Heat Integration study of Combined Cycle Gas Turbine (CCGT) Power Plant Integrated With Post-combustion CO₂ Capture (PCC) and Compression

Xiaobo Luo
Meihong Wang

Process/Energy System Engineering and CCS Group
University of Hull

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OUTLINE

- Motivation
- Model Development
- Integration of CCGT, PCC and compression
- Case studies
- Summary
Motivation

Greenland deglaciation puzzles
Nitrogen isotope data help to resolve puzzling observations during the last deglaciation

by Louise Claire Sime

About 23,000 years ago, the southern margins of the great Northern Hemisphere ice sheets across Europe and North America began to melt. The melt rate accelerated about 20,000 years ago, and global sea level eventually rose by ~180 m as meltwater flowed into the oceans. Ice cores from the Greenland and Antarctic ice sheets show the rise in atmospheric CO₂ concentrations that accompanied this shift in global ice volume and climate. However, temperature reconstructions have raised questions about whether the increase in CO₂ concentrations and atmospheric temperatures had a significant impact on the global climate. This study aims to address the relative contributions of natural and anthropogenic forcings to the warming observed during the last deglaciation.

(Paleoclimate)

Greenland temperature response to climate forcing during the last deglaciation

Christo Buizert,1,2 Vasilios Gkinis,2,3 Jeffrey P. Severinghaus,4 Feng He,5 Benoit S. Lecavalier,6 Philippe Kindler,7 Markus Leuenberger,8 Anders E. Carlson,9 Bo Vintner,9 Valérie Masson-Delmotte,10 James W. C. White,2 Zhengyu Liu,10,11 Bette Otto-Bliesner,11 Edward J. Brook1

For 650,000 years, atmospheric carbon dioxide had never been above this line

For 650,000 years, atmospheric carbon dioxide had never been above this line

2014 level

1950 level

(Sources: Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO2 record)
**Motivation**

No Action

No Action: The median warming level or the temperature at which there is a 50% chance of falling above or below that level (even odds) is 5.2 °C.

Policies enacted

Policies enacted: The median warming level or the temperature at which there is a 50% chance of falling above or below that level (even odds) is 2.3 °C.

*CO₂ emissions and warming prediction (M. Pourkashanian, 2014 in 10th ECCRIA)*

Global CO₂ emissions and warming prediction (ETH Zurich, 2009)
Motivation

Next Steps in CCS: Policy Scoping Document
August 2014

The Policy Scoping Document summarises the Government’s policies and actions taken so far in supporting Carbon Capture & Storage (CCS), and it seeks views and evidence on a possible phase 2 of CCS deployment in the UK.

CCU (Carbon Capture and Utilisation) Chapter 11
Clustering Chapter 6
Part-Chain (capture) Chapter 7

BECCS (Bio-energy with carbon capture and storage) Chapter 10
Raising Finance Chapter 5
Financial Incentives and Electricity Market Reform Chapter 4

ICCS (Industrial Carbon Capture & Storage) Chapter 9

Part-Chain (storage) Chapter 9
EOR (Enhanced Oil Recovery) Chapter 8

CO₂ - Carbon Dioxide

Phase 1
UK’s first potential commercial scale CCS projects Peterhead and White Rose.

Phase 2, 3
Potential further CCS deployment, building on infrastructure and experience of Phase 1 projects. Decreasing amounts of potential government support.

accs@decc.gsi.gov.uk

Funded by the European Union
Motivation

BLUE map emission reduction plant (IEAGHG, 2012)
Motivation

LCOE of FID 2013 CCS technologies (£/MWh 2012 money) (DECC of UK, 2013)
Motivation

Aim

- Technical readiness
- Better economic improvements
- Financial Support
- Engineering R&D

The aim of this study is to evaluate integration options of CCGT power plant with PCC process and compressors via process modelling and simulation, in order to improve the thermal efficiency of the power plant and to reduce the cost of CCS deployment.

Objectives

- model development and validation of CCGT power plant
- model development and validation of PCC and CO$_2$ compression
- process integration between CCGT and PCC and compression
- Case studies including evaluation of heat integration options
CCGT Model Development and Validation

- Net power output: $453\text{MW}_e$

- Gas turbine model: GE 9371FB

- HRGS: 3 level pressure with reheat
  - High pressure steam are 170 bar and 600 °C compared with 120 bar and 556°C in normal.
  - The pressure and temperature of intermediate pressure steam are 40 bar and 600 °C compared with 30 bar and 550°C in normal.
  - Similar steam conditions will be common practice for NGCC plant by 2020 suggested by original equipment manufacturers (OEMs)

