Parallel Session H: Capture 3

Oxyfuel and Exhaust Gas Recirculation Processes in Gas Turbine Combustion for Improved Carbon Capture Performance

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Selective Exhaust Gas Recirculation for Carbon Capture with Gas Turbines: Integration, Intensification, Scale-up and Optimisation

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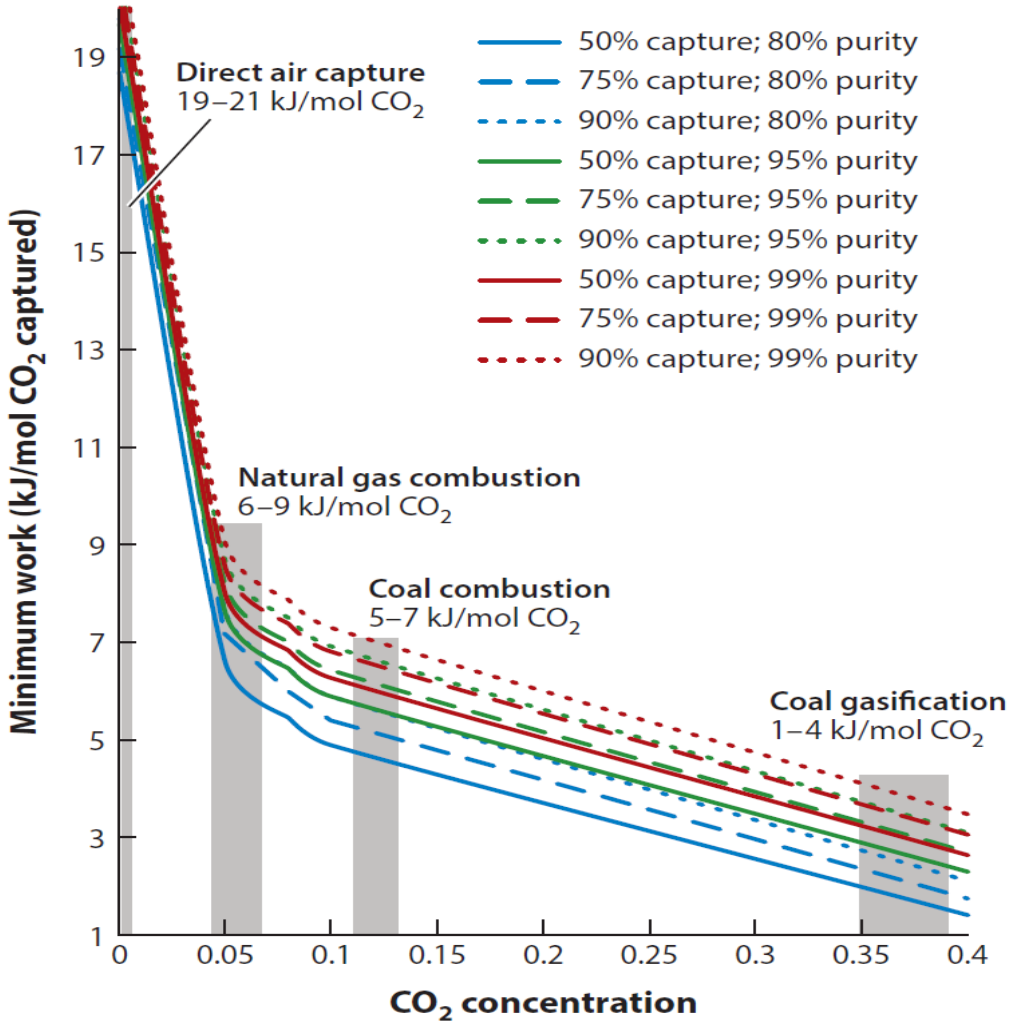
Background

- DLE gas turbine systems typically rely on lean burn processes to control NO_X.
- This results in low CO_2 exhaust concentrations, which requires large and costly scrubbing plant.
- Moreover, the energy required per tonne of CO_2 is also increased as the CO_2 concentration is lowered.
- This is also affected by purity requirement.
- From a CCS perspective, the aim of oxyfuel or EGR is to increase CO_2 exhaust concentration, without compromising operations.



Minimum work required for CO_2 capture based upon initial gas concentration, percent capture, and final purity of CO_2.

Wilcox et al Ann Rev Chem Biomol Eng. 2014;5:479-505.

Oxyfuel combustion research

EP/K000446/1
Funder: Call 1 UKCCSRC Research projects
Partners: Cardiff University (Marsh, Bowen, Griffiths)
Duration: 01/03/13 - 28/02/14
FEC value: £101k

Background

- Energy sector decarbonization efforts create potential for future oxyfuel CCS plants coupled with GT cycles
  - Oxyfuel CCS-GT could provide high CO_2 purity for post-combustion processing and sequestration.
  - Oxyfuel combustion environment results in increased burning velocities, increased flame temperatures, and augments lean and rich stability limits.

Research aims

- To show how flame location changes in relation to O_2 mole fraction and equivalence ratio, in conjunction with the local flow field of the swirl zone.
- To demonstrate whether the flowfield is affected by the different diluents capacity to absorb heat. Hence to determine if the shift in heat release position will affect fluid dynamics.
- To measure exhaust gas concentrations with N_2 and CO_2 diluted O_2/CH_4 swirling flames.

Flowfield and heat transfer

$$Da = \frac{(l_0/u'_{RMS})}{(\alpha/S_L^2)} = \frac{flow\ time\ scale}{chemical\ time\ scale}$$

Different velocity, length and chemical timescales lead to a variety of extinction conditions, thus affecting blowoff conditions.

- Consideration of chemical and flow timescales within the reaction zone.
- In the case of methane oxycombustion with variable diluents, the interaction between chemical and flow properties must be measured.

Properties of oxygen and diluents at 1000K and 0.1 MPa.

Substance	O_2	N_2	CO_2
ρ (kg/m^3)	0.385	0.337	0.529
c_p (J/mol.K)	34.9	32.7	54.3
λ (10^3W/m.K)	79.7	66.0	70.6
μ (10^6Pa.s)	49.1	41.6	41.3

Test conditions

Test	N_2 flow (mole/s)	O_2 flow (mole/s)	β	O_2:CH_4
N1	0.479	0.127	0.21	2.72
N2	0.419	0.188	0.30	4.01
N3	0.364	0.243	0.40	5.18
N4	0.303	0.303	0.50	6.47
N5	0.243	0.364	0.60	7.77
N6	0.182	0.425	0.70	9.06

Total premixed molar flow rate of 0.654 moles/sec

Test	CO_2 flow (mole/s)	O_2 flow (mole/s)	β	O_2:CH_4
C1	0.390	0.104	0.21	2.21
C2	0.341	0.153	0.30	3.27
C3	0.296	0.198	0.40	4.22
C4	0.247	0.247	0.50	5.27
C5	0.198	0.296	0.60	6.32
C6	0.148	0.346	0.70	7.38

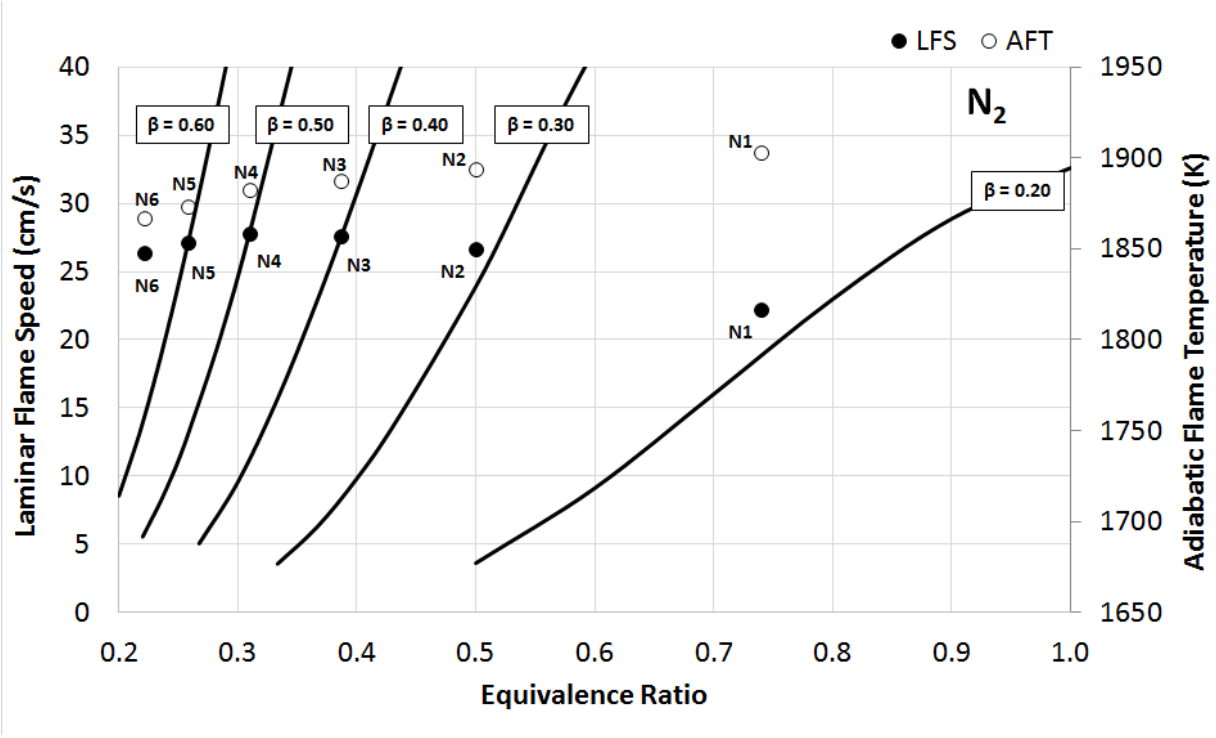
Total premixed molar flow rate of 0.543 moles/sec

