8th International Gas Turbine Conference – IGTC-16

EGR and S-EGR on a Micro-Gas Turbine for Enhanced CO_2 Capture Performance

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Contents

- 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 CO_2 concentration/partial pressure in the flue gas
  - ~ high O_2 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

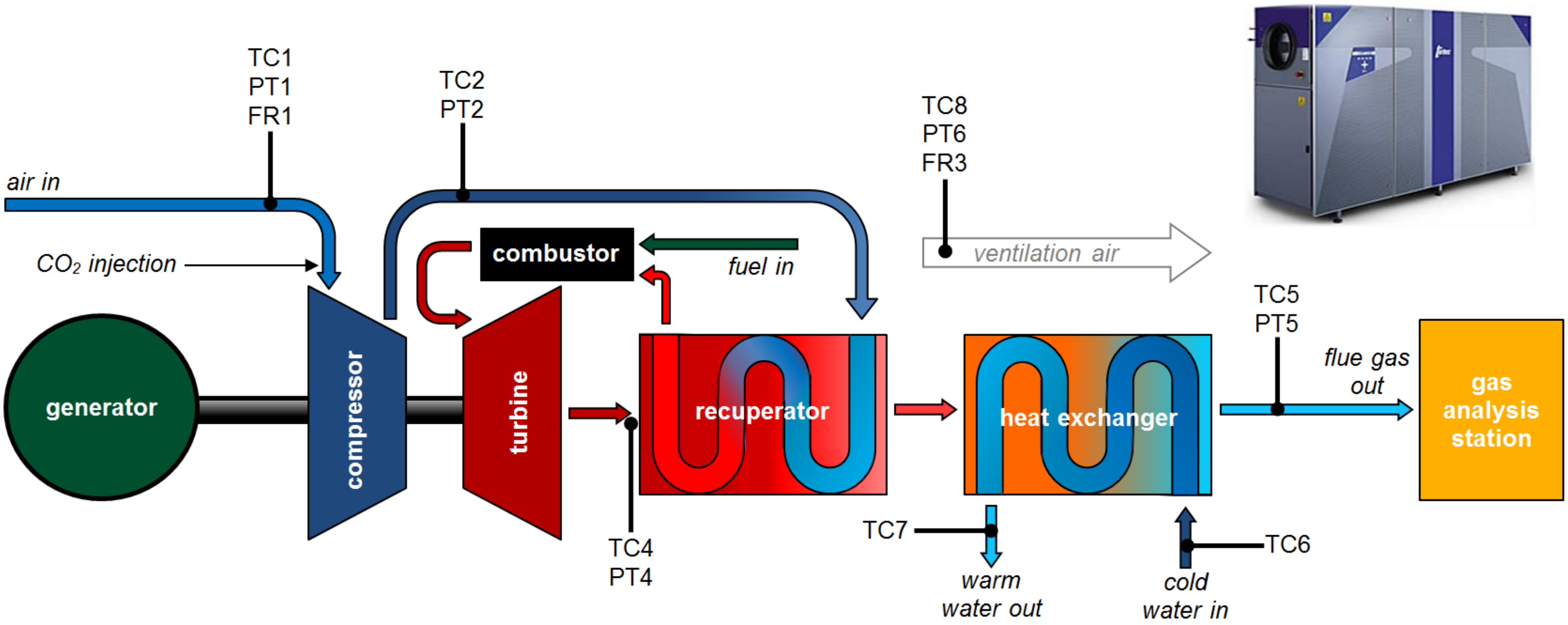
EPSRC-funded Projects

- 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 CO_2 and limit O_2 in the flue gas
- Use of a modified Turbec T100 PH Series 1 micro-gas turbine to assess the effects of CO_2-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

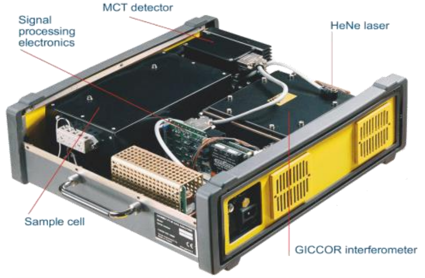
Turbec T100 Gas Turbine at UKCCSRC PACT Facilities

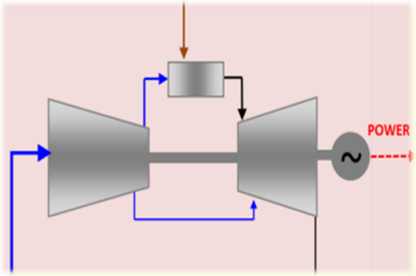


Turbec T100 Turbine

TURBEC T100 SPECIFICATION	
Compressor ratio	4.5 : 1
Maximum fuel gas consumption	330 kW
Turbine inlet temperature	~950°C
Turbine outlet temperature	~645°C
Maximum generator speed	70,000 rpm
Exhaust gas flow	0.80 kg/s
Electrical power generation	50-100 kW
Electrical efficiency	30%
Thermal power generation	up to 165 kW
Total CHP efficiency	77%
CO_2 concentration	1.3-1.8 vol%
Emissions at full load*	<15 ppm/v NOx and CO