- EOS: PR-BM for gas cycles and STEAMNBS for steam cycles

- Model validation with published data for the results from GT PRO® (IEAGHG, 2012)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>IEAGHG, (2012)</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel flow rate (kg/s)</td>
<td>16.62</td>
<td>16.62</td>
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<tr>
<td>Air flow rate(kg/s)</td>
<td>656.94</td>
<td>656.94</td>
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<tr>
<td>Temperature of flue gas to HRSG (°C)</td>
<td>638.4</td>
<td>638.4</td>
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<tr>
<td>Flow rate of flue gas to HRSG (kg/s)</td>
<td>114.97</td>
<td>114.97</td>
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<td>HP turbine inlet pressure, temperature (bar/°C)</td>
<td>172.5/601.7</td>
<td>172.6/601.7</td>
</tr>
<tr>
<td>IP turbine inlet pressure, temperature (bar/°C)</td>
<td>41.4/601.5</td>
<td>41.5/601.0</td>
</tr>
<tr>
<td>LP turbine inlet pressure, temperature (bar/°C)</td>
<td>5.8/293.3</td>
<td>5.8/293.1</td>
</tr>
<tr>
<td>Condenser pressure and temperature (mbar/°C)</td>
<td>0.04/29.2</td>
<td>0.039/29.0</td>
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<tr>
<td>Gas turbine power output (MWel)</td>
<td>295.238</td>
<td>295.03</td>
</tr>
<tr>
<td>Steam turbine power output (MWel)</td>
<td>171.78</td>
<td>170.71</td>
</tr>
<tr>
<td>Net plant power output (MWel)</td>
<td>455.15</td>
<td>453.872</td>
</tr>
<tr>
<td>Net plant efficiency (%,LHV)</td>
<td>58.87</td>
<td>58.74</td>
</tr>
</tbody>
</table>
PCC Model Development and Validation

- Model complexity and accuracy for reactive absorption process
  - Rate-based mass transfer
  - Kinetics-controlled reactions
  - Electrolytes system

[Diagram of the CO₂ absorption process with labels for absorber, stripper, cross exchanger, and flows of lean amine, rich amine, flue gas, steam, and CO₂ to compression.]

[Diagram of mass transfer processes showing rate-based approach and reaction equilibrium.]
Rate-based mass transfer
- two films theory
- discretization of liquid film

MEA-H$_2$O-CO$_2$ system
- Kenitic-controlled
- ELEC-NRTL physical property method

The equilibrium reactions are defined as:

\[ 2H_2O \leftrightarrow H_3O^+ + OH^- \]
\[ HCO_3^- + H_2O \leftrightarrow H_3O^+ + CO_3^{2-} \]
\[ MEA^+ + H_2O \leftrightarrow MEA + H_3O^+ \]

The following set of rate-controlled reactions has been defined:

\[ CO_2 + OH^- \rightarrow HCO_3^- \]
\[ HCO_3^- \rightarrow CO_2 + OH^- \]
\[ MEA + CO_2 + H_2O \rightarrow MEACOO^- + H_3O^+ \]
\[ MEACOO^- + H_3O^+ \rightarrow MEA + CO_2 + H_2O \]
- University of Texas at Austin pilot plant.
- Column diameter is equal to 0.427 m
- Two 3.05 m packing bed sections
- 32.5 wt% aqueous MEA solvent
- Closed loop absorption and stripping facility
PCC Model Development and Validation

- Validation by pilot plant data from the University of Texas at Austin

<table>
<thead>
<tr>
<th>Case</th>
<th>Lean loading [mol CO₂/mol MEA]</th>
<th>Rich loading [mol CO₂/mol MEA]</th>
<th>CO₂ capture level [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
<td>Experimental based model</td>
<td>Zhang et al. model</td>
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<tr>
<td>28</td>
<td>0.287</td>
<td>0.412</td>
<td>0.405</td>
</tr>
<tr>
<td>32</td>
<td>0.279</td>
<td>0.428</td>
<td>0.432</td>
</tr>
<tr>
<td>47</td>
<td>0.281</td>
<td>0.539</td>
<td>0.480</td>
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</tbody>
</table>

(a) Case 28 Absorber Temperature Profile
(b) Case 28 Regenerator Temperature Profile

(a) Case 32 Absorber Temperature Profile
(b) Case 32 Regenerator Temperature Profile

(a) Case 47 Absorber Temperature Profile
(b) Case 47 Regenerator Temperature Profile
PCC Model Development and Validation