CH_4 flow = 0.75 g/s = 37.5 kW

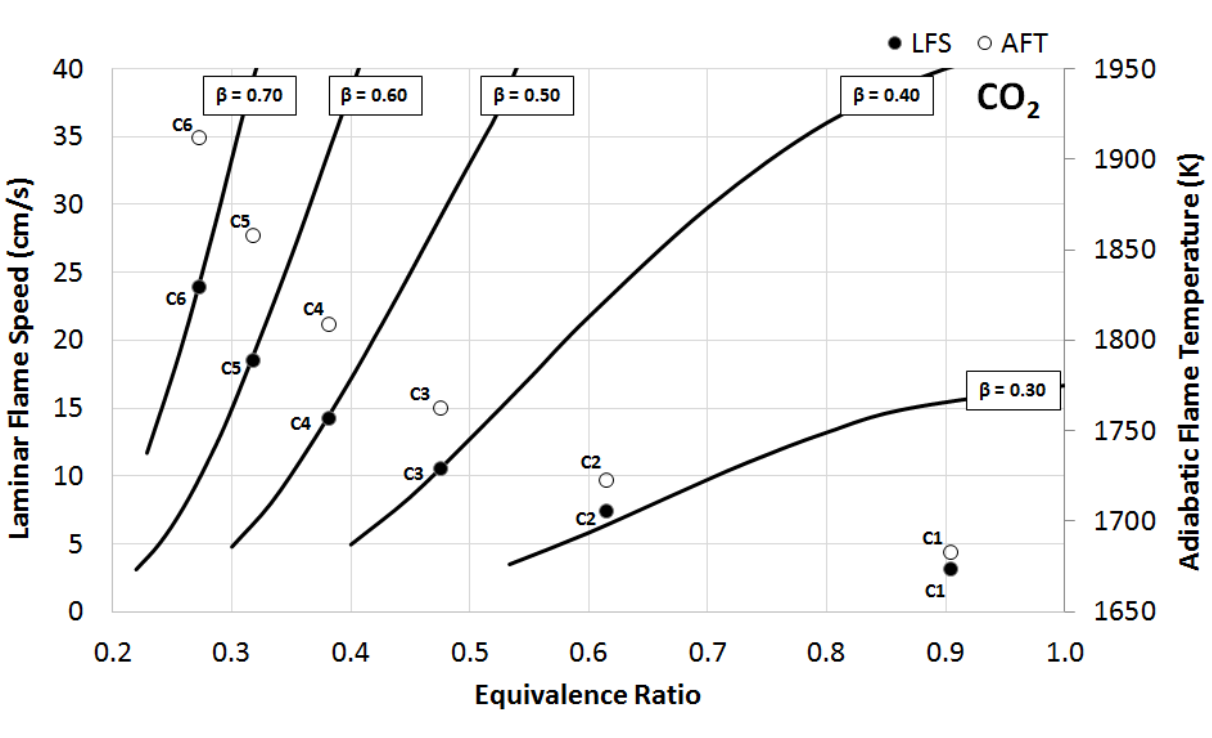
β = molar proportion of O_2 in oxidant

CHEMKIN Simulations

Nitrogen diluted oxy-methane flame

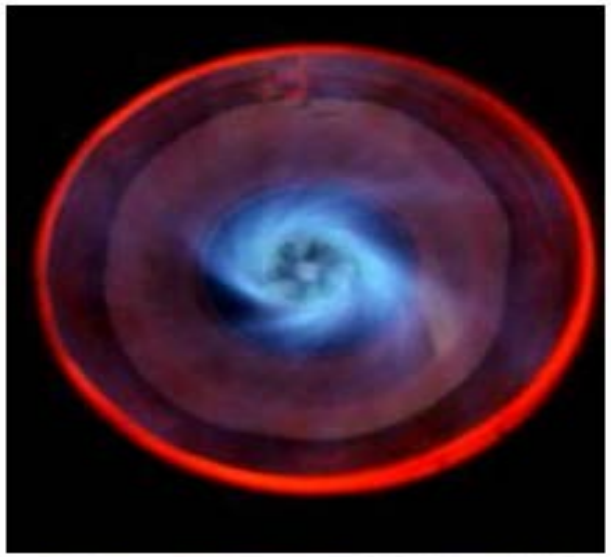


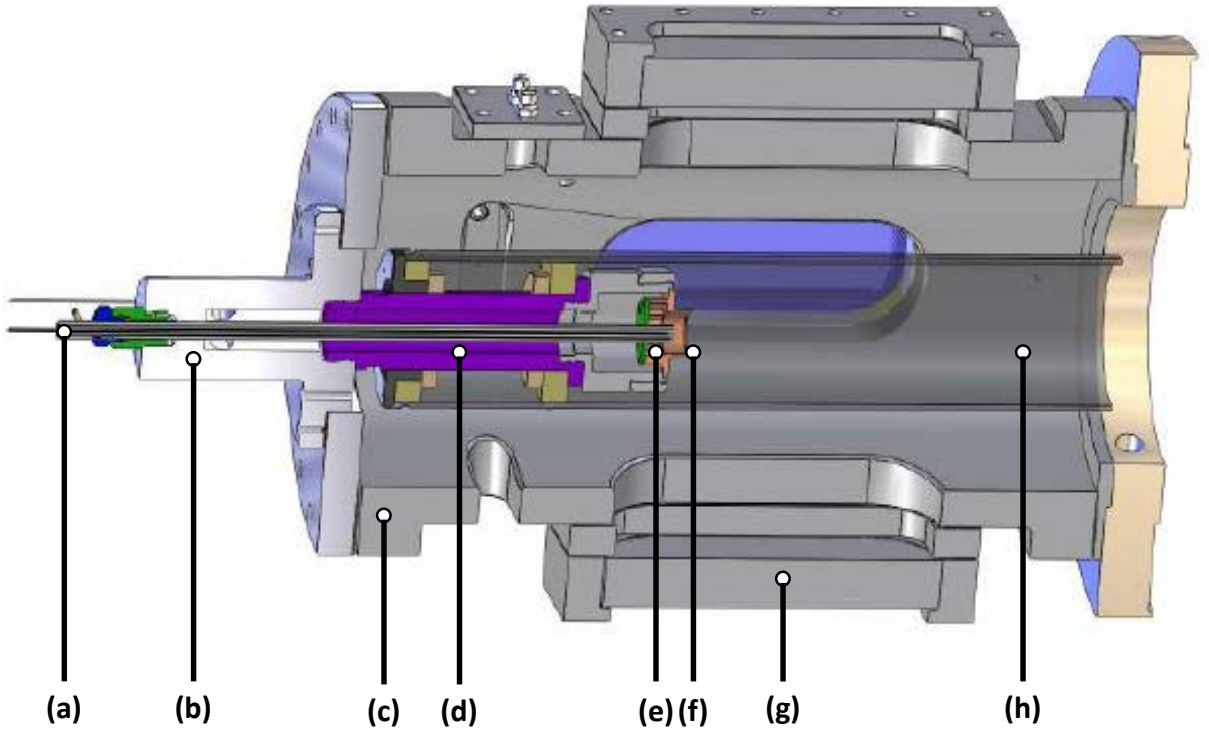
Carbon dioxide diluted oxy-methane flame



- PREMIX coded laminar flame speed calculator utilised in CHEMKIN-PRO to model the reactant mixtures for ambient conditions of temperature (293 K) and pressure (0.1 MPa) with GRI-Mech 3.0 reaction mechanism.
- 53 chemical species and 325 reactions, with solutions based on an adaptive grid of 1000 points, mixture-averaged transport properties, and trace series approximation.

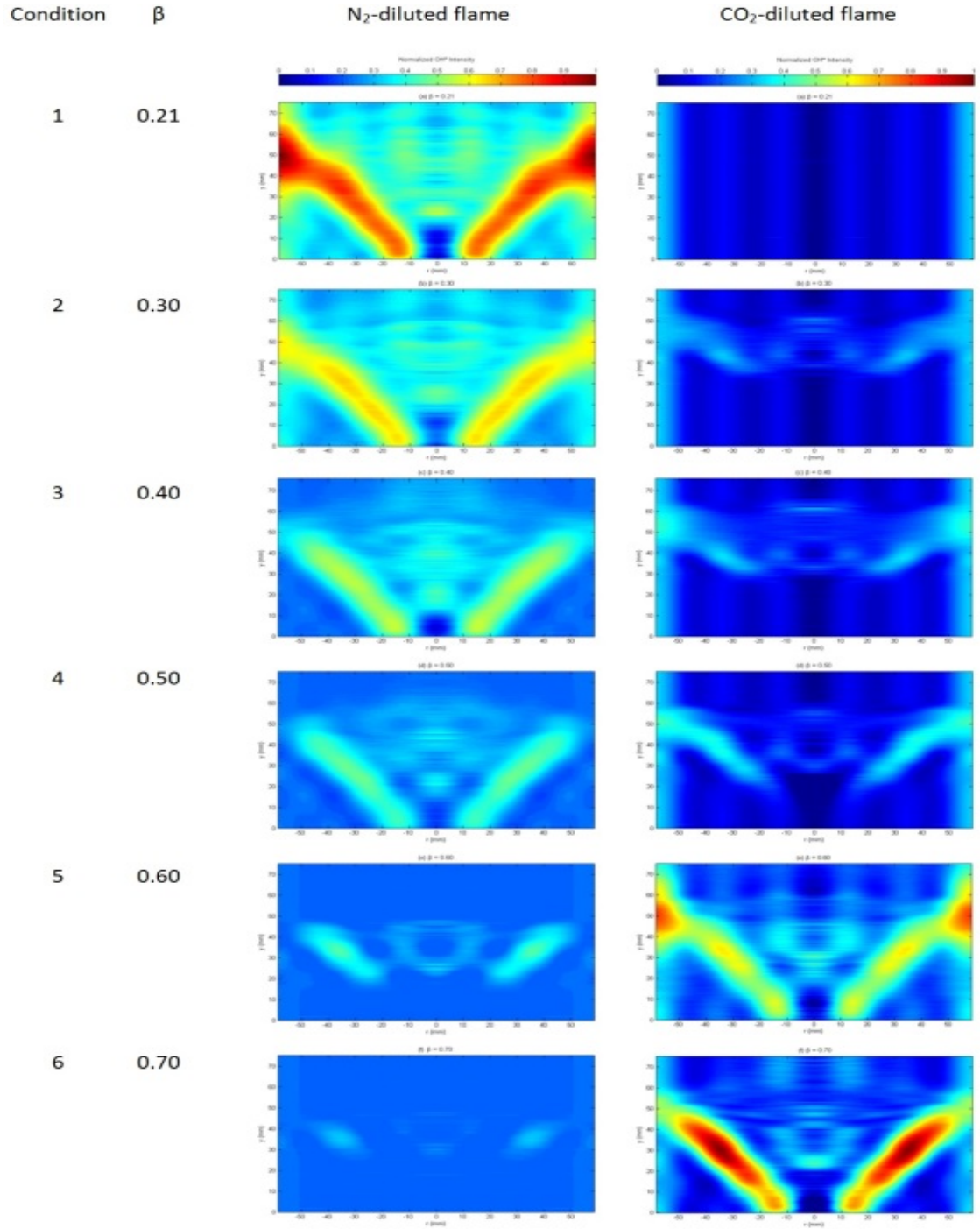
High-Pressure Generic Swirl Burner (HPGSB)
Geometric swirl number = 1.04





Exhaust gas sampling probe 10 diameters from chamber

LAYOUT OF THE HPGSB WITH IGNITER (a), INLET PLENUM (b), HPOC CASING (c), PREMIXING CHAMBER (d), SLOT TYPE RADIAL-TANGENTIAL SWIRLER (e), EXIT NOZZLE (f), QUARTZ WINDOW (g), AND QUARTZ CONFINEMENT TUBE (h)