** emissions at 15% O_2 and 15°C air inlet temperature*





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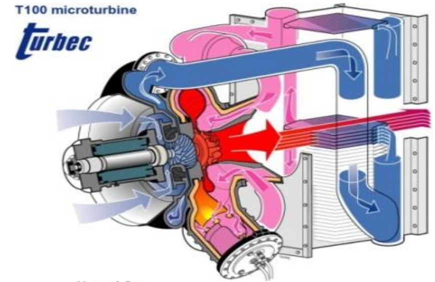
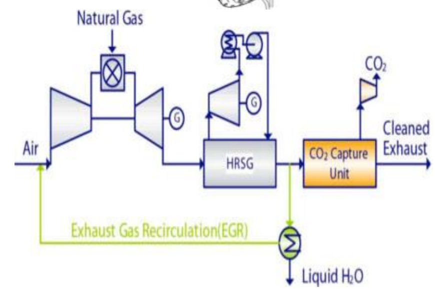
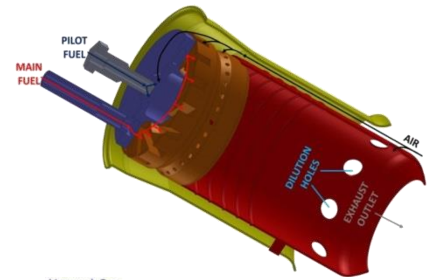
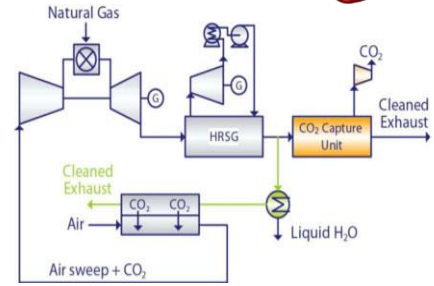
PACT Test Campaigns

- 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









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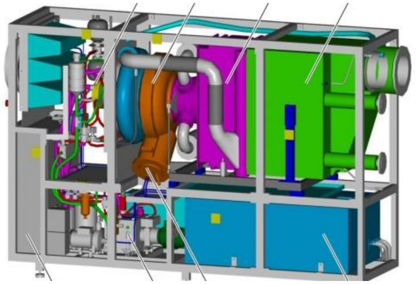
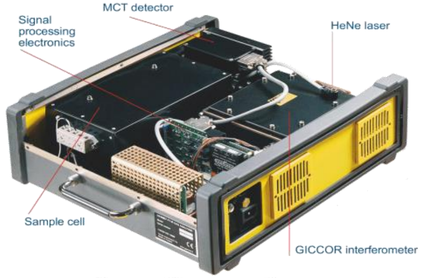
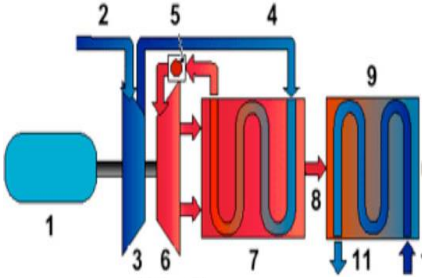
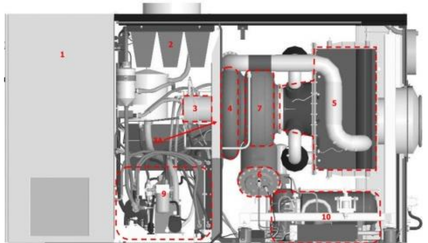
Parameters Monitored

- 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_2H_6, C_2H_4, C_3H_8, C_6H_{14} and total organic carbon
  - ~ total NO (NO and NO_2), SOx, N_2O, NH_3 and CHOH







