EGR and S-EGR on a Micro-Gas Turbine for Enhanced CO₂ Capture Performance

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● EPSRC Gas-FACTS and SELECT
● Turbec T100 micro-gas turbine
● Test conditions and monitoring
● Results of EGR testing at PACT on turbine parameters and emissions
● Implications for capture
● Conclusions
Background to Gas-CCS

- Interest in gas due to high efficiencies and lower carbon intensities than coal – coupling with post-combustion carbon capture can help decarbonise the energy supply and meet stringent emissions reduction targets.

- Challenges to overcome:
  ~ low CO₂ concentration/partial pressure in the flue gas
  ~ high O₂ concentrations in the flue gas
  ~ high flue gas flowrates

- Different methods to address these through research programmes to investigate ways in which to improve capture performance through gas turbine modifications.
EPSRC-funded Projects

- EPSRC Gas-FACTS (EP/J020788):
  ~ future advanced capture technology options for gas-CCS
  ~ gas turbine modifications and advanced carbon capture
  ~ gas turbine options for improved CCS performance and advanced capture testing for future gas power systems

- EPSRC SELECT (EP/M001482):
  ~ integration, intensification, scale-up and optimisation of selective EGR CCGT systems with carbon capture
  ~ provide useful data to support real design improvements in flexibility to fit into the complicated energy system
  ~ includes system integration and process intensification, system scale-up/pilot-plant studies, system optimisation and whole systems performance assessments
Aims and Objectives

- To explore EGR/S-EGR technologies on a micro-gas turbine to increase CO₂ and limit O₂ in the flue gas
- Use of a modified Turbec T100 PH Series 1 micro-gas turbine to assess the effects of CO₂-enhanced operation across the operating envelope of the turbine, in terms of:
  - mechanical impacts on the turbine
  - overall efficiency
  - detailed emissions analysis
- To improve capture performance and minimize reboiler duty, quantifying the increase in overall plant efficiency
Turbec T100 Gas Turbine at UKCCSRC PACT Facilities

- Experimental work at the UK Carbon Capture and Storage Research Centre’s (UKCCSRC) Pilot-scale Advanced CO\textsubscript{2} Capture Technology (PACT) National Core Facilities for combustion and carbon capture technology
- Use of the Series 1 Turbec T100 PH gas turbine, with CO\textsubscript{2} injection to the compressor inlet
- Integrated with the on-site carbon capture plant
- Modelling of the combustion chamber using CFD
# Turbec T100 Turbine

## TURBEC T100 SPECIFICATION

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor ratio</td>
<td>4.5 : 1</td>
</tr>
<tr>
<td>Maximum fuel gas consumption</td>
<td>330 kW</td>
</tr>
<tr>
<td>Turbine inlet temperature</td>
<td>~950°C</td>
</tr>
<tr>
<td>Turbine outlet temperature</td>
<td>~645°C</td>
</tr>
<tr>
<td>Maximum generator speed</td>
<td>70,000 rpm</td>
</tr>
<tr>
<td>Exhaust gas flow</td>
<td>0.80 kg/s</td>
</tr>
<tr>
<td>Electrical power generation</td>
<td>50-100 kW</td>
</tr>
<tr>
<td>Electrical efficiency</td>
<td>30%</td>
</tr>
<tr>
<td>Thermal power generation</td>
<td>up to 165 kW</td>
</tr>
<tr>
<td>Total CHP efficiency</td>
<td>77%</td>
</tr>
<tr>
<td>CO₂ concentration</td>
<td>1.3-1.8 vol%</td>
</tr>
<tr>
<td>Emissions at full load*</td>
<td>&lt;15 ppm/v NOx and CO</td>
</tr>
</tbody>
</table>

* emissions at 15% O₂ and 15°C air inlet temperature
PACT Test Campaigns

- Baseline test conditions: standard operation across all turndown ratios without any CO$_2$ addition

- CO$_2$-enhanced operation for the simulation of EGR and S-EGR conditions:
  - variation in power output from 50-80 kW
  - variation in CO$_2$ injection/enhancement flowrate from 0-175 kg/hr
  - EGR/S-EGR ratios of 0-356% tested
Parameters Monitored

- **GT metrics:**
  - System temperatures including air inlet, compressor inlet/outlet, calculated TIT, TOT and exhaust gas
  - System pressures, including compressor outlet
  - Engine speed
  - Air and fuel flowrates

- **Extensive emissions analysis:**
  - Standard exhaust gas analysis (CO, CO$_2$, O$_2$)
  - UHC: including CH$_4$, C$_2$H$_6$, C$_2$H$_4$, C$_3$H$_8$, C$_6$H$_{14}$ and total organic carbon
  - Total NO (NO and NO$_2$), SOx, N$_2$O, NH$_3$ and CHOH
## Baseline Tests

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>50 kW</th>
<th>60 kW</th>
<th>70 kW</th>
<th>80 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumption (m³/hr)*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flue Gas Flowrate (kg/min)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine Speed (rpm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressor Outlet Temp (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressor Outlet Pressure (bar)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TIT (°C, calculated)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOT (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flue Gas (dry basis)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₂ (vol%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ (vol%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO (ppm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total NOx (ppm)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

EGR and S-EGR operation achieved via CO₂ injections to the compressor inlet altered a number of **GT parameters** (including system temperatures, engine speed, fuel consumption and thus turbine efficiency) and **emissions**.
EGR Impacts – GT Parameters

- Compressor Outlet Temperature (°C)
- Turbine Inlet Temperature (°C)

Power Output (kW) vs. Compressor Outlet Temperature (°C)

