THE FUTURE OF GAS TURBINE TECHNOLOGY
8TH INTERNATIONAL GAS TURBINE CONFERENCE

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ETN

INNOVATIVE LOW CARBON CYCLES

Selective Exhaust Gas Recycling For Carbon Capture Applications: Combustion and Operability Measurement

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- Research aim
- Theory – CCS and S-EGR
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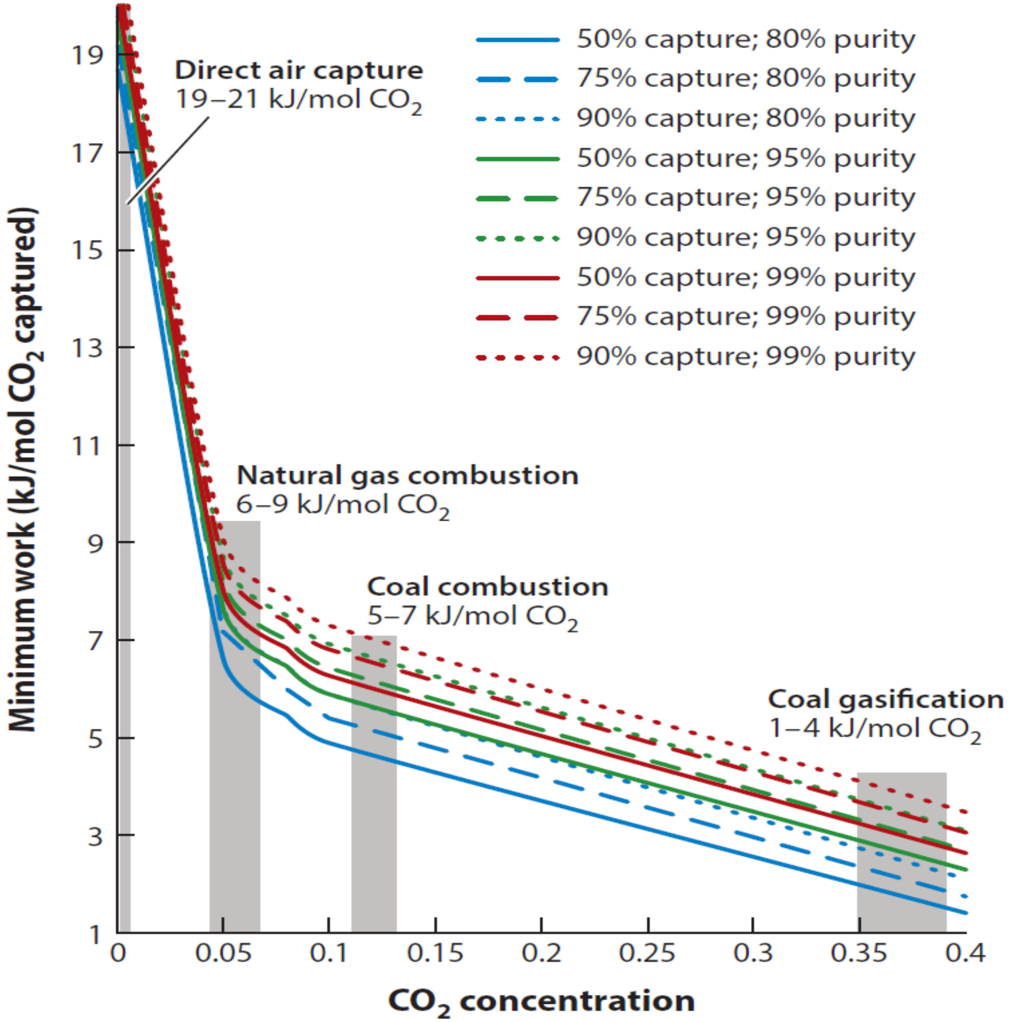
Background

- 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 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.