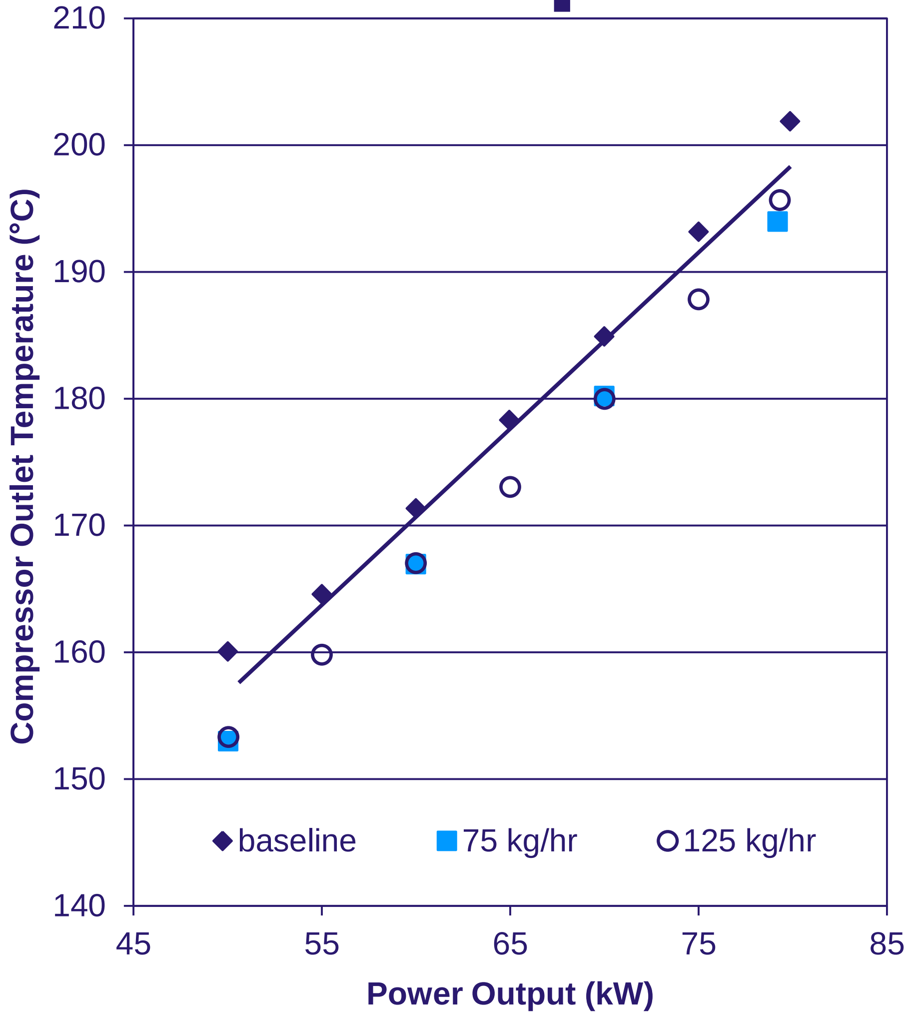


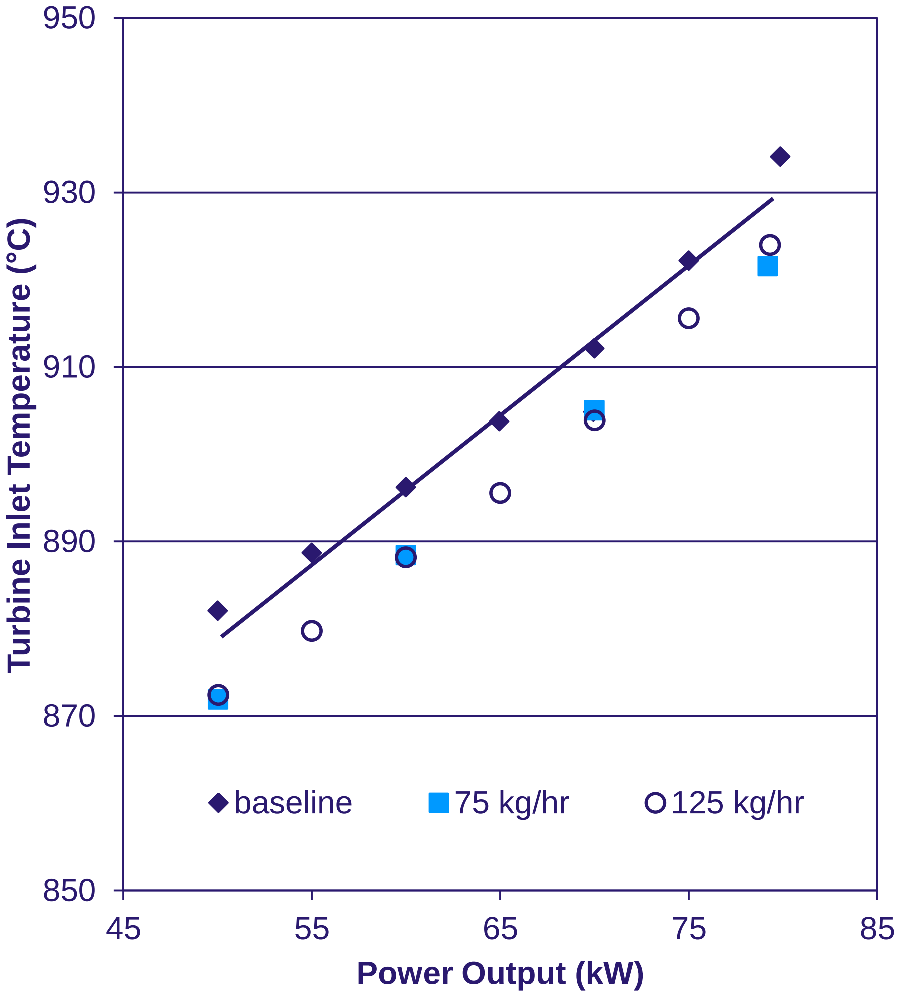
Baseline Tests

VARIABLE		50 kW	60 kW	70 kW	80 kW
Fuel Consumption (m^3/hr)*					
Flue Gas Flowrate (kg/min)					
Engine Speed (rpm)					
Compressor Outlet Temp (°C)					
Compressor Outlet Pressure (bar)					
TIT (°C, calculated)					
TOT (°C)					
Flue Gas (dry basis)	O_2 (vol%)				
	CO_2 (vol%)				
	CO (ppm)				
	Total NOx (ppm)				

EGR and S-EGR operation achieved via CO_2 injections to the compressor inlet altered a number of ***GT parameters*** (including system temperatures, engine speed, fuel consumption and thus turbine efficiency) and ***emissions***