- Scale-up to match full scale power plant with a capacity of 453MWₑ

### Table 9: Absorber and Regenerator sizing first guess: assumptions and results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ concentration in flue gas (mol%)</td>
<td>4.4</td>
</tr>
<tr>
<td>CO₂ capture level (%)</td>
<td>90</td>
</tr>
<tr>
<td>CO₂ captured (kg/s)</td>
<td>41.4</td>
</tr>
<tr>
<td>Columns flooding (%)</td>
<td>65</td>
</tr>
<tr>
<td>Lean loading (mol/mol)</td>
<td>0.32</td>
</tr>
<tr>
<td>Rich loading (mol/mol)</td>
<td>0.461</td>
</tr>
<tr>
<td>L/G (mol/mol)</td>
<td>1.79</td>
</tr>
<tr>
<td>Reboiler duty (kW)</td>
<td>188,805</td>
</tr>
<tr>
<td>Reboiler duty (GJ/tonne CO₂)</td>
<td>4.56</td>
</tr>
<tr>
<td>Lean solvent MEA concentration (wt%)</td>
<td>32.5</td>
</tr>
<tr>
<td>Lean solvent temperature (K)</td>
<td>303.15</td>
</tr>
<tr>
<td>Absorber columns pressure (bar)</td>
<td>1</td>
</tr>
<tr>
<td>Absorber columns pressure loss (bar)</td>
<td>0.069</td>
</tr>
<tr>
<td>Absorber columns packing</td>
<td>IMTP no. 40</td>
</tr>
<tr>
<td>Absorber columns packing height (m)</td>
<td>25</td>
</tr>
<tr>
<td>Absorber columns cross-section area (m²)</td>
<td>307.91</td>
</tr>
<tr>
<td>Regenerator column pressure (bar)</td>
<td>2.1</td>
</tr>
<tr>
<td>Regenerator column pressure loss (bar)</td>
<td>0.01355</td>
</tr>
<tr>
<td>Regenerator column packing</td>
<td>Flexipack 1Y</td>
</tr>
<tr>
<td>Regenerator column packing height (m)</td>
<td>15</td>
</tr>
<tr>
<td>Regenerator column cross-section area (m²)</td>
<td>81.71</td>
</tr>
</tbody>
</table>
Supersonic shock wave compression technology (Ramgen Power Systems Ltd., 2008)

- only needs 2 stages of compression (VS. 5 to 8 stages for the conventional multi-stage approach)
- 50% potential capital cost saving (Ciferno et al, 2009)
- the discharge temperature: 220°C-240°C (VS. 70°C-90°C for conventional multi-stages)
Supersonic shock wave compression

- Compression model was validated with published data from RAMGEN Power System (Shawn Lawlor, 2010)

- Key parameters of compression train (for this study):
  - Outlet pressure: >=136 bar
  - Efficiency: 0.85
  - Pressure ratio: 8.65
  - Recover temperature: 90°C
  - Exit temperature of intercoolers: 20°C
Basic interfaces of CCGT integrated with PCC

- Flue gas from HRSG to the capture plant
- Low pressure steam extraction for solvent regeneration
- Steam condensate returns to NGCC power plant
- Electrical power supply for the capture plant
### CCGT Integrated with PCC

<table>
<thead>
<tr>
<th></th>
<th>NGCC without CO₂ capture</th>
<th>NGCC with CO₂ capture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas turbine power output (MW&lt;sub&gt;el&lt;/sub&gt;)</td>
<td>295.03</td>
<td>295.03</td>
</tr>
<tr>
<td>Steam turbine power output (MW&lt;sub&gt;el&lt;/sub&gt;)</td>
<td>170.71</td>
<td>113.56</td>
</tr>
<tr>
<td>Power island auxiliary power consumption (MW&lt;sub&gt;el&lt;/sub&gt;)</td>
<td>11.69</td>
<td>9.7</td>
</tr>
<tr>
<td>CO₂ capture level (%)</td>
<td>–</td>
<td>90</td>
</tr>
<tr>
<td>CO₂ captured (kg/s)</td>
<td>–</td>
<td>41.4</td>
</tr>
<tr>
<td>CO₂ compression power consumption (MW&lt;sub&gt;el&lt;/sub&gt;)</td>
<td>–</td>
<td>15.73</td>
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<tr>
<td>Mechanical power consumption in capture process (MW&lt;sub&gt;el&lt;/sub&gt;)</td>
<td>–</td>
<td>4.24</td>
</tr>
<tr>
<td>Desorber reboiler duty (MW&lt;sub&gt;th&lt;/sub&gt;)</td>
<td>–</td>
<td>188.8</td>
</tr>
<tr>
<td>Steam extracted for reboiler (kg/s)</td>
<td>–</td>
<td>76.39</td>
</tr>
<tr>
<td>Specific reboiler duty (MJ&lt;sub&gt;th&lt;/sub&gt;/kg CO₂)</td>
<td>–</td>
<td>4.56</td>
</tr>
<tr>
<td>Net plant power output (MW&lt;sub&gt;el&lt;/sub&gt;)</td>
<td>453.872</td>
<td>378.92</td>
</tr>
<tr>
<td>Net plant efficiency (%, fuel lower heating value)</td>
<td>58.74</td>
<td>49.04</td>
</tr>
<tr>
<td>Efficiency decrease(%-points) compared with reference case</td>
<td>–</td>
<td>9.70</td>
</tr>
</tbody>
</table>
Exhaust gas recirculation (EGR)

