Experience with CO₂ Capture from Coal Flue Gas in Pilot-scale

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Overview CASTOR Project

CASTOR: CO₂ from Capture to Storage

- 4-year EU project (2004 – 2008) in the 6th Framework Programme
- Aim: To reduce the cost of CO₂ post-combustion capture and contribute to the feasibility & acceptance of the geological storage concept

R&D
IFP (FR)  
TNO (NL)  
SINTEF (NO)  
NTNU (NO)  
BGS (UK)  
BGR (DE)  
BRGM (FR)  
GEUS (DK)  
IMPERIAL (UK)  
STUTTGARTT U. (DE)  
TWENTE U. (NL)  
OGS (IT)

Oil & Gas
STATOILHYDRO (NO)  
GDF (FR)  
REPSOL (SP)  
ENITecnologie (IT)  
ROHOEL (AT)

Power Companies
DONG Energy (DK)  
VATTENFALL (SE/DK)  
E.ON (DE/UK)  
ELECTRABEL (BE)  
RWE (DE)  
PPC (GR)  
POWERGEN (UK)

Manufacturers
ALSTOM POWER (FR)  
DOOSAN BABCOCK (UK)  
SIEMENS (DE)  
BASF (DE)  
GVS (IT)

Co-ordinator : IFP
CASTOR Pilot Plant Objectives

The test facility shall
- Prove long-term stable operation on coal flue gas
- Act as a test facility for dedicated tests (e.g. test of novel solvents)

Provide information about
- Operation costs
- Maintenance costs
- Reliability
- Operation flexibility
- Environmental issues
- Engineering experience
Esbjerg Power Station (ESV)

- 400 MW_e pulverized bituminous coal
- High dust SCR deNO_x plant
- 3 zones cold-sided ESP
- Wet limestone FGD (saleable gypsum)
CASTOR Pilot Plant Specifications

- Pilot plant erected and commissioned during 2005
- Design of pilot plant based on a commercial CO$_2$ production plant (MEA)
- Pilot plant operates on a slip stream taken directly after the wet FGD
- Design flue gas conditions: ~47°C saturated, <10 ppm SO$_2$, <65 ppm NO$_x$, <10 mg/Nm$^3$ dust

Key design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
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<tbody>
<tr>
<td>Flue gas capacity</td>
<td>5000 Nm$^3$/h</td>
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<tr>
<td>CO$_2$ production (at 12% CO$_2$)</td>
<td>1000 kg/h</td>
</tr>
<tr>
<td>Absorption degree</td>
<td>90%</td>
</tr>
<tr>
<td>Max solvent flow</td>
<td>40 m$^3$/h</td>
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<tr>
<td>Max stripper pressure</td>
<td>2 bar$_g$</td>
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CASTOR Pilot Plant Flow Diagram

- Flue gas from power plant
- Wash section
- Make up water
- Treated flue gas
- MEA/MEA heat exchanger
- Rich MEA
- Mechanical filters
- Lean MEA
- Reclaimer
- CO₂ Out
- Cooling water circuit
- Condensate
- Steam
- Reboiler
CASTOR Pilot Plant

Cleaned Flue Gas and CO₂ Product
are returned to the power plant's flue gas duct
CASTOR Pilot Plant Test Programme

Four test campaigns have been conducted in CASTOR:

- 1000 hours using standard solvent ”30%-wt. MEA” (Jan. – Marts 2006)
- 1000 hours using standard solvent ”30%-wt. MEA” (Dec. 2006 – Feb. 2007)
- 1000 hours using novel solvent ”CASTOR 1” (April – June 2007)
- 1000 hours using novel solvent ”CASTOR 2” (Sep. – Dec. 2007)
Outline of Test Campaigns

- **Test 1 – Parameter variation**
  a) Optimisation of solvent flow rate (at 90% capture)
  b) Variation of reboiler steam input at optimum solvent flow
  c) Variation of stripper pressure (at 90% capture)

- **Test 2 – 500 hours of continuous operation**
  - Operation at ”optimised” conditions
  - Achieving 90% CO₂ capture (on average)
  - Quantification of solvent consumption and degradation
  - Characterisation of corrosion behaviour

- **Test 3 – Miscellaneous tests**
  - Absorber pressure drop measurements
  - Emission measurements
  - Etc.
Tests with MEA: Proving the concept

The operation of the pilot plant with the standard solvent (30% MEA) for more than 2000 hours has among others demonstrated that:

- The amine based post combustion process is stable and reliable
- The process functions at the tail-end of a coal fired power plant
- More than 90% CO₂ capture can be achieved
- The energy requirement with the standard solvent is relatively high
2nd MEA Test: Solvent Flow Rate Optimisation

Specific steam consumption and CO₂ recovery at stripper pressure 0.85 bar, and flue gas flow ≈5000 Nm³/h.