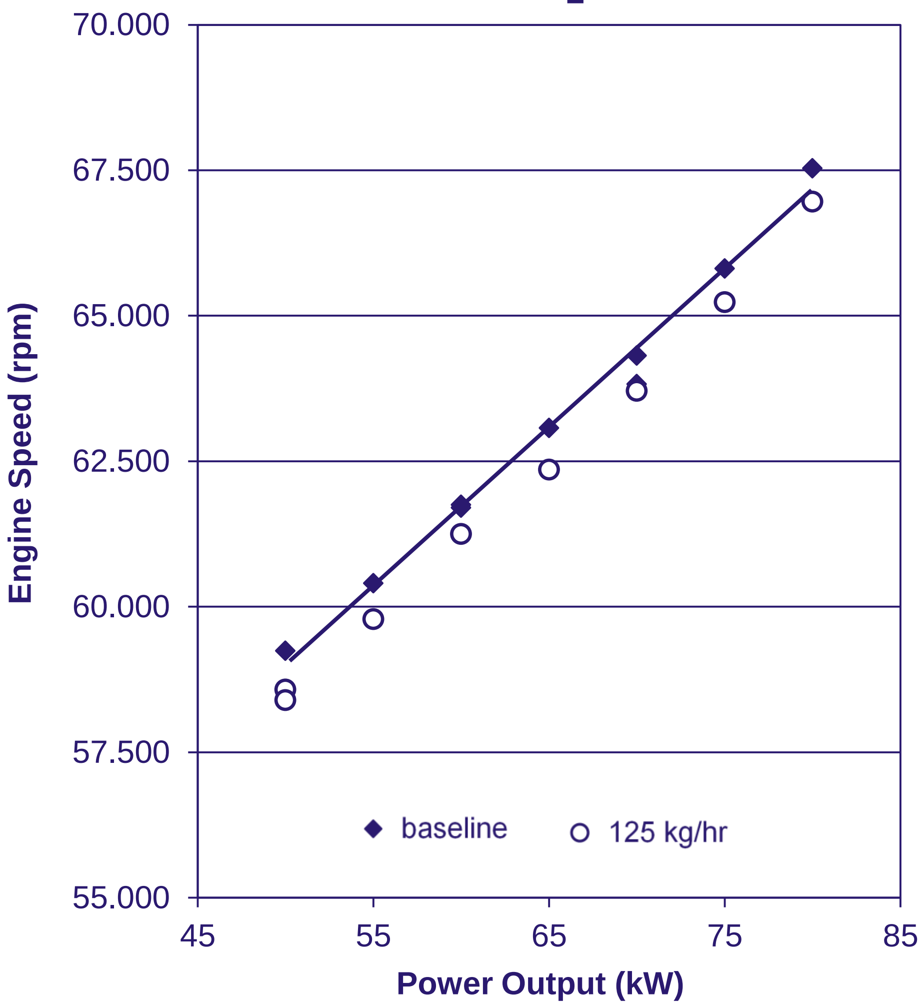
EGR Impacts – GT Parameters

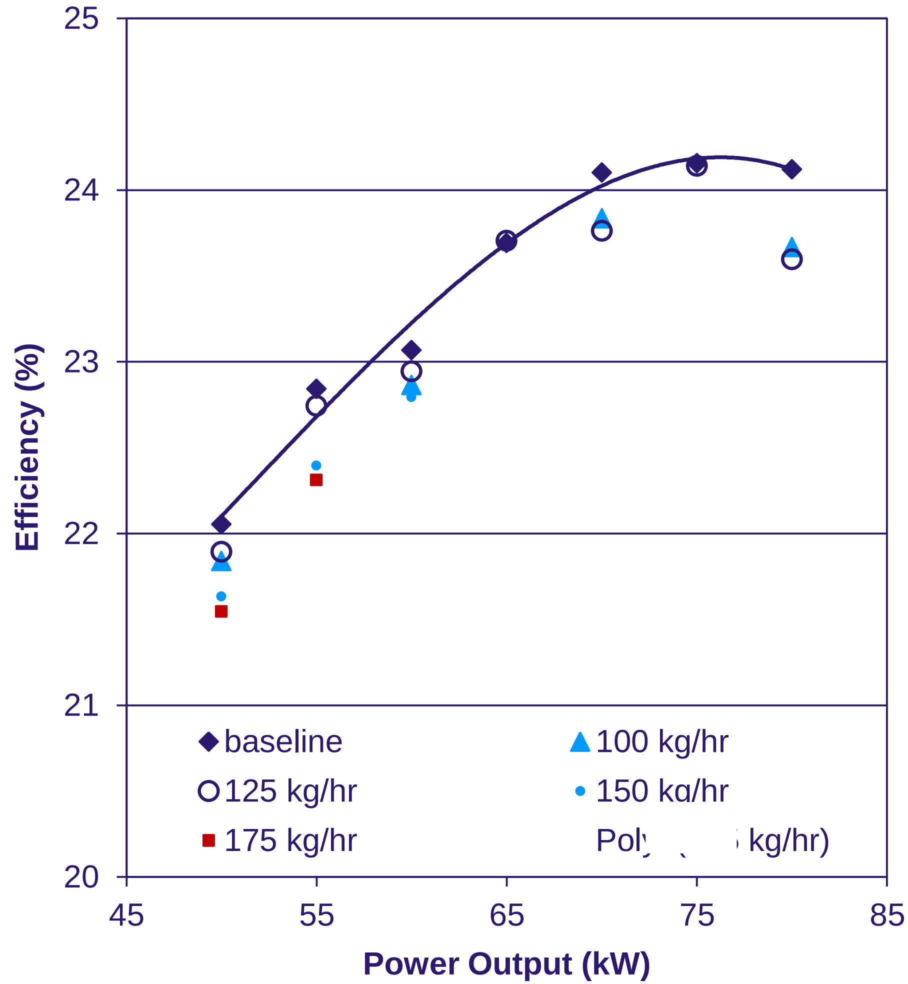




engine speed and efficiency