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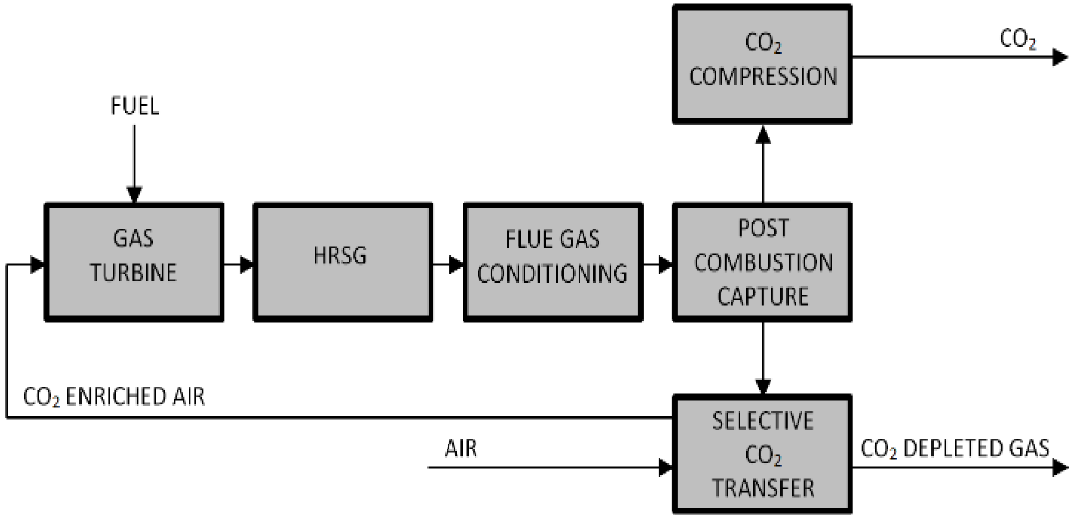
Background

- 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).

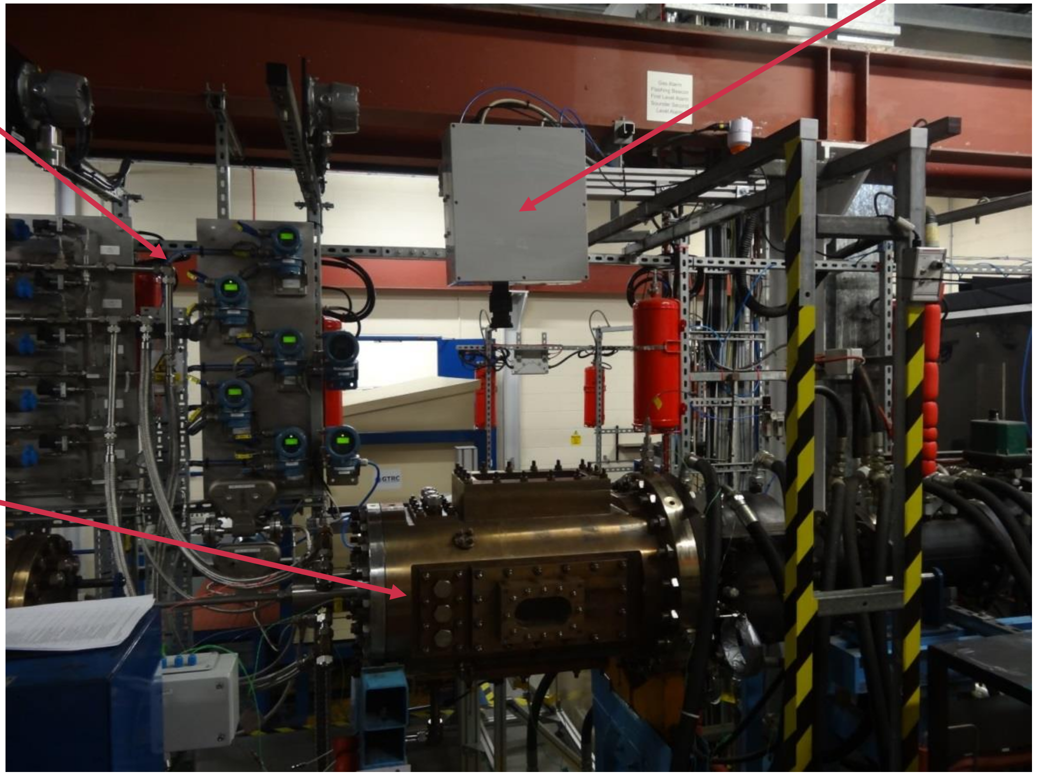
Research aims

- Combustion experiments at two inlet pressure and temperature conditions to:
  - Simulate the combustion environment of a theoretical S-EGR process in a generic gas turbine burner.
  - Characterise the effect of CO_2 as a diluent, in terms of operational premixed CH_4/air flame stability, heat release, and measured exhaust gas composition.
  - Compare these results to a small-scale gas turbine (at PACT), operated with high inlet CO_2 concentrations.