Power Output (kW) vs. Turbine Inlet Temperature (°C)

- baseline
- 75 kg/hr
- 125 kg/hr
EGR Impacts – GT Parameters

Engine speed and efficiency
EGR Impacts – Emissions

Carbon Dioxide Concentration (vol%)

Power Output kW

- baseline
- 30% EGR
- 50% EGR
- 50kg/h
- 75kg/h
- 125kg/h
- 150kg/h
- 175 kg/hr
EGR Impacts – Emissions

CO and CH$_4$

- CO Concentration (ppm) vs. Power Output (kW)
- Methane Concentration (ppm) vs. Power Output (kW)

Data points for different EGR rates and power outputs:
EGR Impacts – Emissions

NOx Emission Index

Power Output (kW)

Baseline
100 kg/hr
125 kg/hr

NOx Emissions Index (g/kWh)
Summary of EGR Impacts at Baseload Performance

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>0 kg/hr</th>
<th>125 kg/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumption (m³/hr)*</td>
<td>22.9</td>
<td>23.8</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>22.1</td>
<td>21.9</td>
</tr>
<tr>
<td>Engine Speed (rpm)</td>
<td>59,112</td>
<td>58,392</td>
</tr>
<tr>
<td>TIT (°C, calculated)</td>
<td>881</td>
<td>872</td>
</tr>
<tr>
<td>TOT (°C)</td>
<td>645</td>
<td>641</td>
</tr>
<tr>
<td>Flue Gas (dry basis)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₂ (vol%)</td>
<td>18.5</td>
<td>17.9</td>
</tr>
<tr>
<td>CO₂ (vol%)</td>
<td>1.4</td>
<td>4.9</td>
</tr>
<tr>
<td>CO (ppm)</td>
<td>22.4</td>
<td>139</td>
</tr>
<tr>
<td>NOx EI (g/kWh)</td>
<td>1.63</td>
<td>1.43</td>
</tr>
</tbody>
</table>
Validated CFD Modelling

- Flame temperatures could not be measured experimentally so CFD models were employed to confirm the impact of CO$_2$ on the flame region using ANSYS Fluent 15.0
  - a Flamelet Generated Manifold approach
  - realizable k-ε
  - taking into account both conjugate and radiative heat transfer under steady-state operation

- Investigate temperatures and laminar flame speeds using 1D laminar flame flame calculations
Validated CFD Modelling

- Temperatures in the combustor were reduced by ~70 K in the flame region, which would significantly limit thermal NOx generation.

- Laminar flames speeds were reduced by up to 25% (1.6 m/s to 1.2 m/s at equivalence ratios around 1).
Validated CFD Modelling (LES)

- Instantaneous temperature animations:
  \( \sim \text{ from } t = 0.02 \text{ s to } t = 0.03 \text{ s, with combustor residence time } 0.02 \text{ s} \)

Plane 1: \( y = 0.0 \text{ m} \)

Plane 2: \( z = -0.09 \text{ m} \)
Implications for Capture

- Implications of EGR/S-EGR on a solvent-based post-combustion capture process using 30 wt% MEA

- Higher CO₂ concentrations in the flue gas resulted in:
  - higher lean and rich CO₂ loadings
  - a reduction in specific reboiler duty by 30%
  - reductions in the regeneration energy and solvent sensible heat
  - reductions in the desorption energy
  - increases in steam generation rates in the stripper

- Considerable performance improvements can be seen by coupling EGR/S-EGR-based gas power with CCS, providing the combustion system is optimized

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1 Akram, et al. (2016) *Int J Greenh Gas Con* 47, 137-150
2 for the the increases in CO₂ in this paper
Conclusions

- CO₂-enhanced operation of a micro-gas turbine simulated EGR/S-EGR – up to 175 kg/hr (~350%) and the impacts on GT metrics and emissions were quantified

- CO₂ has a higher heat capacity and decreased system temperatures by up to 10°C, but even more so in the flame region, as confirmed by validated CFD models. This limited thermal NOx formation, halving the NOx EI

- It also slowed engine speeds, often by >1000 rpm, and at high EGR with low turndown ratios, produced high levels of emissions (CO/UHC) that can negatively affect capture solvents, by causing degradation
Take Home Messages

- EGR/S-EGR can increase CO$_2$, lower O$_2$ and reduce flue gas volumes to optimize post-combustion capture.

- The results show that turbines at low turndown ratios will be significantly more impacted by EGR/S-EGR regimes and thus the recycle ratio will need to be altered to maximize both turbine and capture efficiencies over the whole operating envelope.

- The generation of empirical evidence for the improvement of gas-CCS performance can be used to assist and inform the deployment of these technologies to decarbonize the energy supply and meet climate change targets.
Acknowledgements

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  - thank the Engineering and Physical Sciences Research Council (EPSRC) for funding this research (grants EP/J020788 and EP/M001482) and the University of Leeds Low Carbon CDT
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CFD Modelling – LES

**Case:** baseline 80 kW boundary conditions from experiments and process modelling results

**Numerical settings:**
- Grid: hybrid tetra-hexa mesh consisting of 15M elements (11M fluid cells + 4M solid cells)
- Conjugate heat transfer is included
- LES subgrid-scale stress model: Sigma model from Nicoud (2011) implemented in ANSYS Fluent via User Defined Function
- Chemical mechanism: GRI 3.0 (325 species, 53 reactions for natural gas combustion)
- Chemistry tabulation: Flamelet Generated Manifold employing 1D premixed freely propagating flamelets to represent the combustion process
- Subgrid-scale combustion model: presumed beta-PDF function for the mixture fraction \( Z \) and the progress variable \( c \)