EGR Impacts – GT Parameters





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CO_2

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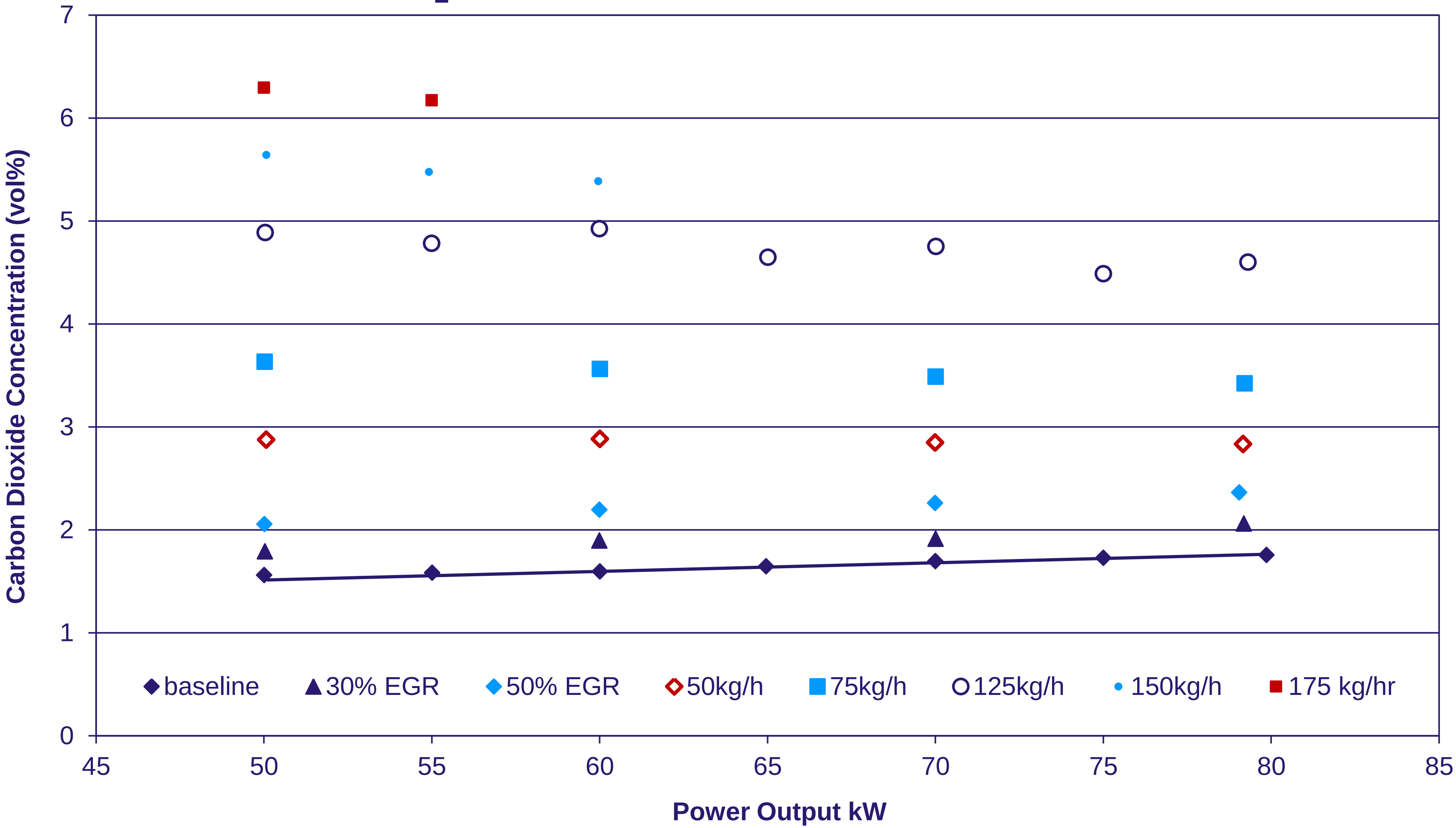
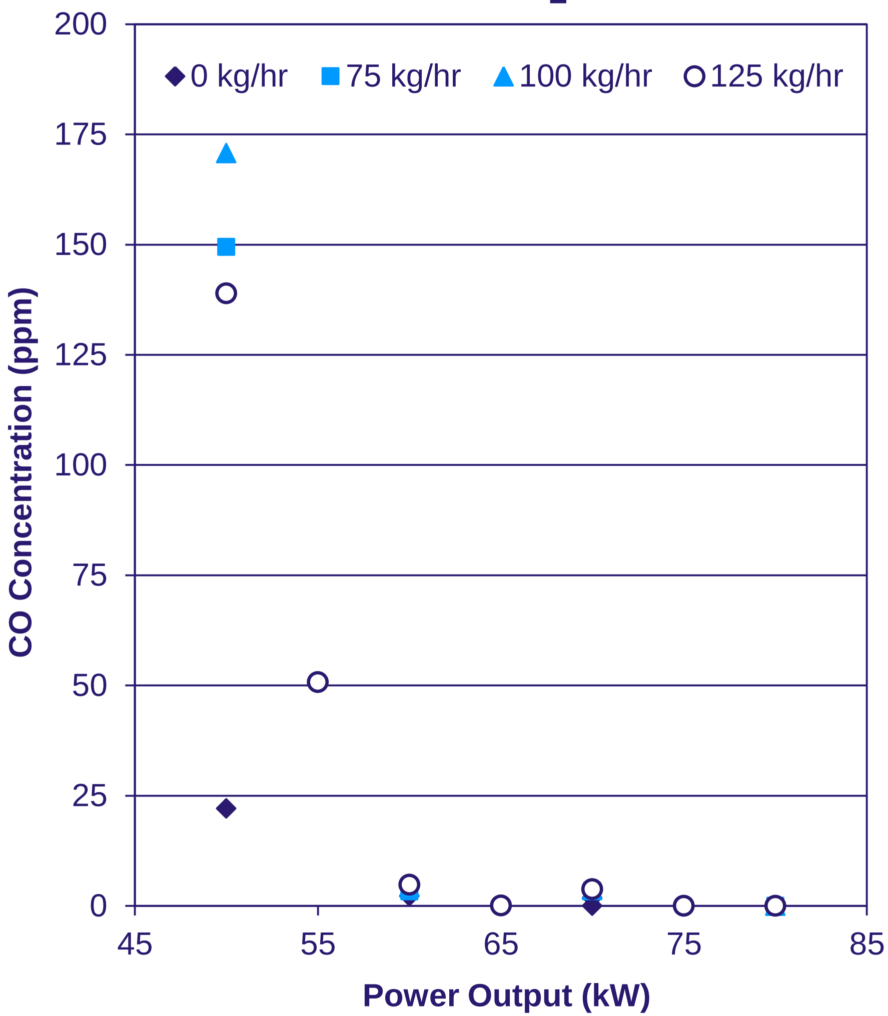
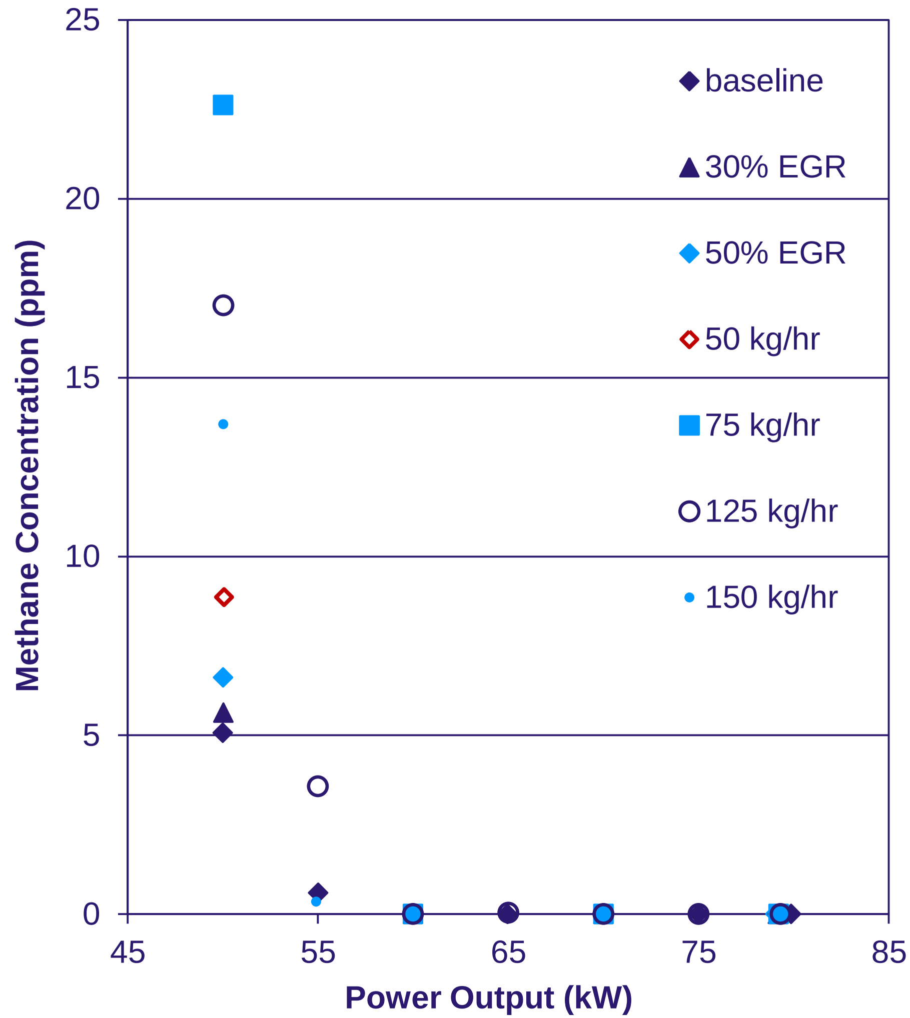
EGR Impacts – Emissions