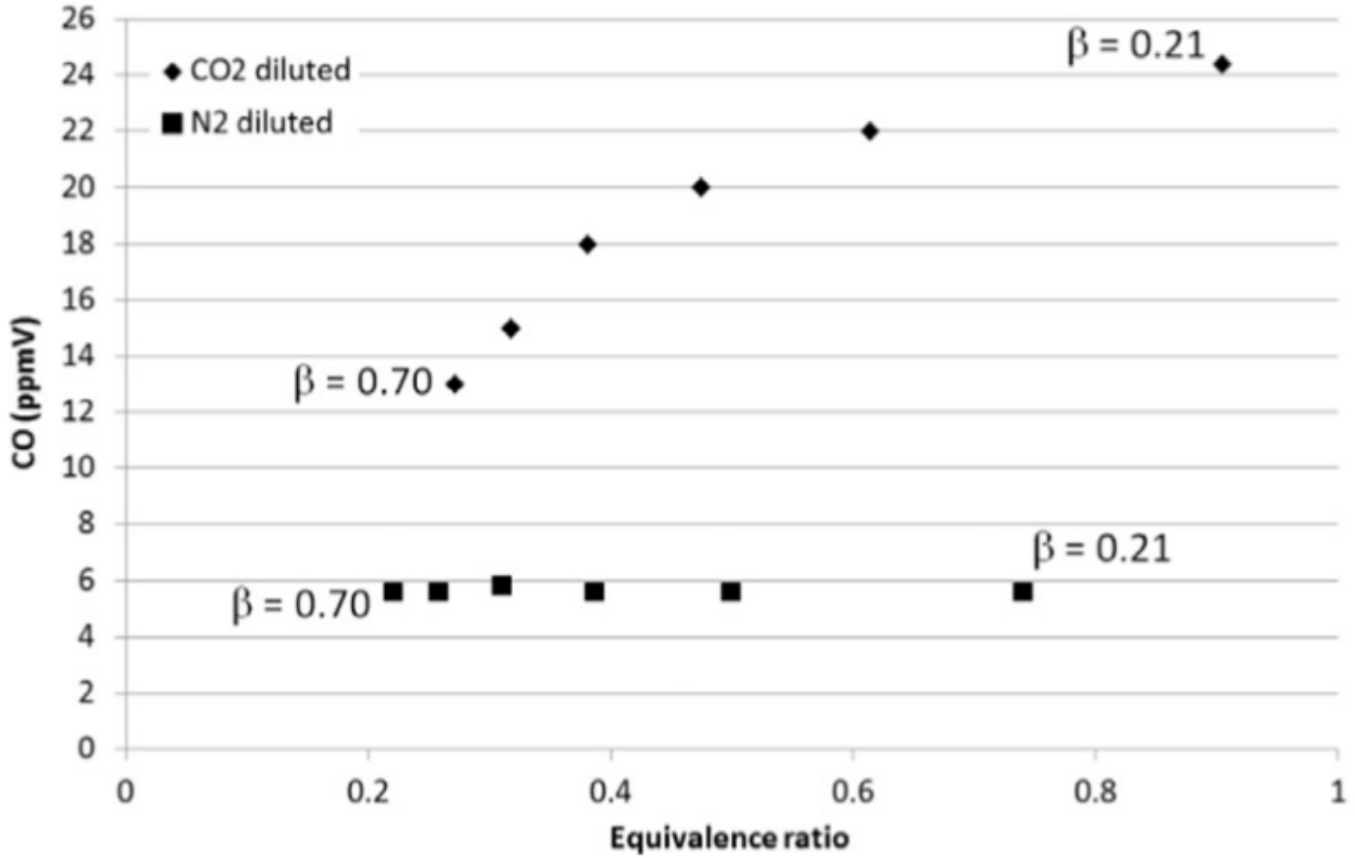


Abel Averaged Chemiluminescence Results

- For N_2 dilution Increasing the O_2 concentration reduces the OH* emission intensity across the flame.

- For CO_2 dilution more oxygen increases the flame strength, and anchors the flame at the burner tip. More CO_2 extracts heat, causing a global weakening and lift-off.

Measured CO



Data have not been normalised to account for effective dilution in the product stream, because equivalent volumetric flow rates are maintained for all tests.

Key findings

- It is possible to operate a modern swirl burner with a variety of oxygen concentrations.
- These flames will also operate with CO_2 / O_2 mixtures, but the operating points are different to that of air.
- The high heat capacity of CO_2 removes excessive amounts of heat from the flame, causing an increase in CO.
- Perhaps there is a compromise to increase CO_2 concentration without the need for pure O_2 as the comburant?

EPSRC
Engineering and Physical Sciences Research Council

SELECTIVE EXHAUST GAS RECIRCULATION FOR CARBON CAPTURE WITH GAS TURBINES (SELECT)

SELECT

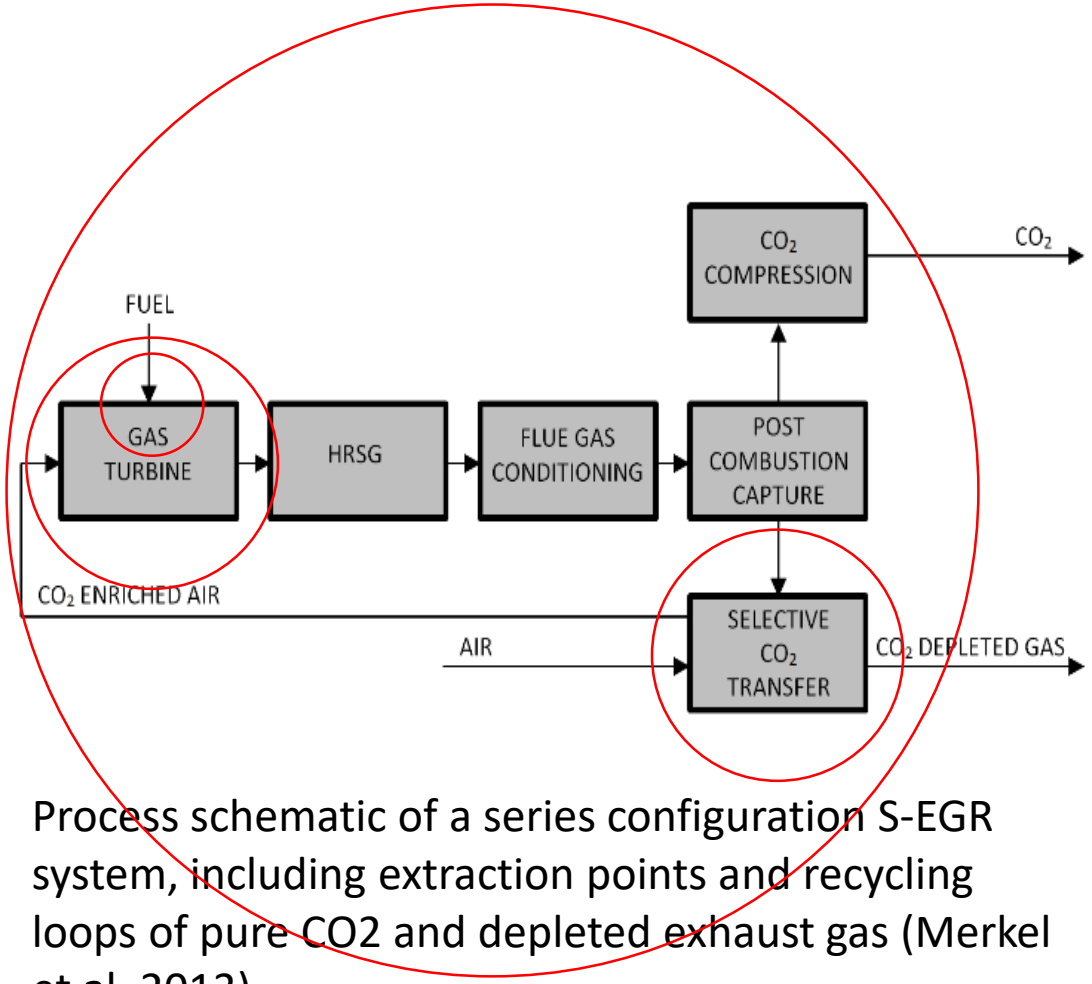
EPSRC Reference:	EP/M001482/1				
Title:	Selective Exhaust Gas Recirculation for Carbon Capture with Gas Turbines: Integration, Intensification, Scale-up and Optimisation.				
Principal Investigator:	Marsh, Dr R				
Other Investigators:	Valera-Medina, Dr A	Bowen, Professor P	Jia, Dr J		
	Shin, Dr D	Lucquiaud, Dr MS	Gibbins, Professor J		
	Hughes, Dr KJ	Valluri, Dr P	Ma, Professor L		
	Pourkashanian, Professor M	McCann, Professor H			
Researcher Co-Investigators:					
Project Partners:	Costain	Howden Group Technology	Industrial Tomography Systems plc		
	SSE Energy Supply Limited UK	Sulzer			
Department:	Sch of Engineering				
Organisation:	Cardiff University				
Scheme:	Standard Research				
Starts:	01 December 2014	Ends:	31 May 2018	Value (£):	1,099,891
EPSRC Research Topic Classifications:	Carbon Capture & Storage				
EPSRC Industrial Sector Classifications:	Energy				
Related Grants:					

Panel History:	Panel Date	Panel Name	Outcome
	05 Jun 2014	Challenges in Carbon Capture for CCS	Announced

Summary on Grant Application Form

Background

- Selective Exhaust Gas Recycling (S-EGR) has been suggested as a GT-CCS technique to improve CO_2 concentrations of the flue gas such that the cost and volume of the capture unit can be minimised.
- This can potentially deliver process intensification and enhanced net cycle efficiency.
- In essence, the S-EGR concept recycles CO_2 enriched exhaust rather than exhaust gas only, therefore minimising the recycling of nitrogen within the EGR loop.



Process schematic of a series configuration S-EGR system, including extraction points and recycling loops of pure CO2 and depleted exhaust gas (Merkel et al, 2013).

Project aims

1. The first extensive test programme of combustion under S-EGR conditions at the Gas Turbine Research Centre at Cardiff University to generate fundamental data on flame temperature, stability etc.
2. The first extensive test programme of gas turbine operation with S-EGR at the UKCCSRC PACT facilities, at low-turn down conditions and for transient behaviour.
3. The first experimental programme at PACT assessing the energetics performance of post-combustion technologies at these flue gas concentration and flow rates.
4. A process intensification and optimisation of innovative and modular CO_2 absorber configurations programme operated at lower flow rate, typical of S-EGR systems.
5. The first application of Electrical Impedance Tomography to CO_2 absorption with amine solvents to characterise gas/liquid flows on structured packings for the characterisation of the above configurations.