- The flow rate of flue gas going to the capture plant reduces 38%
- CO$_2$ concentration increase to 7.3 mol% from 4.4 mol%
- The vent O2 in flue gas decease to 6.6 mol% from 11.4 mol%
## NGCC Integrated with PCC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>without EGR</th>
<th>with EGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ concentration in flue gas (mol%)</td>
<td>4.4</td>
<td>7.32</td>
</tr>
<tr>
<td>CO₂ capture level (%)</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>CO₂ captured (kg/s)</td>
<td>41.4</td>
<td>40.9</td>
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<tr>
<td>Columns flooding (%)</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Lean loading (mol/mol)</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>Rich loading (mol/mol)</td>
<td>0.461</td>
<td>0.472</td>
</tr>
<tr>
<td>L/G (mol/mol)</td>
<td>1.79</td>
<td>2.71</td>
</tr>
<tr>
<td><strong>Reboiler duty (kW)</strong></td>
<td>188,805</td>
<td>176,227</td>
</tr>
<tr>
<td><strong>Reboiler duty (GJ/tonne CO₂)</strong></td>
<td>4.56</td>
<td>4.31</td>
</tr>
<tr>
<td>Lean solvent MEA concentration (wt%)</td>
<td>32.5</td>
<td>32.5</td>
</tr>
<tr>
<td>Lean solvent temperature (K)</td>
<td>303.15</td>
<td>303.15</td>
</tr>
<tr>
<td>Absorber columns pressure (bar)</td>
<td>1</td>
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<tr>
<td>Absorber columns pressure loss (bar)</td>
<td>0.069</td>
<td>0.054</td>
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<td><strong>Absorber columns cross-section area (m²)</strong></td>
<td>307.91</td>
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<td>Regenerator column pressure (bar)</td>
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<td>Regenerator column pressure loss (bar)</td>
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<td>0.01344</td>
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<tr>
<td><strong>Regenerator column cross-section area (m²)</strong></td>
<td>81.71</td>
<td>75.43</td>
</tr>
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</table>
CCGT Integrated with PCC

- Pretreat
- Capture
- Compression
- HRSG
- Gas Turbine
- Steam Turbine
- Compression
- Pretreat
- Capture
- Compression
- HRSG
- Gas Turbine
- Steam Turbine
Case Study

Case settings:

- Reference case: CCGT power plant stand alone

- Case 1: CCGT integrated PCC without EGR

- Case 2: CCGT integrated PCC with EGR
  - EGR ratio is 0.38 to maintain 16% O\textsubscript{2} concentration in combustion air
  - A cooler is added to cold down the recycled gas to 15°C to get rid of most of free water

- Case 3: Case 2+ compression heat integration with HRSG
  - An economizer heat exchanger was added to integrate the compression heat to generate more low pressure steam for LP turbine
  - No optimal design was conducted for other parts of HRSG configuration

- Case 4: Case 2+ compression heat integration with stripper reboiler
  - A multi-hot-stream kettle model was used for stripper reboiler
  - The outlet temperatures of hot streams are 135°C to meet a minimum pinch temperature for the reboiler
CCGT Integrated with PCC

- Pretreat
- Capture
- Compression
- Gas Turbine
- Steam Turbine
- Compression
- Pretreat
- Capture