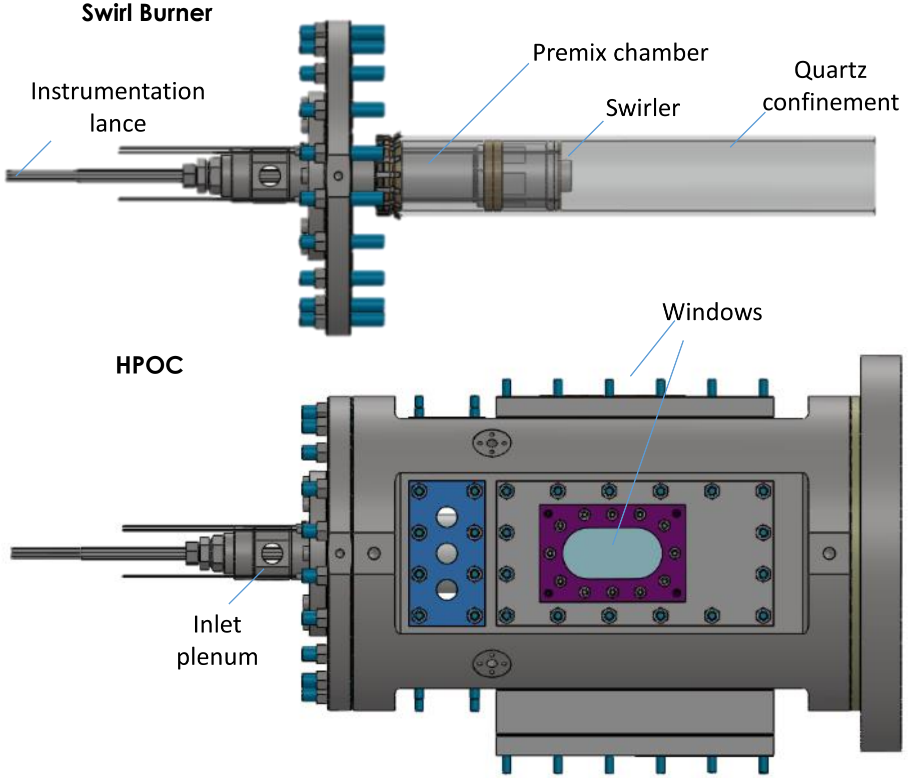
Test conditions

Condition	Air (g/s)	CO_2 (g/s)	CH_4 (g/s)	Pressure (bar_a)	Air + CO_2 flow (mol/s)
42kW LF	17.1 – 14.9	2 - 5	0.84	1.1	0.64
42kW MF	21.5 – 18.8	1 - 5	0.84	1.1	0.77
42kW HF	26.1 – 24.8	0 - 2	0.84	1.1	0.90
84kW LF	30.6 – 28.6	9.1 - 12	1.68	2.2	1.27
84kW MF	39.1 – 35.6	8 - 13.1	1.68	2.2	1.54
84kW HF	52.2 – 49.4	0 – 4	1.68	2.2	1.81

High-Pressure Generic Swirl Burner (HPGSB)



>>> FLOW >>>



Schematic view of the swirl burner employed with the High Pressure Optical Chamber (HPOC)