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SELECTIVE EXHAUST GAS RECIRCULATION FOR CARBON CAPTURE WITH GAS TURBINES (SELECT)

SELECT

WP1 System Integration and Process Intensification of Selective EGR Gas Turbines (Edinburgh)

- WP 1.1: Selective EGR system concept and modelling (Ed)
- WP 1.2: Novel absorber configs for selective EGR gas turbine capture (Ed)
- WP 1.3: Integration of GT operation with capture pilot: ramping part-load behav (Sheff)

- M1.1 Integrated process model of gas turbines combined cycle with S-EGR
- M1.2 Design/commissioning of packd columns fitted with tomo sensors
- M1.3 Integration of S-EGR concept between absorber & engine modelled

WP 2: System scale-up: pilot plant studies (Cardiff)

- WP 2.1 Flame stability and burner operation with Selective EGR (Cardiff)
- WP 2.2 Gas Turbine operation at varying Selective EGR ratio (Sheffield)
- WP 2.3 Amine pilot plant test programme with Selective EGR (Sheffield)
- WP 2.4 Tomography at amine pilot (Edinburgh)

- M2.1 GTRC testing complete + results on burner performance
- M2.2 Gas Turbine testing at PACT completed
- M2.3 Amine testing completed
- M2.4 Commissioning of tomography sensors customised for PACT facility

WP 3: System optimisation and whole systems performance assessment (Sheffield)

- WP 3.1 Dynamic simulation (Sheffield)
- WP3.2 Multiphase CFD for absorber (Edinburgh)

- M3.1 Dynamic simulation results produced
- M3.2 3D transient multiphase model validated against tomographic data

WP 4: Selective EGR CCGT design guidelines, impact and dissemination (Cardiff)

- WP 4.1 Summary of S-EGR benefits
- WP 4.2 Forecast of cost benefits
- WP 4.3 Recommendation for capture at enhanced levels
- WP 4.4 Technical publications

- M4.1 Benefits summary reported to Expert Panel and feedback provided
- M4.2 Quantitative estimation of likely LCOE modification
- M4.3 Recommendations, in conjunction with Expert Pan feedback

M4.4 Delivery of the Impact Handbook to UKCC SRC.

WP1 – System Integration and Process Intensification

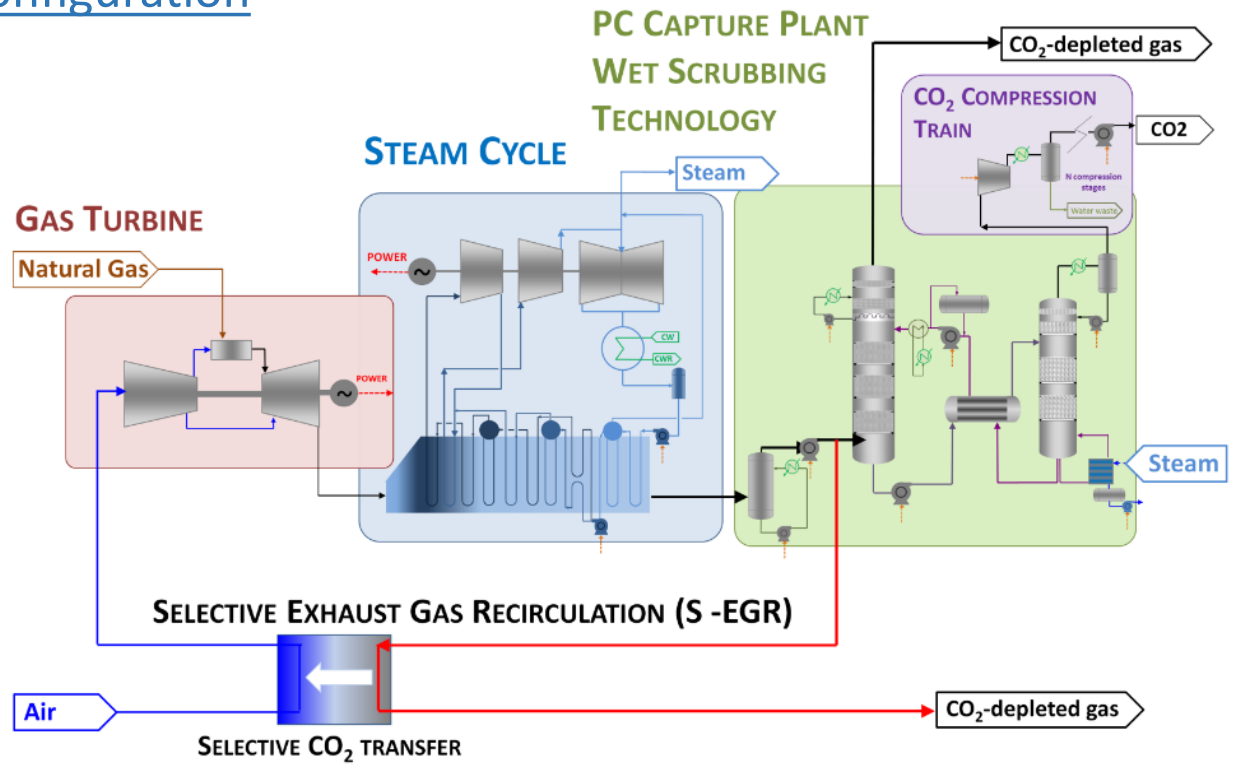
Selective EGR system concept and modelling

- Developed a **generic model** of a CCGT power plant with PCC, using MEA based chemical absorption, to identify an operating frame work and to **investigate the effect of S-EGR** on:
  - The compressor and turbine performance,
  - The gas and steam power cycles,
  - The post-combustion capture system.
- Defined the **operating conditions in the combustor**, e.g. comburent/oxidant composition and equivalence ratio.
- Identified the **operating and design parameters of the selective CO_2 transfer system** which have a larger effect on the CCGT power plant performance with PCC and EGR / S-EGR.

Potential configurations

- Limits: O_2 min concentration (16% ElKady et al. 2009) for flame stability and CO emissions

Parallel configuration

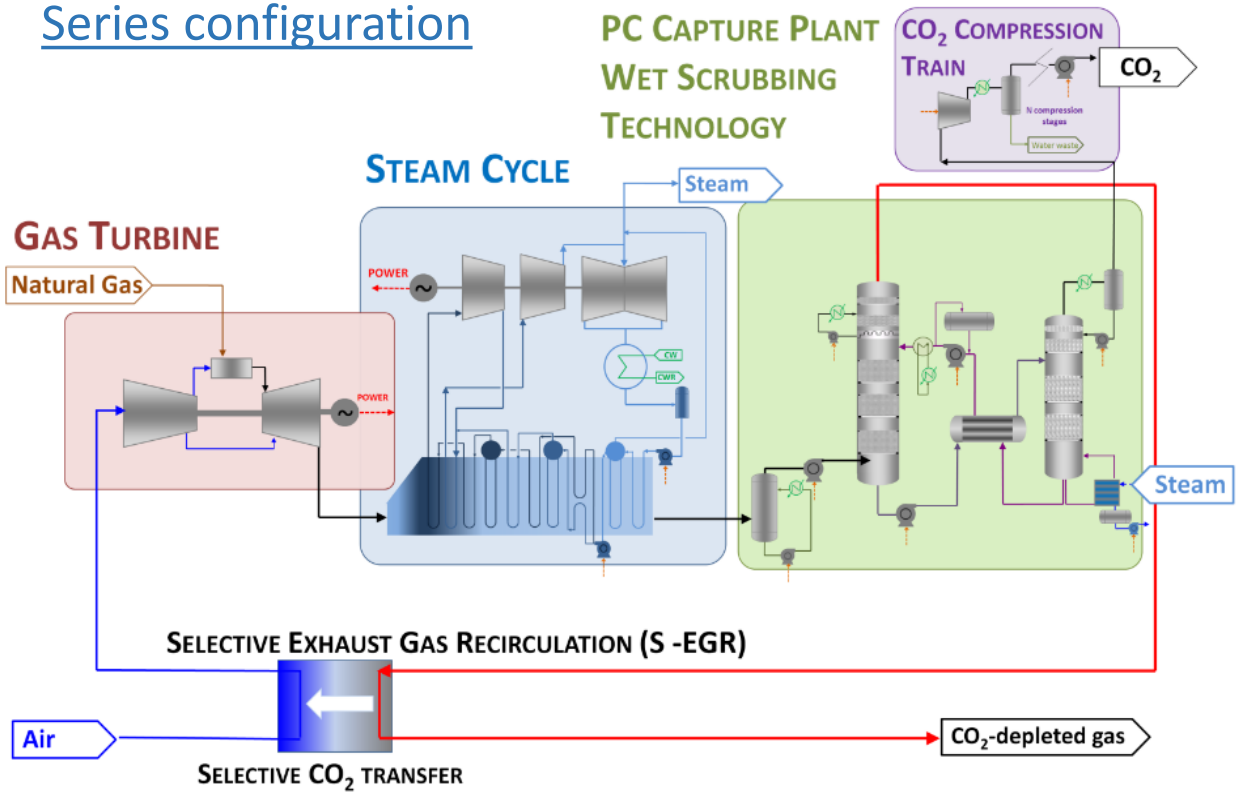


*L. Herraiz Palomino, 2016, Selective Exhaust Gas Recirculation in Combined Cycle Gas turbine power Plants With Post-Combustion Carbon Capture, Ph.D. Thesis, University of Edinburgh

Potential configurations

- Limits: O_2 min concentration (16% ElKady et al. 2009) for flame stability and CO emissions

Series configuration



Operational parameters:

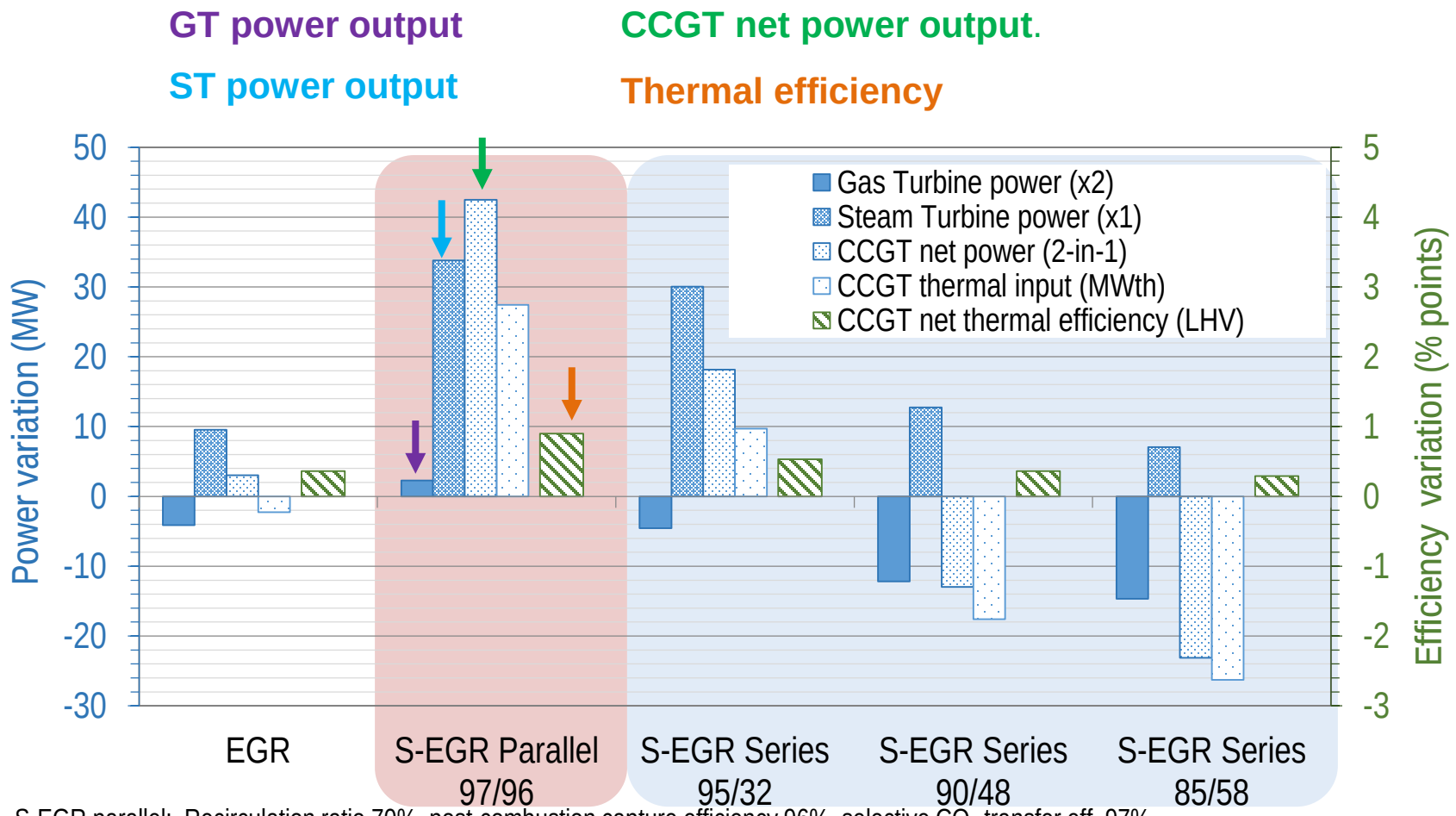
- Post combustion CO_2 capture efficiency
- Selective CO_2 transfer efficiency
- SEGR ratio (parallel config.)

*L. Herraiz Palomino, 2016, Selective Exhaust Gas Recirculation in Combined Cycle Gas turbine power Plants With Post-Combustion Carbon Capture, Ph.D. Thesis, University of Edinburgh

Key findings

- Selective Exhaust Gas Recirculation (S-EGR) results in a higher CO_2 concentration in the exhaust flue gas, and
  - **Operated in Parallel** reduces the flow rate of the gas fed to the PCC system,
  - **Operated in Series** reduces the required CO_2 efficiency in the PCC system.

Configuration/ Case		Air-based combustion (reference case)	EGR	S-EGR Parallel 97/96	S-EGR Series 95/31	S-EGR Series 90/48	S-EGR Series 85/58
Recirculation ratio	%		35	70	N/A	N/A	N/A
Overall CO_2 capture level	%	90	90	90	90	90	90
PCC efficiency	%	90	90	96	31	48	58
Selective CO_2 transfer eff.	%	N/A	N/A	97	95	90	85
O_2 conc. in comburent	%mol	20.74	16.40	18.68	18.92	19.91	20.22
CO_2 conc. in comburent	%mol	0.03	2.41	9.96	8.79	4.03	2.52
Flue gas flow rate @ PCC inlet	kg/s	658	418	200	659	642	637
Flue gas CO_2 conc. at PCC	%mol	4.34	6.56	14.12	12.91	8.15	6.65



S-EGR parallel: Recirculation ratio 70%, post-combustion capture efficiency 96%, selective CO_2 transfer eff. 97%.
S-EGR series 95/32: post-combustion capture efficiency 31%, and selective CO_2 transfer efficiency 95%.
S-EGR series 90/48: post-combustion capture efficiency 48%, and selective CO_2 transfer efficiency 90%.
S-EGR series 85/58:post-combustion capture efficiency 58%, and selective CO_2 transfer efficiency 85%.

Key findings

Effect on the Power Plant

- S-EGR results in a **small effect on the compressor and turbine performance**, evaluated by quantifying the deviation of the **dimensionless parameters groups** constituting the compressor and turbine performance maps.

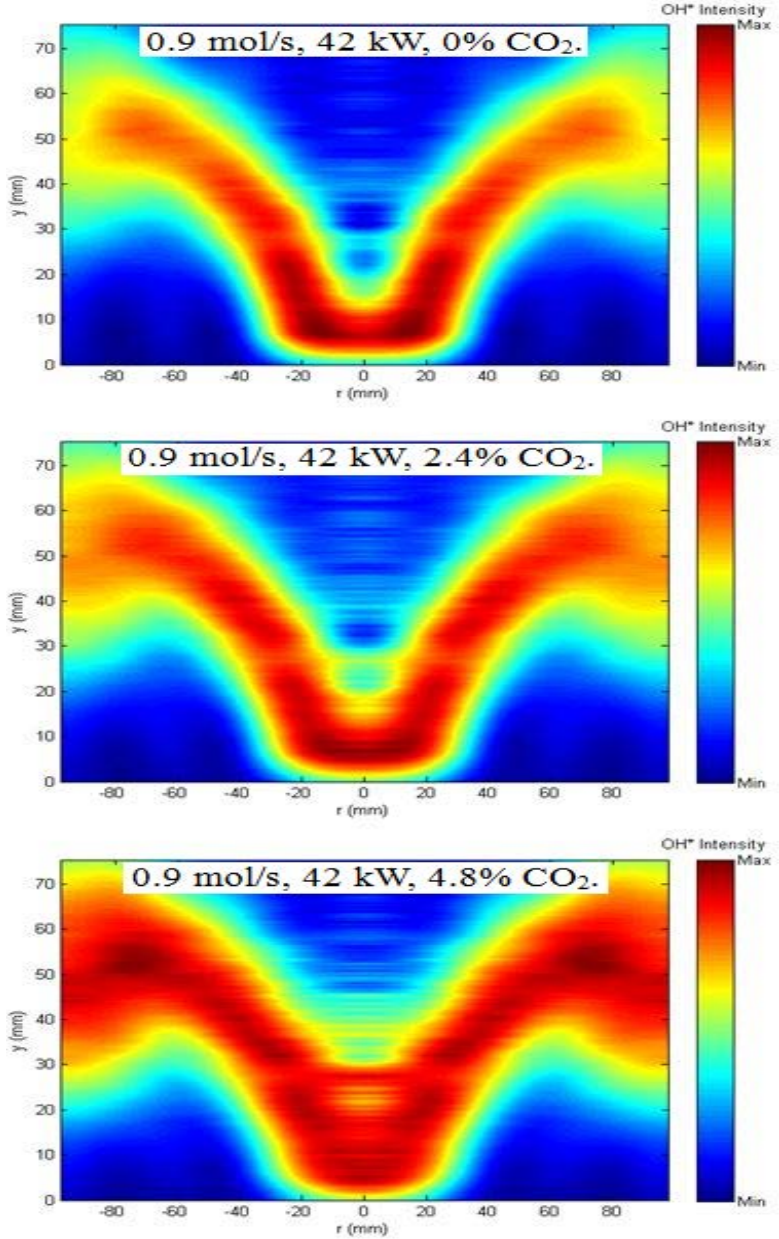
  => Current class of gas turbine engines can operate without a significant deviation from the compressor and the turbine design points.

- A high CO_2 concentration results in an increase of the CO_2-enriched air density, despite the higher temperature, increasing the mass flow rate through the turbomachinery.

- A high CO_2 concentration in the working fluid results in a higher GT exhaust temperature, which results in an increase in the heat available in the bottoming cycle.

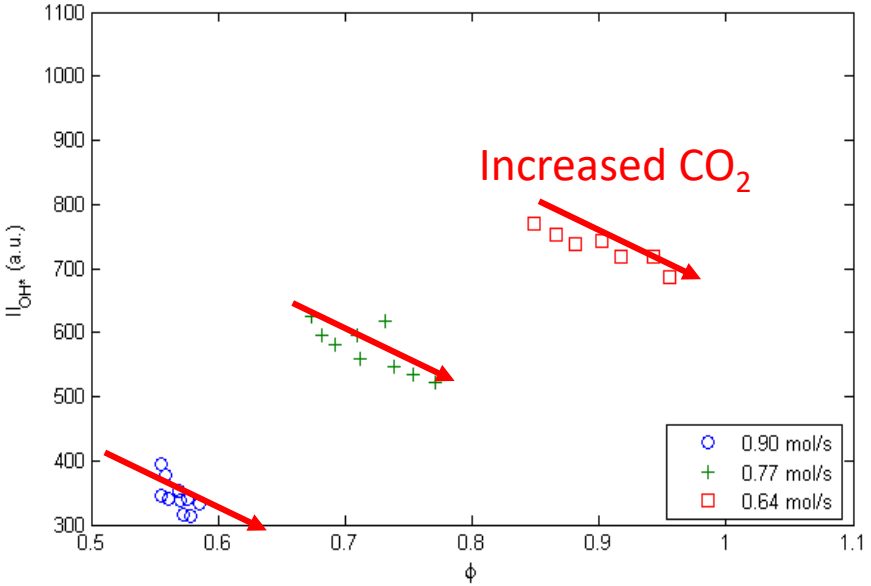
WP2 – Pilot Plant Studies

Swirl Burner Chemiluminescence Results

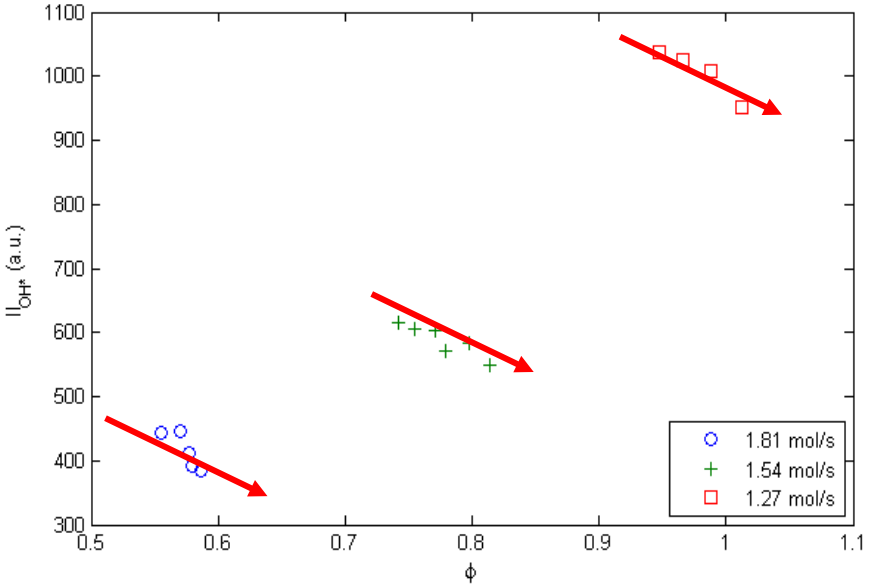


- The three images clearly show that with increasing CO_2 flow, the heat release zone extended, with OH* intensities shifting further downstream in the flow.
- In the top image, (0% CO_2 addition), the heat release zone (and thus presumed flame location) lies along the outward expanding shear layer.
- As the CO_2 concentration increases and the reaction progress slows, the flame migrates downstream and is influenced by the outer recirculation zone and impingement on the confinement walls, yielding a more M-shaped flame.