Steam consumption (GJ/ton CO₂) vs. CO₂ recovery (%)

- Steam consumption
- CO₂ recovery

Absorber L/G ratio (kg/kg)
2nd MEA Test: 500 Hours of Continuous Operation

Average steam consumption: $\approx 3.7$ GJ/ton CO$_2$  
Average CO$_2$ capture: 88 %
Emission measurements have been conducted on flue gas and CO₂ exhaust streams:

- Very low emission of MEA and other alkanolamines
- Detectable emissions of the more volatile degradation products: NH₃ (25 mg/Nm³), acetaldehyde, acetone, formaldehyde
- Remaining acidic components in the coal flue gas (SO₂, HCl) are quantitatively removed
- High purity of the produced CO₂. Degradation products present in trace amounts
Overview of Operating Experience with CASTOR 1 & 2

General operating experience with CASTOR 1

- Initially, the operation with CASTOR 1 was complicated by foaming. The problems diminished when a proper antifoam agent was added
- Difficult to reach high CO₂ loadings of solvent because of relatively slow kinetics
- => Difficult to obtain 90% CO₂ recovery
- => No improvement in regeneration energy compared to MEA

General operating experience with CASTOR 2

- Stable operation (antifoam agent applied right from beginning)
- Possible to reach relatively high CO₂ loadings
- Small improvement in regeneration energy compared to MEA
- 90% CO₂ recovery can be reached
- Loss of solvent!
Comparison of Regeneration Energies with MEA, CASTOR 1 & 2

Specific steam consumption at stripper pressure 0.85-1.0 bar, flue gas flow ≈5000 Nm³/h and ≈90% CO₂ recovery
MEA, CASTOR 1 & 2 Tests: Flue Gas Impurities & Corrosion

Flue gas impurities
- Typically, good balance between SO₂ input & sulphur uptake
- Fouling of packings and process equipment seems low
- 1–300 ppm: Cl, Ca, K, Mg, Na, P & Si
- < 1 ppm: Cr, Cu, Hg, Mo, Ni, Pb & V

Corrosion studies
- MEA: High corrosion rate for carbon steel at regenerator, low with stainless. Low corrosion with carbon and stainless steels at absorber
- CASTOR 1 & 2: Low corrosion with carbon and stainless steels at all positions
Growth in Degradation Products during 500 hours Tests

- **MEA**
- **CASTOR 2**

**Heat stable salts (%w/w) vs. Hours elapsed of test**

- Red line for MEA
- Blue line for CASTOR 2

- Vertical axis: Heat stable salts (%w/w)
- Horizontal axis: Hours elapsed of test

- Data points showing increase in heat stable salts for both MEA and CASTOR 2 over the test duration.
Summary CASTOR 2 vs. MEA

Improvements with CASTOR 2 compared to MEA

- Decreased regeneration energy 3.7 => 3.5 GJ/ton CO₂ (further improvement is plausible)
- Increased CO₂ carrying capacity i.e. reduced pumping works
- Degradation rate significantly reduced
- Low corrosiveness

... and the drawbacks

- Possible loss of solvent by physical mechanisms (entrainment & evaporation)
- Cost of solvent
Implications: 600 MWₑ bituminous coal fired power plant

Power plant without CO₂ capture:
- Advanced super critical boiler, 45.2 % electrical efficiency (LHV, net) => 769 g CO₂/kWhₑ

Power plant with MEA based CO₂ capture including compression to 110 bar:
- 33.7 % efficiency (penalty 11.5 %-points) => 104 g CO₂/kWhₑ (86% reduction)

Power plant with CASTOR 2 based CO₂ capture including compression to 110 bar:
- 35.2 % efficiency (penalty 10 %-points) => 99 g CO₂/kWhₑ (87% reduction)

CASTOR 2 offers about 1.5%-points improvement according to the standard MEA process, however the penalty is still significant
Conclusions

Four 1000 hours test campaigns with MEA and novel solvents have been conducted at the CASTOR pilot plant in Esbjerg. The campaigns have indicated that:

- Stable operation on coal-derived flue gas is possible
- The impact of flue gas impurities can be handled
- Regeneration energy with MEA: ≈3.7 GJ/ton CO₂ at 90 % CO₂ removal
- MEA emission very low, but detectable emissions of volatile degradation products (e.g. NH₃, acetaldehyde, acetone)
- Small improvement in regeneration energy with CASTOR 2: ≈3.5 GJ/ton CO₂ at 90 % CO₂ removal (further improvement plausible)

Implications for further work:

- Possible to develop solvents with greater chemical stability and that are less corrosive
- Possible to develop solvents with improved regeneration energy compared to MEA, however, difficult to obtain major improvements with solvent alone
Outlook Pilot Plant Activities

- The CASTOR project ended in January 2008
- A 3-year follow up EU project "CESAR" was launched 1\textsuperscript{st} of February this year.
- Pilot plant activities in CESAR:
  - Implementation of process improvements at the Esbjerg Pilot Plant e.g. Inter-cooling
  - 3 x 2000 hours test campaigns (1 benchmark & 2 novel solvents)
  - Focus on minimization of the energy consumption
  - Focus on dynamic behavior
  - Focus on the environmental impact of amine scrubbers