Selective EGR on a Micro Gas Turbine for Post-Combustion Carbon Capture Applications

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Presentation Overview

- Introduction to Gas-CCS and Selective EGR
- Research Facilities and the Micro-Gas Turbine
- Experimental Test Campaign
- Modelling Approaches:
  - process simulations using gCCS
  - CFD analysis using ANSYS Fluent
    - RANS calculations
    - LES calculations
- Conclusions
Introduction to Gas-CCS

- Carbon capture is important to decarbonise the energy supply, but the performance of post-combustion solvent scrubbing is highly dependent on the CO$_2$ partial pressure.
- Gas turbines have low CO$_2$ exhaust levels and would benefit from increases in this to ensure efficient capture.
- Options for improved CCS performance with natural gas systems include exhaust gas recirculation (EGR), selective exhaust gas recirculation (S-EGR), supplementary/external firing and humidification of the gas turbine cycle.
- S-EGR can also address other challenges for gas-CCS, including high remaining O$_2$ and large volumetric flowrate.
Introduction to S-EGR

- EGR: recycle up to 40% of the flue gas (limits O₂)
- Selective EGR recycles only some of the CO₂ in the flue gas
- S-EGR can treble the CO₂ concentration in the exhaust across the same decrease in O₂ in the inlet air*

Aim: to quantify the impacts of S-EGR operation on mGT performance, through changes in terms of combustion temperatures, flame stability and pollutant emissions

PACT Research Facilities

UK Carbon Capture and Storage Research Centre's Pilot-Scale Advanced CO₂ Capture Technology (PACT) Facilities

- National specialist R&D facilities for advanced fossil-fuel energy, bioenergy and carbon capture technology research for power generation and industrial applications
- Aims to bridge the gap between academic bench-scale R&D and industrial pilot trials and provide shared access to industrial and academic users
- The PACT facilities form part of the UK Carbon Capture and Storage Research Centre and are supported by BEIS and the EPSRC as part of the RCUK Energy Programme
PACT Micro-Gas Turbine

- Two Turbec T100 PH gas turbines fuelled with natural gas:
  - GT Series 1 (manufactured in 2000)
  - GT Series 3 (manufactured in 2012)

- Combined heat and power design:
  - 100 kW_{e} at an electrical efficiency of ~30%
  - plus ~165 kW_{th} improves the overall efficiency to ~77%

- Single, centrifugal compressor (pressure ratio of 4.5 : 1) plus a radial turbine on the same shaft as the generator

- Lean, premixed combustor results in low NOx, CO, UHCs

- Modified to include:
  - additional instrumentation for temperatures/pressures/flowrates
  - CO_{2} injection into the air inlet
  - humidification via steam injections into the compressed air flow
Experimental Test Campaign

- Six cases were assessed:
  - three air-fired tests
  - three comparative CO$_2$-enhanced cases

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>AIR-FIRED BASELINES</th>
<th>S-EGR TEST CASES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case Name</td>
<td>Base-50</td>
<td>CO$_2$-50</td>
</tr>
<tr>
<td>Base-65</td>
<td>Base-80</td>
<td>CO$_2$-65</td>
</tr>
<tr>
<td>Base-80</td>
<td></td>
<td>CO$_2$-80</td>
</tr>
<tr>
<td>Power Output (kWe)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>CO$_2$ Flowrate (kg/hr)</td>
<td>0</td>
<td>125</td>
</tr>
<tr>
<td>Effective Recycle Ratio (%)</td>
<td>0</td>
<td>332</td>
</tr>
</tbody>
</table>

- Key mGT performance indicators were evaluated: pressures, temperatures, flowrates, engine speed, power set point/output, exhaust gas analysis and system efficiency

- Experimental data was used as inputs for process simulations – outputs of both were then employed as the boundary conditions for the CFD analysis
Experimental Test Campaign

- Key results:
  - simulated S-EGR had significant impacts on the system temperatures, due to the higher specific heat capacity of the CO₂
Experimental Test Campaign

- Key results:
  - Significant changes in $O_2$ and $CO_2$ concentrations in the exhaust
Experimental Test Campaign

- Key results:
  - simulated S-EGR had significant impacts on unburned species (CO and UHCs) and NOx

[Graphs showing changes in Exhaust Concentration and NOx emissions during different power outputs for baseline and S-EGR conditions.]
Experimental Test Campaign

- Key results:
  - the same mass throughput in the system was achieved at a lower volume attributable to the denser CO$_2$ from cryogenic storage, resulting in consistently slower turbine speeds.
Model 1: Process Simulations

**FUTURE WORK:** Integrate CFD models of key rate controlling components into process simulations to assess dynamic behaviour and operation – improve accuracy
Model 1: Process Simulations

- PSE’s gCCS platform is a systems modelling tool for the whole CCS chain, including power generation and capture.
- The temperature and pressure of the oxidizer at the inlet of the combustor was calculated using the available experimental data.