Abel inverted chemiluminescence images at 42 kW, 1.1 bar_a and 0.9 mol/s total flow for three CO_2 concentrations in the inlet premix.



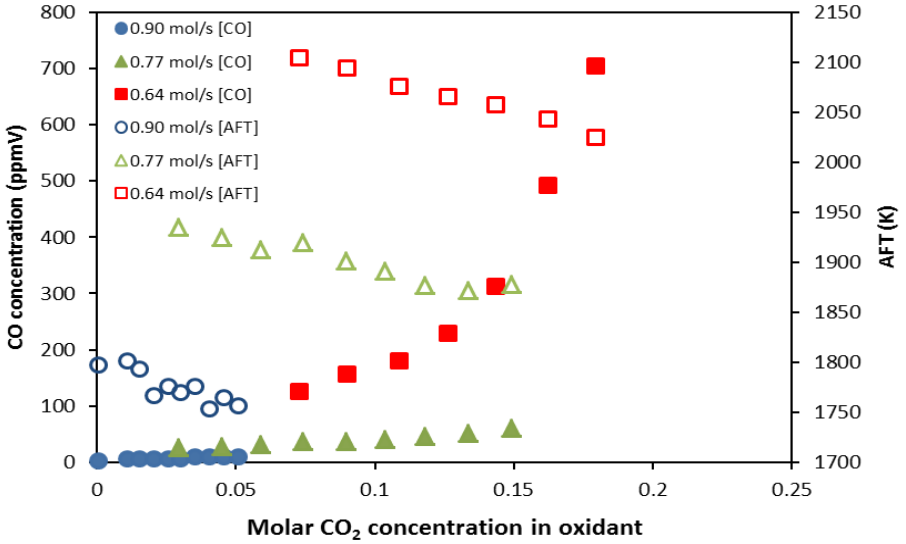
Average image chemiluminescence intensities for each flow and CO_2 condition at 42 kW, 1.1 bar_a.



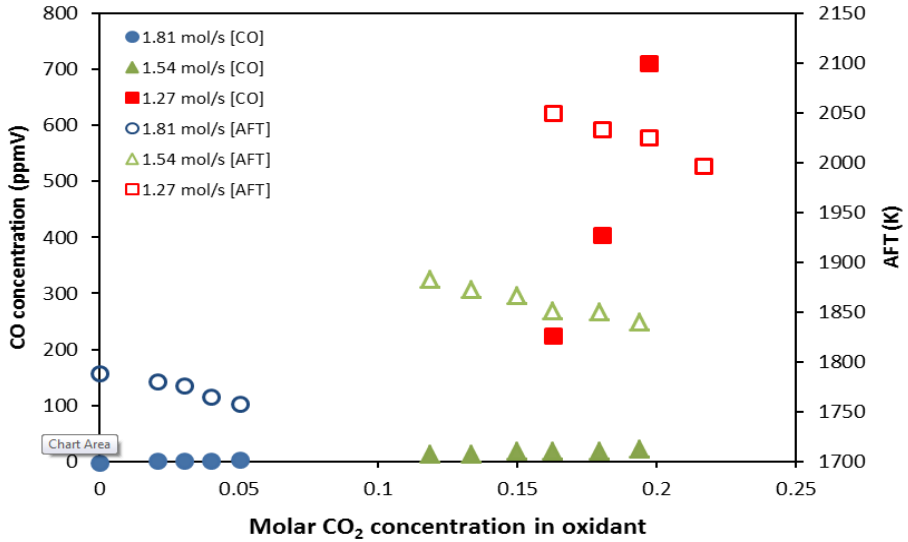
Average image chemiluminescence intensities for each flow and CO_2 condition at 84 kW, 2.2 bar_a.

Abel Averaged Chemiluminescence Results

- The effect of increasing CO_2 concentration was consistently shown to reduce the overall averaged intensity, and hence heat release, with highest values corresponding to the highest equivalence ratio, and hence hottest conditions.



Measured CO concentrations and modelled AFT for each flow and CO_2 condition at 42 kW, 1.1 bar_a.



Measured CO concentrations and modelled AFT for each flow and CO_2 condition at 84 kW, 2.2 bar_a.

Measured CO

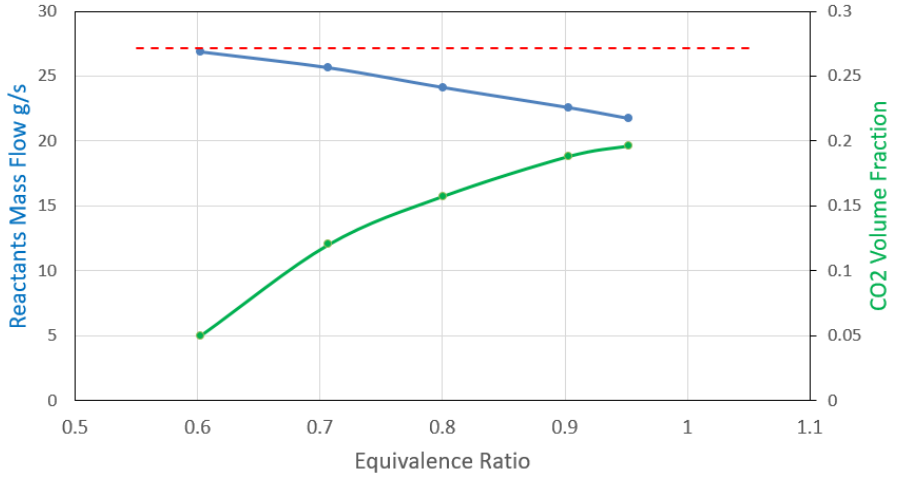
- Adding CO_2 was identical and repeatable for each molar flow rate and power combination - an expected reduction in AFT, coupled with an increase in measured CO concentration.
- However, if equivalent CO_2 loadings are compared (where datasets overlap on the horizontal axis) between different flow conditions (and hence Ø value), higher CO readings are measured for a step increase in AFT, driven by incomplete combustion.
- Results therefore suggest that cooler, leaner operation is required to minimise CO production for the increased addition of CO_2.
- Moreover, an increase in pressure was shown to reduce equivalent CO concentrations between the two datasets.

Operating limits

Key aim is operate close to stoichiometric conditions, thus have no oxygen in the exhaust