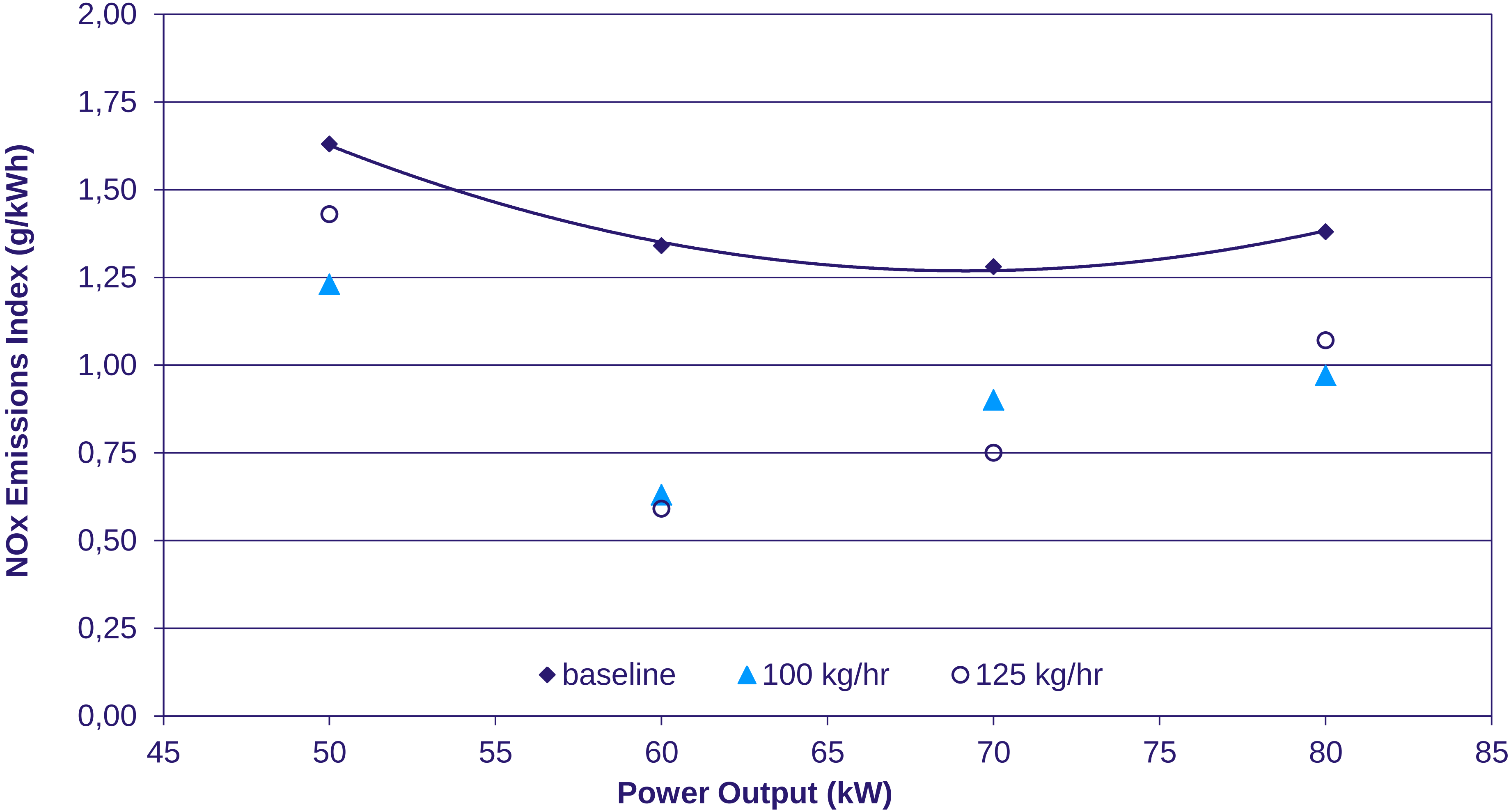
CO and CH_4

EGR Impacts – Emissions





EGR Impacts – Emissions



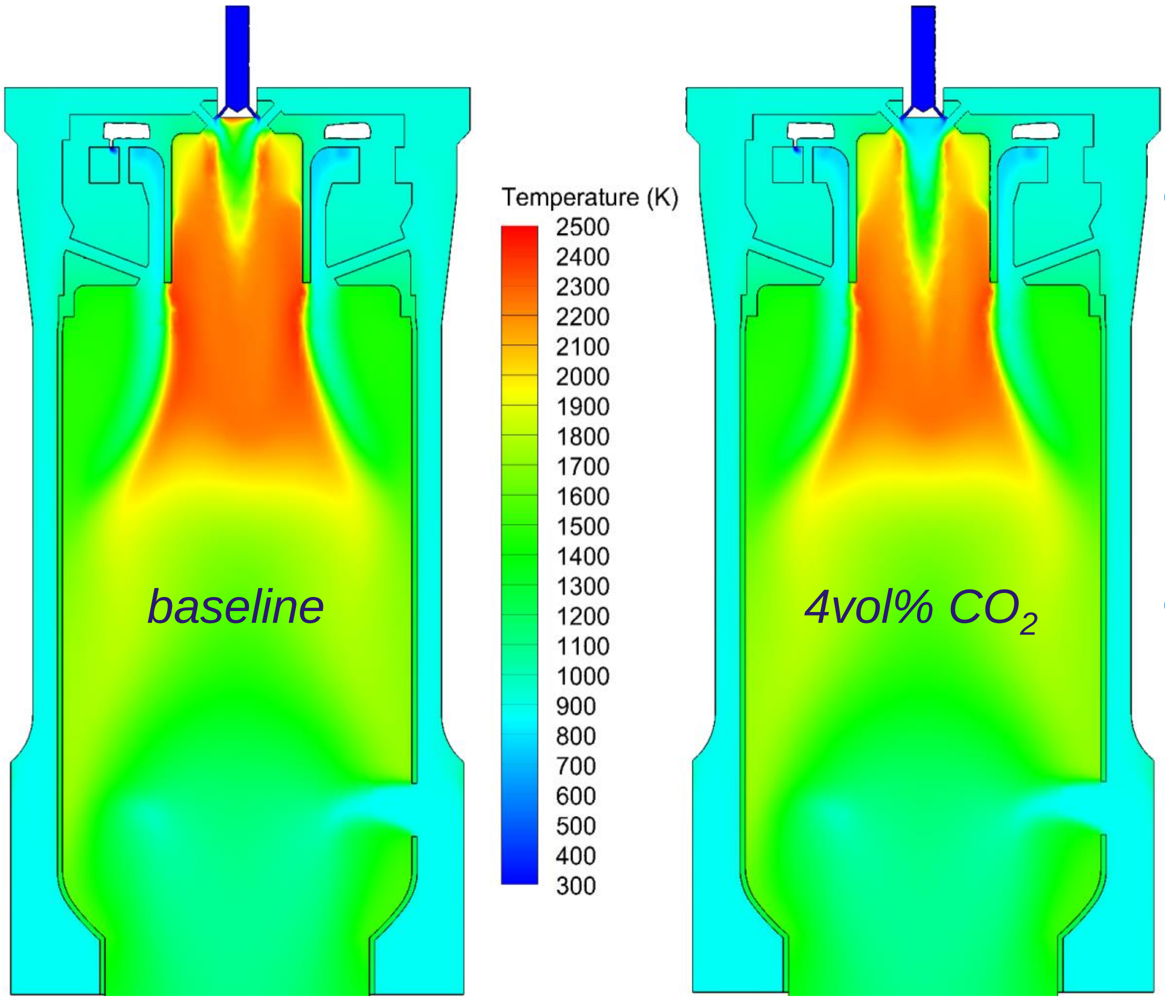
Summary of EGR Impacts at Baseload Performance

VARIABLE		0 kg/hr	125 kg/hr
Fuel Consumption (m^3/hr)*		22.9	23.8
Efficiency (%)		22.1	21.9
Engine Speed (rpm)		59,112	58,392
TIT (°C, calculated)		881	872
TOT (°C)		645	641
Flue Gas (dry basis)	O_2 (vol%)	18.5	17.9
	CO_2 (vol%)	1.4	4.9
	CO (ppm)	22.4	139
	NOx EI (g/kWh)	1.63	1.43

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 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)