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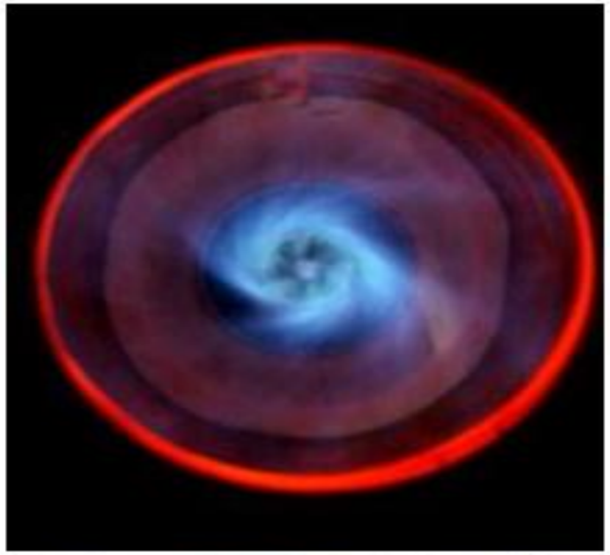
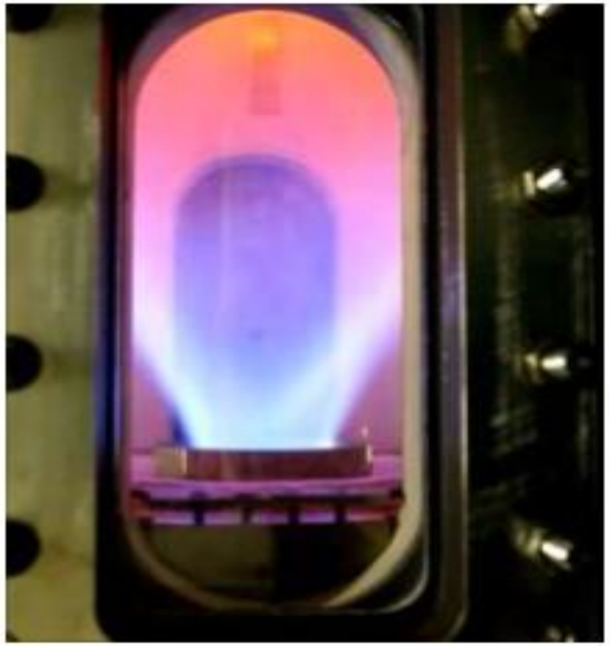
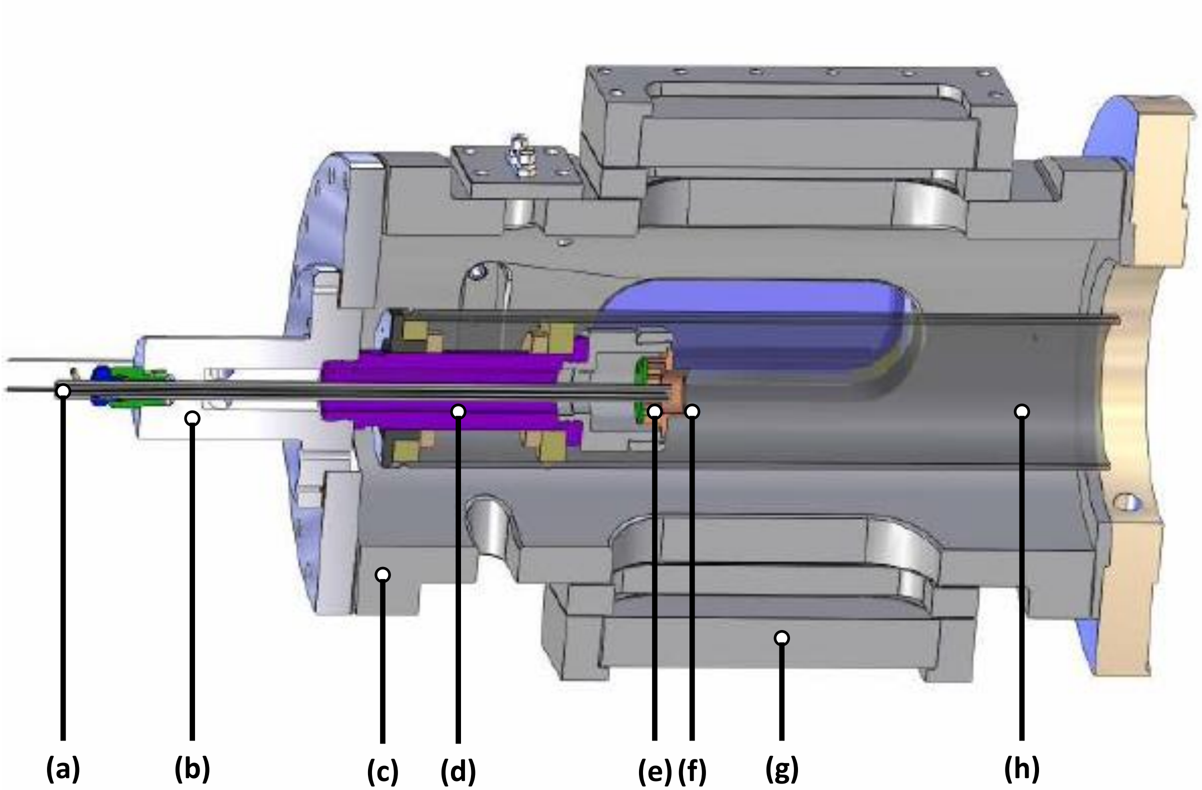
High-Pressure Generic Swirl Burner (HPGSB)
Geometric swirl number = 1.04