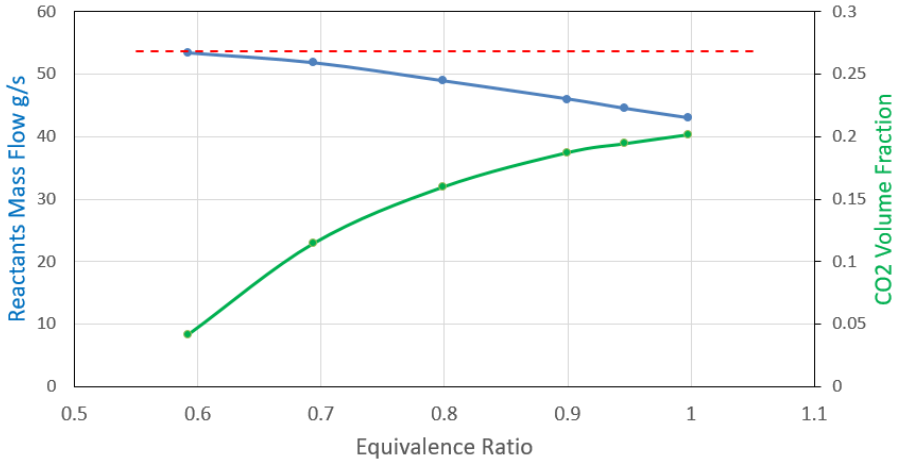
42kW

1.1 bara



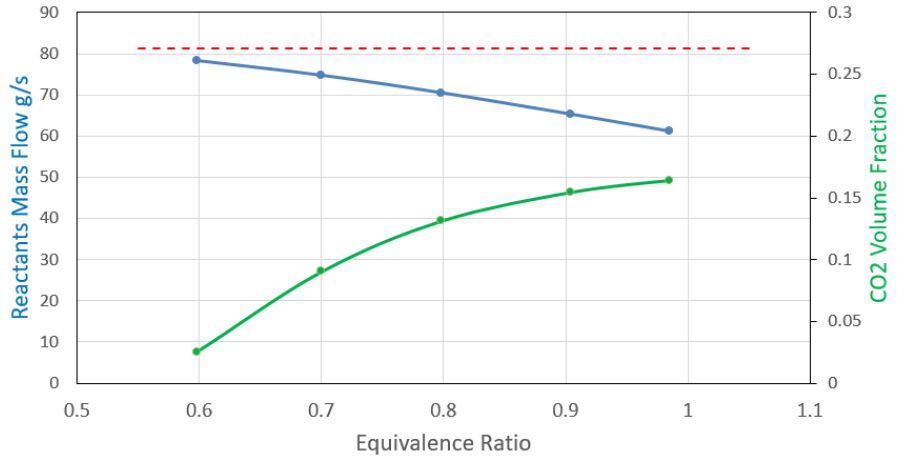
84kW

2.2 bara



126kW

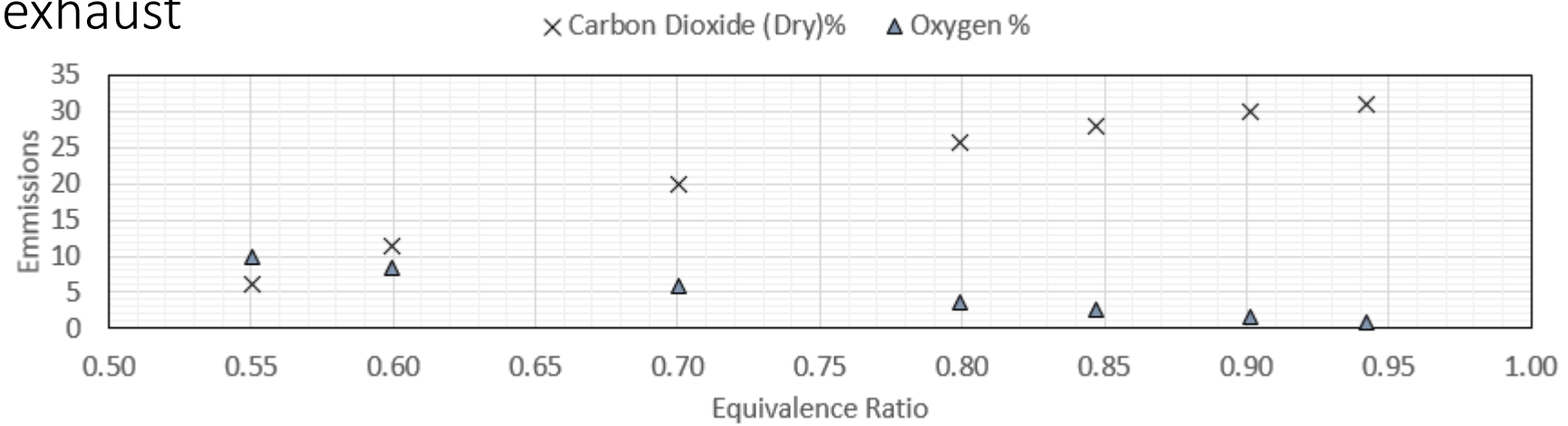
3.3 bara



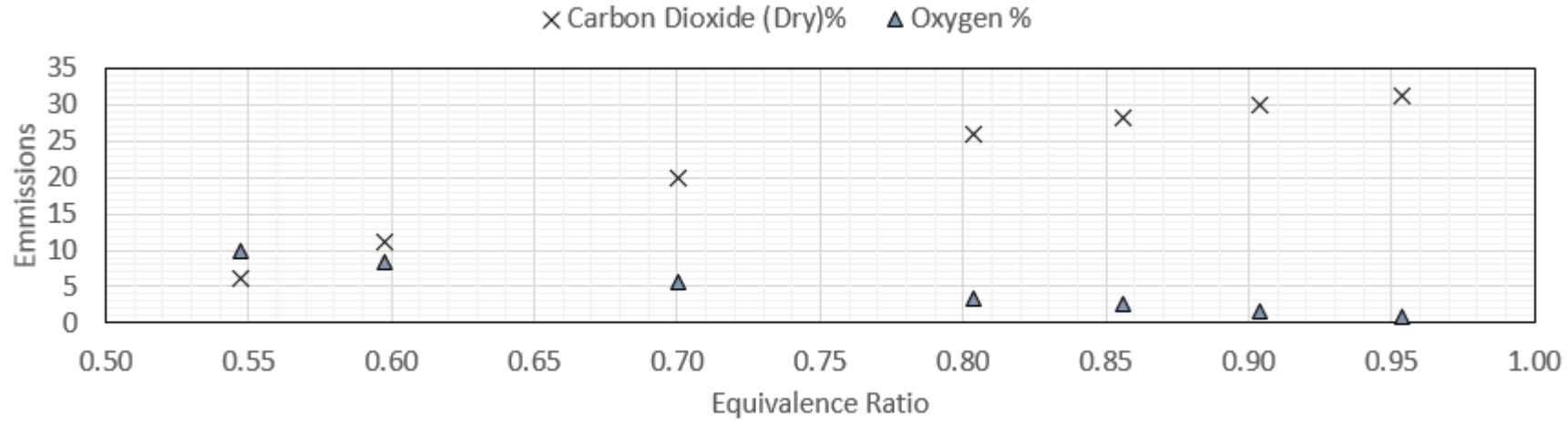
Operating limits

Key aim is operate close to stoichiometric conditions, thus have no oxygen in the exhaust

42kW, 1.1 bara

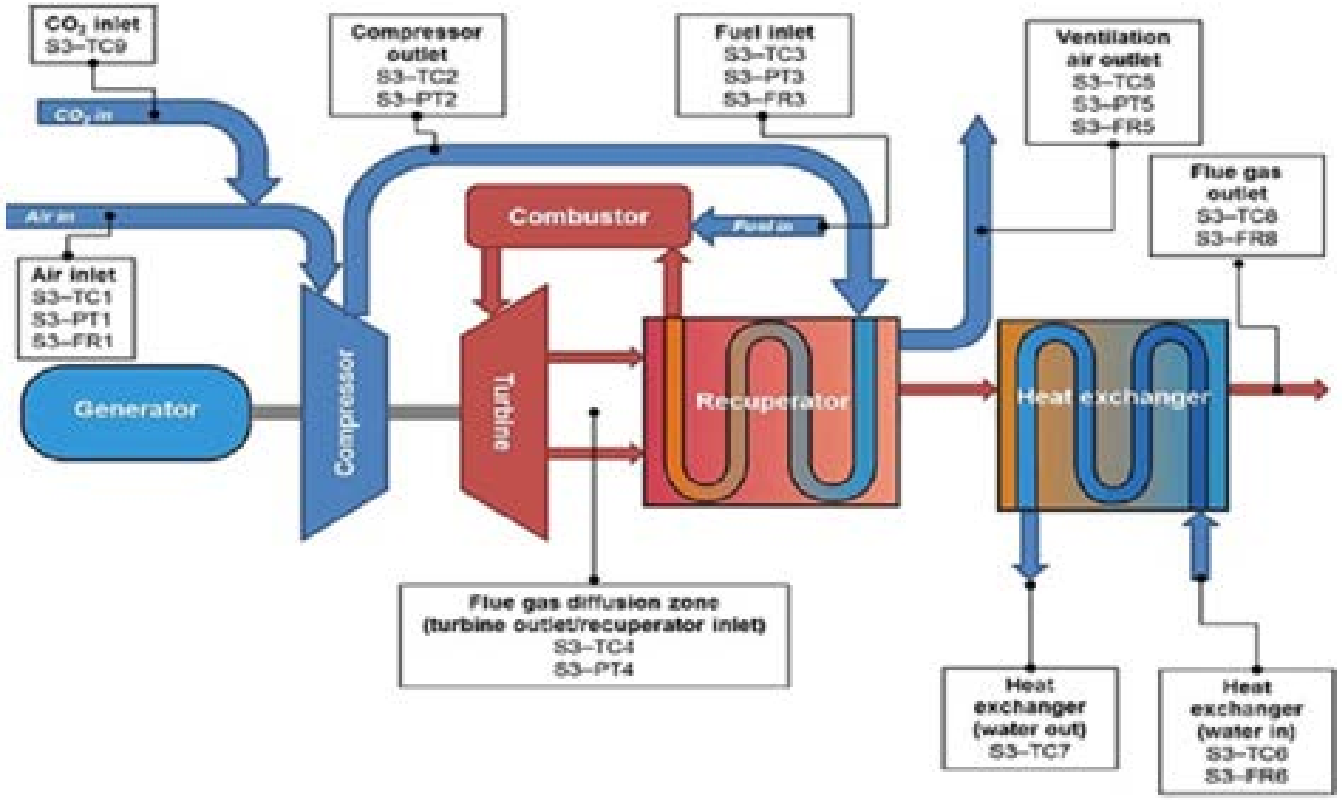


84kW, 2.2 bara



Gas turbine testing at PACT

- Using Turbec T100 engine at PACT.
- Modified to allow for CO_2 injection at inlet.
- Current testing aim is to provide up to 11% molar CO_2 at inlet.



Comparison to engine test at PACT, Sheffield.

Gas analysis results for the nominal and CO_2 diluted conditions in the Turbec T100 engine.

Power (kW)	CO (ppmV dry)		NO_X (ppmV dry)	
	0 g/s CO_2	34.7 g/s CO_2	0 g/s CO_2	34.7 g/s CO_2
50	22.0	143.0	1.6	1.4
55	4.3	52.0	-	-
60	2.2	4.9	1.3	0.6
65	2.0	0.1	-	-
70	1.8	3.8	1.3	0.8
75	0.4	0.0	-	-
80	0.0	0.0	1.4	1.1

- When engine power is reduced to minimum turndown at 50 kW, the nominal (0 g/s CO_2) CO concentrations increase as the flame weakens, but the effect of CO_2 dilution is more pronounced at the low power settings.
- This is in close agreement with the GTRC burner tests, illustrating that the CO_2 has a marked effect on flame chemistry at high concentrations.
- The values of NO_X appear largely unaffected by CO_2 injection, given the lean-burn and high dilution arrangement of the T100.
- In the burner experiments there is no additional dilution downstream of the burner, and hence the relationship between CO_2 dilution and NO_X is more pronounced.

Key Findings – Engine and burner tests

- The increased addition of CO_2 necessitated a change in stable operating equivalence ratio. The largest quantities (20% mol) of CO_2 required near stoichiometric air-fuel ratios.
- An increase in CO_2 concentration was shown to promote downstream migration on the flame and thickening of the heat release profile, as adiabatic flame temperature and burning rate were reduced.
- Increase in CO_2 addition, together with the necessary enhancement in equivalence ratio, both led to a rise in exhaust CO concentrations. The quantities measured may be detrimental to downstream CO_2 capture processes, and therefore operational conditions must be carefully specified and controlled.
- The efficiency of the capture process may be optimised with regard to operational equivalence ratio, CO_2 loading, and CO emissions. NO_X emissions were also shown to be reduced for the addition of CO_2 with leaner combustion.
- In the T100 engine test the results agree with the burner experiments for CO production, in that high concentrations of CO_2 cool the flame and result in high CO levels.

WP3 – Whole Systems Performance

Dynamic simulation

- Objectives
  - Study gas turbine performance under S-EGR conditions
    - ✓ Incorporate improved CFD models in the process simulation flowsheet
  - Determine the ability of the capture plant to control power output and the impact on performance parameters such as the capture rate and energy consumption

Process simulation

- Steady state
  - Pilot scale (PACT)
    - ✓ The model of the mGT and that of the PACT amine capture plant are built – refinement (e.g. compressor/turbine maps) & validation with experimental data required
  - Commercial scale NGCC plant
    - ✓ Using data from a DoE report*
    - ✓ Several configurations analysed – including techno-economics

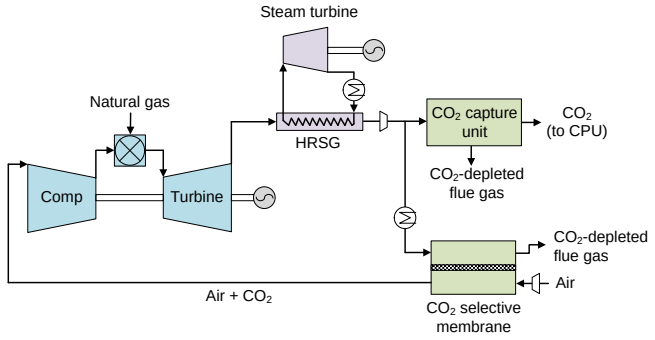
Source: National Energy Technology Laboratory, Current and Future Technologies for Natural Gas Combined Cycle (NGCC) Power Plants (2013).