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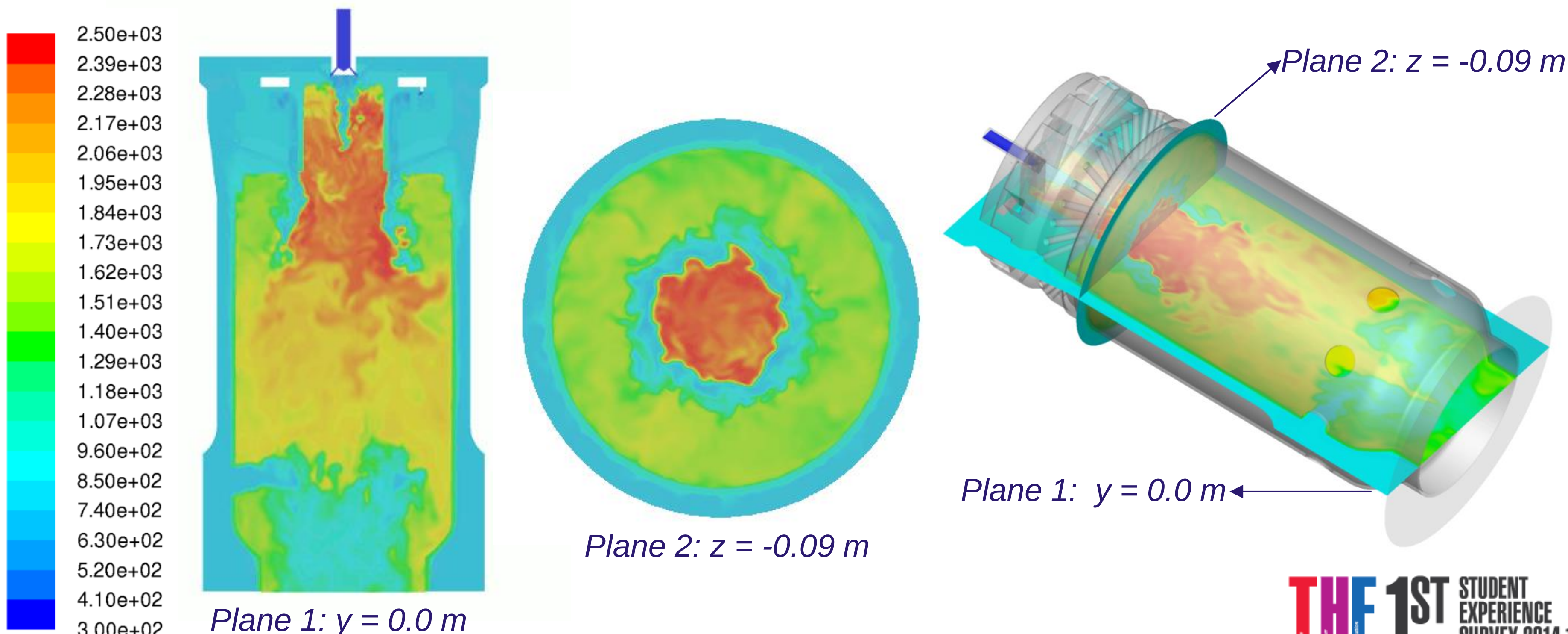
Validated CFD Modelling (LES)

- Instantaneous temperature animations:
  - ~ from t = 0.02 s to t = 0.03 s, with combustor residence time 0.02 s



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Implications for Capture

- Implications of EGR/S-EGR on a solvent-based post-combustion capture process using 30 wt% MEA[1]
- Higher CO_2 concentrations in the flue gas resulted in:
  - ~ higher lean and rich CO_2 loadings
  - ~ a reduction in specific reboiler duty by 30%[2]
  - ~ 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

[1] Akram, *et al*. (2016) ***Int J Greenh Gas Con*** 47, 137-150
[2] for the the increases in CO_2 in this paper

Conclusions

- CO_2-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
- CO_2 has a higher heat capacity and **decreased system temperatures** by up to 10ºC, 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

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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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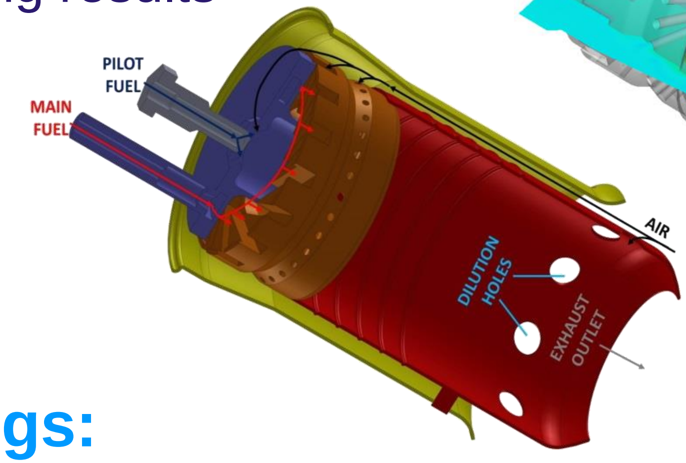
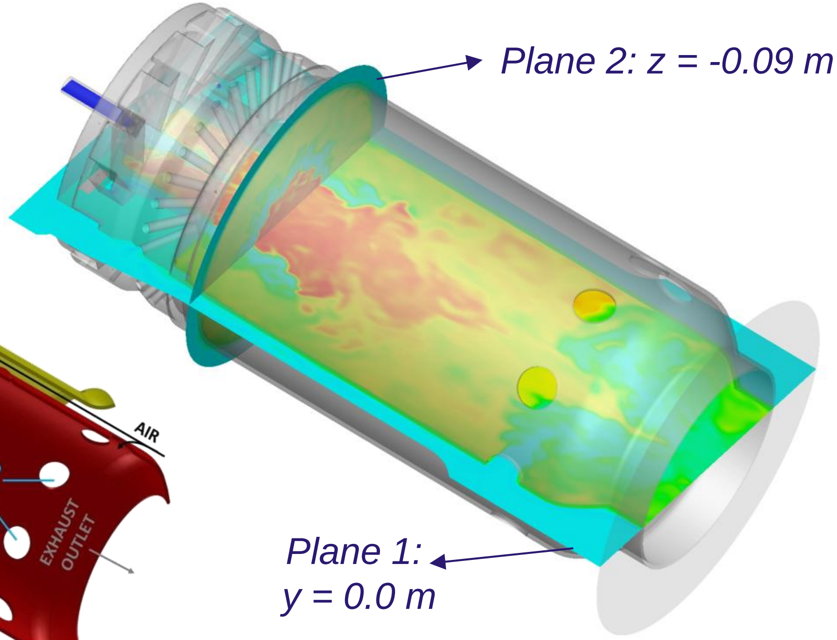
CFD Modelling – LES

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