$

$CO_2$ $\Rightarrow$ $CO$

$H_2$ $\Rightarrow$ $H_2O$

$CO$ $\Rightarrow$ $H_2O$

$H_2O$ $\Rightarrow$ $H_2O$
Process Intensification Intensified

PSA

H₂

99.9%+ H₂

Ads₁

Ads₂

Ads₃

Ads₄

Dry Syngas

>50% H₂

H₂/CO/CO₂

(30% H₂)

SEWGS

H₂O

99%+ H₂

CO₂ capture

H₂S capture

COS conversion

CO conversion

Syngas

<50% CO+CO₂

CO₂

(99%+ CO₂)
The SEWGS process: Hot PSA
Status: Scale

- Multiple scales
  - Facilitating testing of new material and new conditions
  - Many reaction can benefit from this approach

8 x 2g
High Throughput Comparative Testing

10g
Adsorption Isotherms Realistic Conditions

2kg
Industrially Relevant Materials

100kg
Pre-pilot Full-Cycles
Status: from powder to demonstration

- Manufacturing industry
  - Manufacturing facility from lab to pilot scale
  - Ceramic processing
    - Deposition techniques
    - Shaping processes
  - Impregnation
    - Precipitation
    - Deposition Sol-Gel

- Reactor constructors, EPCM’s
  - Reactor design
  - System studies
  - Techno-economic analysis

- End-user
  - Assistance in technology scale-up

- High Temperature Sorbents
- Lab scale demonstration units - Pilot reactors
- On site pilot to full scale plant

Ceramics
Catalysts
Sorbents

S/CH4 [mole/mole]
Efficiency [%]

S/CO2 = 2.7
S/CO2 = 3.6
S/CO2 = 4.5
S/CO2 = 1.8
Development Timeline

- 2004 – First experimental tests
  - proving feasibility of high temperature CO₂ capture
- 2005 – First systems analysis
  - indicating high efficiency compared to base-case systems
- 2006 – High Pressure Single-Column Unit
  - 2m column taking industrial relevant materials
- 2007 – SEWGS for gasification
  - proving feasibility in sour gas applications
- 2008 – Multi-Column Unit
  - 6x6m column system demonstrations of full cycle
- 2010 – Process Improvements
  - significant reduction in steam use for regeneration
- 2011 – New sorbent class
  - boosting performance by 100%
- 2012 – Techno-economic evaluation
  - €23/ton CO₂, 35% lower that base-case state-of-the-art system

Major Innovations

Sorbent Stability
- H₂S recovery
- Shift Activity
- H₂S/CO₂ separation
- “Stress Test”
- Low steam demand WGS
Systems Analysis

Bottom Line – Minimise Steam Use

SEWGS Development Cycle

- System Analysis
- Techno-economics
- SEWGS
- Desired Properties
- Material Development
- Cycle Design
- Ideal Conditions
- Real Conditions
- Pilot Operation

- 2008 $\text{H}_2\text{O}/\text{CO}_2 = 4$
- 2010 $\text{H}_2\text{O}/\text{CO}_2 = 2$
- 2012 $\text{H}_2\text{O}/\text{CO}_2 = 1.5$
- 2014 $\text{H}_2\text{O}/\text{CO}_2 < 1.0$
SEWGS sorbent development

Key was to develop a sorbent that does not form MgCO$_3$ under the relevant process conditions. MgCO$_3$ formation, activated by high pressure steam can cause mechanical degradation. Mg-content is still necessary for large cyclic capacity.

Before

MgO 89 mmol/cm$^3$

After

MgCO$_3$ 35 mmol/cm$^3$
SEWGS “stress test”

- Stability of the CO$_2$ sorbent ALKASORB
  - Combined adsorbing and catalytic activity of material proven in single column rig for more than 5000 cycles using technical gasses
  - No formation of undesirable MgCO$_3$ was observed, which is important since formation of MgCO$_3$ can lead to mechanical failure of the sorbent pellets and can decrease the carbon capture ratio.
## SEWGS in Integrated Gasification Combined Cycle

<table>
<thead>
<tr>
<th></th>
<th>NO CAPTURE</th>
<th>SELEXOL</th>
<th>SEWGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEWGS CCR/CO₂ purity</td>
<td>-</td>
<td>-</td>
<td>95/99</td>
</tr>
<tr>
<td>Net Power Output, [MW]</td>
<td>425.7</td>
<td>383.5</td>
<td>404.4</td>
</tr>
<tr>
<td>Thermal Power Input\textsubscript{LHV}, [MW]</td>
<td>896.5</td>
<td>1053.5</td>
<td>1018.8</td>
</tr>
<tr>
<td>Net Electric Efficiency (LHV base), [%]</td>
<td>47.5</td>
<td>36.4</td>
<td>39.7</td>
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<tr>
<td>CO₂ avoided, [%]</td>
<td>--</td>
<td>86.6</td>
<td>93.7</td>
</tr>
<tr>
<td>SPECCA [MJ\textsubscript{LHV}/kg\textsubscript{CO₂}]</td>
<td>--</td>
<td>3.67</td>
<td>2.06</td>
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<tr>
<td>Specific costs, €/kW</td>
<td>2077.1</td>
<td>2854.7</td>
<td>2586.4</td>
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<tr>
<td>COE, [€/MWh]</td>
<td>65.81</td>
<td>88.74</td>
<td>81.53</td>
</tr>
<tr>
<td>Cost of CO₂ avoided [€/t\textsubscript{CO₂}]</td>
<td>--</td>
<td>37.9</td>
<td>23.3</td>
</tr>
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Giampaolo Manzolini, Ennio Macchi, Matteo Gazzani, Fuel (2012)
SEWGS: moving into the future

- Reactor design
- Sorption-Enhance Reaction modelling
- Validated material
- Detailed techno-economics
- Secured material supply chain
- Infrastructure

Timeline:
- 2004: Proof of Feasibility at lab scale
- 2006: Validation of materials
- 2008: EU project CACHET
- 2011: EU project CAESAR
- 2014: Status
- 2016: STEPWISE demo
- 2018-2020: SEWGS Plant 1
STEPWISE: SEWGS for Blast Furnace Gas

- Pilot Scale Validation
- Comparison with State-of-the-Art:

- 85% reduction
- 60% reduction
- 25% reduction
Ambition and Impact
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Other processes can be intensified!

- Reactor design
- Sorption-Enhance Reaction modelling
- Validated material
- Detailed techno-economics
- Secured material supply chain
- Infrastructure
Thank you for your attention

For more information on SEWGS and other sorption-enhanced process, please contact:

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