Properties of the air stream entering the combustor are required as boundary conditions for the CFD model.
Model 1: Process Simulations

- PSE’s gCCS platform is a systems modelling tool for the whole CCS chain, including power generation and capture

- The temperature and pressure of the oxidizer at the inlet of the combustor was calculated using the available experimental data

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Base-65</th>
<th>CO₂-65</th>
<th>Base-80</th>
<th>CO₂-80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (bar)</td>
<td>3.65</td>
<td>3.62</td>
<td>4.14</td>
<td>4.06</td>
</tr>
<tr>
<td>Fuel Flowrate (kg/hr)</td>
<td>21.4</td>
<td>21.7</td>
<td>25.8</td>
<td>26.9</td>
</tr>
<tr>
<td>Air Flowrate (kg/hr)</td>
<td>2363</td>
<td>2591</td>
<td>2669</td>
<td>2819</td>
</tr>
<tr>
<td>CO₂ Flowrate (kg/hr)</td>
<td>-</td>
<td>125</td>
<td>-</td>
<td>125</td>
</tr>
<tr>
<td>Oxidizer Temperature (K)</td>
<td>828</td>
<td>814</td>
<td>814</td>
<td>801</td>
</tr>
</tbody>
</table>

- The key outputs from the experimental test campaign and the process simulations were used as inputs/boundary conditions for the CFD analysis
Model 2: CFD Analysis

- CFD calculations for the combustor mGT were performed using ANSYS Fluent 15.0
- Flamelet Generated Manifold model was employed to represent the combustion thermo-chemistry
- 1D premixed steady-state laminar flamelet library was generated, employing the GRI3.0 mechanism to describe the combustion chemistry
- Turbulence-chemistry interaction was accounted for by employing a presumed beta-probability density function shape
- 3D model of the combustion chamber developed, accounting for conjugate heat transfer
Model 2: CFD Analysis
Model 2: CFD Analysis

- Mesh: 11m elements for fluid domain, 3.9m solid elements
  - hybrid mesh for the fluid region
  - unstructured tetrahedral discretisation for complex burner region
  - structured hexahedral mesh in the remaining part of the combustor
  - conformal interface between the two
  - prism layers on the walls of the unstructured region

- Steady-state Reynolds-Averaged Navier-Stokes (RANS) approach for turbulence modelling, employing realizable $k$-$\varepsilon$ model for all cases

- Large eddy simulation (LES) approach for baseline and S-EGR cases at 80 kWe, with the Sigma model used for the subgrid-scale stresses
Model 2: CFD Analysis – RANS

Calculated temperature contours for the combustor mid-plane together with 2D streamlines

- Base-65
- CO$_2$-65
- Base-80
- CO$_2$-80
Model 2: CFD Analysis – RANS

- Diluted operation results in reduced laminar flame speeds, narrowing the lean side flammability limits
- Calculated temperature profiles downstream of the burner exit plane during S-EGR operation show reduction in the in-flame temperature of up to ~100 K

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<th>CO₂-65</th>
<th>Base-80</th>
<th>CO₂-80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flame Stabilisation Point (m)</td>
<td>0.061</td>
<td>0.059</td>
<td>0.066</td>
<td>0.061</td>
</tr>
<tr>
<td>Peak Laminar Flame Speed (m/s)*</td>
<td>1.6</td>
<td>1.3</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>CO (ppmv)</td>
<td>1</td>
<td>&lt;1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>UHC (ppmv)</td>
<td>14</td>
<td>29</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Combustor Outlet Temperature (K)</td>
<td>1174</td>
<td>1120</td>
<td>1183</td>
<td>1151</td>
</tr>
</tbody>
</table>

*peak laminar flame speeds were found at φ= 1 calculated with Cantera using the GRI3.0 chemical mechanism
Model 2: CFD Analysis – LES

Temperature contour plots for the combustor mid-plane at 80 kWe

- Transient stability investigated using large eddy simulation
- Combustor residence time calculated at 0.015 s
- LES calculated for 0.06 s
- Difference in computational time: 72 hours for RANS vs. 1400 hours for LES
Model 2: CFD Analysis – LES

- Assessment of combustion stability using LES for power spectrum analysis inside the flame
- No characteristic peak frequency illustrating stability across both firing conditions (air and CO$_2$-enhanced)
Conclusions

- Assessed S-EGR on a mGT through validated CFD models of the combustor – quantified performance variations for a range of turndown and recycle ratios using inputs from experiments and process simulations.

- Steady-state RANS: CO$_2$ dilution resulted in lower flame speeds, reduced in-flame temperatures and modified the location of the flame stabilization point, reducing the flammability range:
  - Could be an issue when considering high dilution levels in lean-premixed combustors that are already operated close to the flammability limits.
  - Reduced NOx emissions with no dramatic increases in CO or UHC.

- LES: S-EGR operation did not result in the on-set of flow- or flame-instabilities within the combustor at the levels investigated.

S-EGR is a viable technique for increasing CO$_2$ partial pressures in the exhaust without detrimental impacts to combustion performance – consequently, it can enhance solvent-based capture efficiency and reduce specific reboiler duty.
THANK YOU!

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