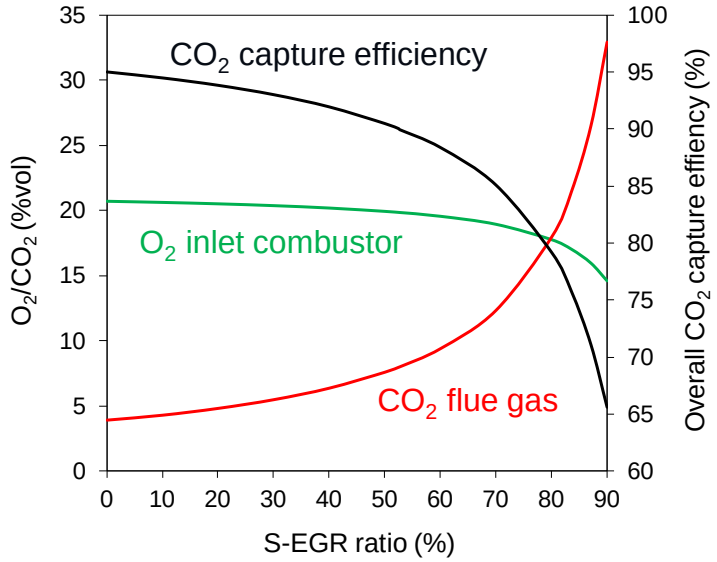
NGCC simulation

- gCCS v1.1.0 software (gPROMS, PSE)
- 4 cases are considered:
  - NGCC without CO_2 capture (**NGCC**)
  - NGCC coupled to an amine capture plant only (**NGCC+CCS**)
  - NGCC with an amine capture plant using exhaust gas recirculation (**NGCC+EGR**)
  - NGCC with an amine capture plant using selective exhaust gas recirculation (**NGCC+S-EGR**)

Parallel S-EGR – previous case

- **NGCC power plant + parallel S-EGR (no membrane model)**
  - The recirculation ratio in parallel S-EGR case was calculated to keep an overall CO_2 capture efficiency of **90%** (O_2>16%vol.)
    - A perfect separation of CO_2 in the membrane with **95%** efficiency
    - CO_2 capture efficiency in the amine capture plant of **95%**



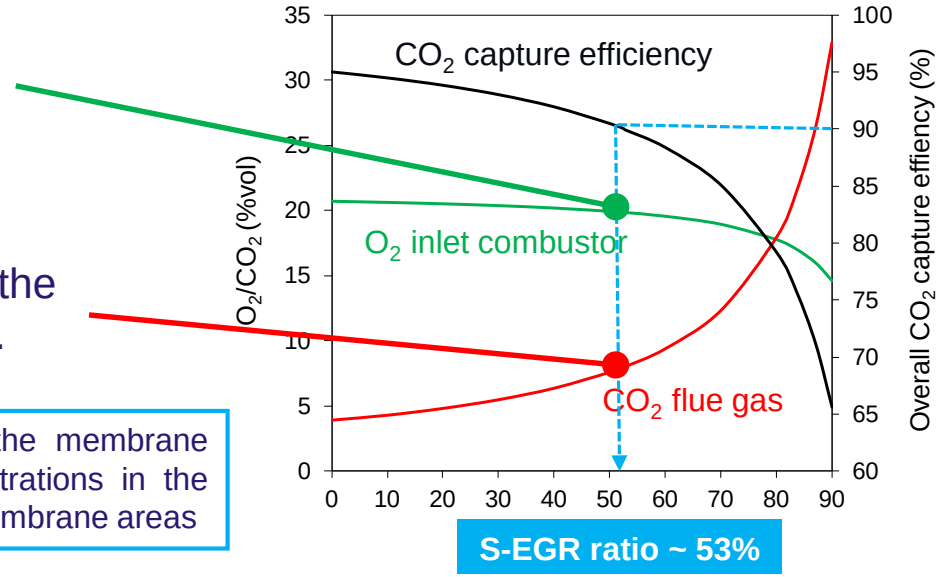


Parallel S-EGR – previous case

- **NGCC power plant + parallel S-EGR (no membrane model)**
  - The recirculation ratio in parallel S-EGR case was calculated to keep an overall CO_2 capture efficiency of **90%** (O_2>16%vol.)

O_2 at the inlet of the combustor is ~20%vol. (CO_2 is ~4%vol.)

The CO_2 content in the flue gas is 8%vol.



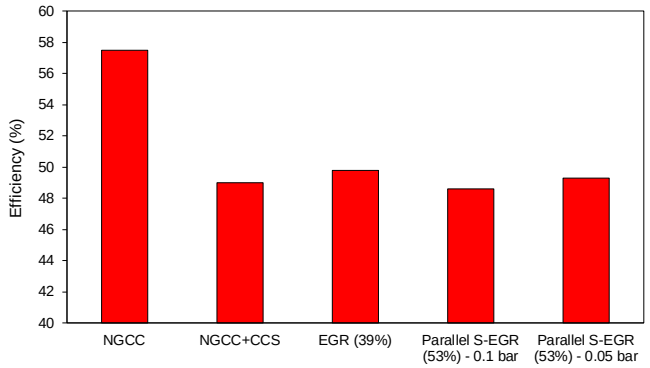
Higher separation efficiencies in the membrane would lead to higher CO_2 concentrations in the flue gas at the expense of larger membrane areas

Parallel S-EGR – previous case

	NGCC	NGCC + CCS	EGR (39%)	Parallel S-EGR (53%)	
GT power output (MW_e)	418.7	418.7	415.0	411.3	
ST power output (MW_e)	231.7	174.0	181.1	184.7	
Total gross power output (MW_e)	650.4	592.7	596.1	596.0	
Power plant auxiliaries (MW_e)	16.3	14.6	14.9	15.0	
EGR/S-EGR auxiliaries (MW_e)	-	-	1.1	16.3	
ACP auxiliaries (MW_e)	-	17.6	11.0	8.9	
Compression auxiliaries[(a)] (MW_e)	-	20.2	20.2	20.2	
Total auxiliary loses (MW_e)	16.3	52.4	47.1	60.4	
Total net power output (MW_e)	634.1	540.2	549.0	535.6	
Efficiency (%)	**57.5**	**49.0**	**49.8**	**48.6**	
CO_2 emissions (kg/MWh_e)	354	42	41	42	
Amine capture plant (ACP)					
Total packing volume (m^3)	**-**	**7264**	**5697**	**4908**	**4908**
Reboiler duty (MJ/kg CO_2)	**-**	**3.95**	**3.74**	**3.71**	**3.71**
Flue gas flowrate to the ACP (kg/s)	**1030**	**1030**	**621**	**488**	**488**
Flue gas composition to ACP (%vol)					
N_2	74.4	74.4	75.9	71.3	71.3
O_2	12.4	12.4	7.7	11.3	11.3
Ar	0.9	0.9	0.9	0.8	0.8
CO_2	**3.9**	**3.9**	**6.5**	**8.0**	**8.0**
H_2O	8.4	8.4	9.0	8.6	8.6

[(a)] The energy requirements for the compression and purification unit (CPU) are taken to be 100 kWhe/t CO_2.

[(b)] Values assuming a pressure drop across the membrane of 0.05 bar (~5%).

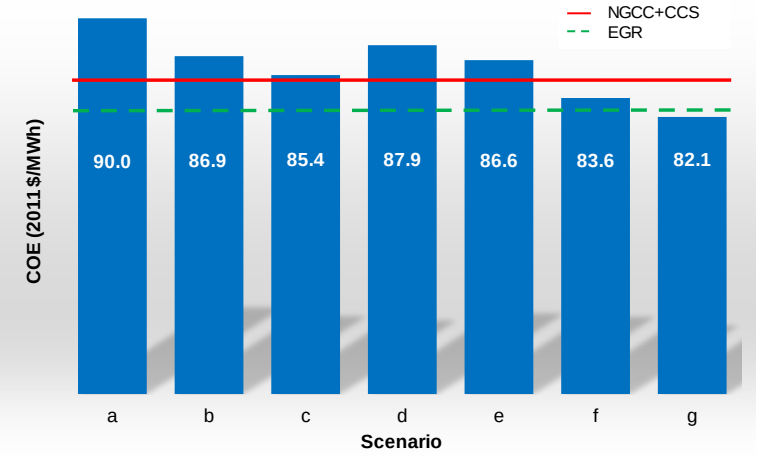


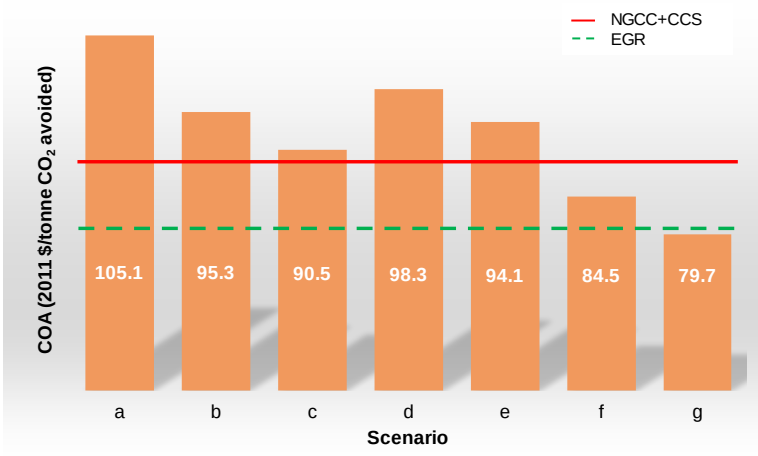
- S-EGR case: auxiliaries consumption in the membrane system plays an important role on the overall efficiency

S-EGR could be competitive against NGCC+CCS,
also leading to more compact amine capture plant designs
(lower flue gas flowrate with higher CO_2 concentration)

Parallel S-EGR – previous case

	Scenario						
	a	b	c	d	e	f	g
Membrane cost fraction	1	0.5	0.25	1	1	0.5	0.25
Capture plant S-EGR cost fraction	1	1	1	0.8	0.8	0.8	0.8
ΔP membrane (bar)	0.1	0.1	0.1	0.1	0.05	0.05	0.05





Overall status and take-home messages

- Modelling has shown that modern gas turbine configurations can operate with S-EGR, which will both reduce cost and plant size.
- Experimental measurements have shown that the presence of CO_2 slows down flame chemistry, but this should keep within capabilities of modern burners.
- Engine tests are showing that S-EGR can be tolerated, provided the engine is run under richer conditions.
- Modelling has shown that mass flow and capture efficiency could be competing factors in system development, so optimisation is necessary.
- Dissemination event planned for 2018.

Parallel Session H: Capture 3

Oxyfuel and Exhaust Gas Recirculation Processes in Gas Turbine Combustion for Improved Carbon Capture Performance

&

Selective Exhaust Gas Recirculation for Carbon Capture with Gas Turbines: Integration, Intensification, Scale-up and Optimisation

Richard Marsh

Cardiff University

School of Engineering

UKCCS RESEARCH CENTRE

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