Case 1
Case 2
Case 3
Case 4
HRSG
Gas Turbine
Steam Turbine

Funded by the European Union
## Results

<table>
<thead>
<tr>
<th>Description</th>
<th>Reference</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
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</thead>
<tbody>
<tr>
<td>NGCC without EGR</td>
<td>295.03</td>
<td>295.03</td>
<td>294.64</td>
<td>294.64</td>
<td>294.64</td>
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<tr>
<td>NGCC +PCC without EGR</td>
<td>170.71</td>
<td>113.56</td>
<td>117.69</td>
<td>120.14</td>
<td>121.85</td>
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<td>Gas turbine power output (MW\textsubscript{el})</td>
<td>11.69</td>
<td>9.7</td>
<td>9.7</td>
<td>9.7</td>
<td>9.7</td>
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<tr>
<td>Steam turbine power output (MW\textsubscript{el})</td>
<td>–</td>
<td>14.8</td>
<td>14.8</td>
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<td>Power island auxiliary power consumption (MW\textsubscript{el})</td>
<td>–</td>
<td>4.24</td>
<td>2.035</td>
<td>2.035</td>
<td>2.035</td>
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<tr>
<td>CO\textsubscript{2} compression power consumption (MW\textsubscript{el})</td>
<td>–</td>
<td>4.56</td>
<td>4.31</td>
<td>4.31</td>
<td>4.31</td>
</tr>
<tr>
<td>Mechnical power consumption in capture process (MW\textsubscript{el})</td>
<td>–</td>
<td>453.872</td>
<td>379.85</td>
<td>385.795</td>
<td>388.245</td>
</tr>
<tr>
<td>Desorber reboiler duty (MW\textsubscript{th})</td>
<td>–</td>
<td>188.8</td>
<td>176.2</td>
<td>176.2</td>
<td>176.2</td>
</tr>
<tr>
<td>Steam extracted for reboiler (kg/s)</td>
<td>–</td>
<td>76.39</td>
<td>71.06</td>
<td>71.06</td>
<td>65.50</td>
</tr>
<tr>
<td>CO\textsubscript{2} captured (kg/s)</td>
<td>–</td>
<td>41.4</td>
<td>41.4</td>
<td>41.4</td>
<td>41.4</td>
</tr>
<tr>
<td>Specific reboiler duty (MJ\textsubscript{th}/kg CO\textsubscript{2})</td>
<td>–</td>
<td>4.56</td>
<td>4.31</td>
<td>4.31</td>
<td>4.31</td>
</tr>
<tr>
<td>Net plant power output (MW\textsubscript{el})</td>
<td>58.74</td>
<td>49.16</td>
<td>49.93</td>
<td>50.25</td>
<td>50.47</td>
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<tr>
<td>Net plant efficiency (%, fuel lower heating value)</td>
<td>–</td>
<td>9.58</td>
<td>8.81</td>
<td>8.49</td>
<td>8.27</td>
</tr>
<tr>
<td>Overall efficiency improvement(%-points) compared with case 1</td>
<td>–</td>
<td>–</td>
<td>0.77</td>
<td>1.09</td>
<td>1.31</td>
</tr>
</tbody>
</table>

*EGR* stands for Exhaust Gas Recirculation.
Results

![Bar chart showing plant efficiency (%LHV) for Reference, Case 1, Case 2, Case 3, and Case 4. The bars are labeled with 'Net plant efficiency' and 'Efficiency decrease'.]

![Bar chart showing loss of power electricity (MW) for Reference, Case 1, Case 2, Case 3, and Case 4. The bars are labeled with 'Loss as steam extraction', 'PCC auxiliary', 'CO2 compression', and 'Power isand consumption'.]
Summary

- The efficiency (LHV) decreases to 49.16% from 58.74% for conventional capture plant (Case 1):
  - ~7.40% points for steam extraction for solvent regeneration
  - ~0.55% points for capture plant auxiliary power consumption
  - ~1.92% points for CO₂ compression

- EGR has a lower CAPEX investment because of smaller cross-section area of
  - the absorber (216.42m² VS 303.15m² → 28.6% reduction)
  - the stripper (75.43m² VS 81.71m² → 7.69% reduction)

- EGR has 0.77% points efficiency improvement (Case 2 VS Case 1) because of:
  - 7% lower steam consumption
  - 52% blower power consumption
  - A litter lower solvent pumps power consumption
Summary

- Compression heat integration with HRSG has 0.32% points efficiency improvement (Case 3 VS Case 2). Optimal design of HSRG configuration combining compression heat could help to achieve more efficiency improvement for Case 3.

- Compression heat integration with stripper reboiler achieves 0.54% points efficiency improvement (Case 4 VS Case 2). The return temperature of the stream from compression train is 135°C (in Case 4) after is introduced to heat the reboiler, which provide the potentials to do more integration.

- In a summary, CCGT with EGR integrated with PCC and supersonic shock wave compression with compression heat integration into main process could be the future direction of carbon capture deployment for CCGT power plant.


Acknowledgement

- EU FP7 Marie Curie IRSES (PIRSES-GA-2013-612230)
  - Funded by the European Union

- 2013 China-Europe SMEs energy saving and carbon reduction research project (No.SQ2013ZOA100002)

- Water and Energy Workshop

Organized and sponsored by

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