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)

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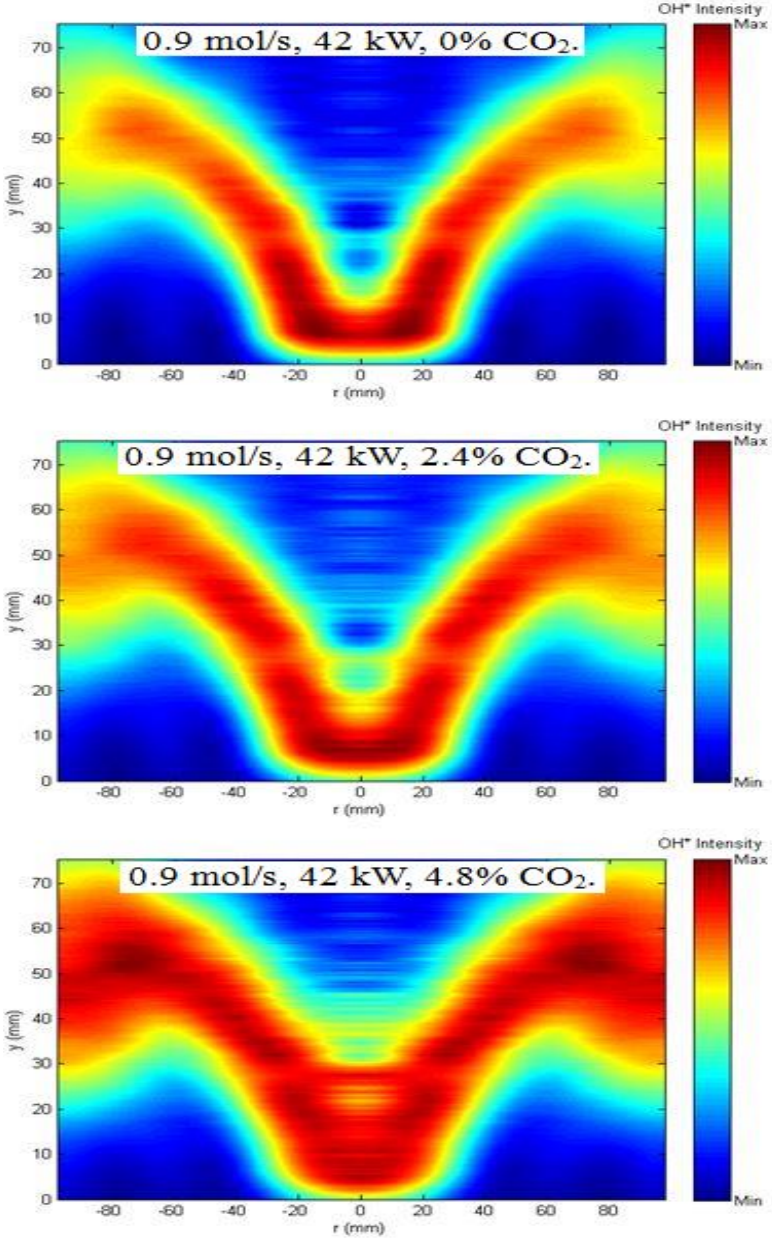
Chemiluminescence Results



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.

- 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.

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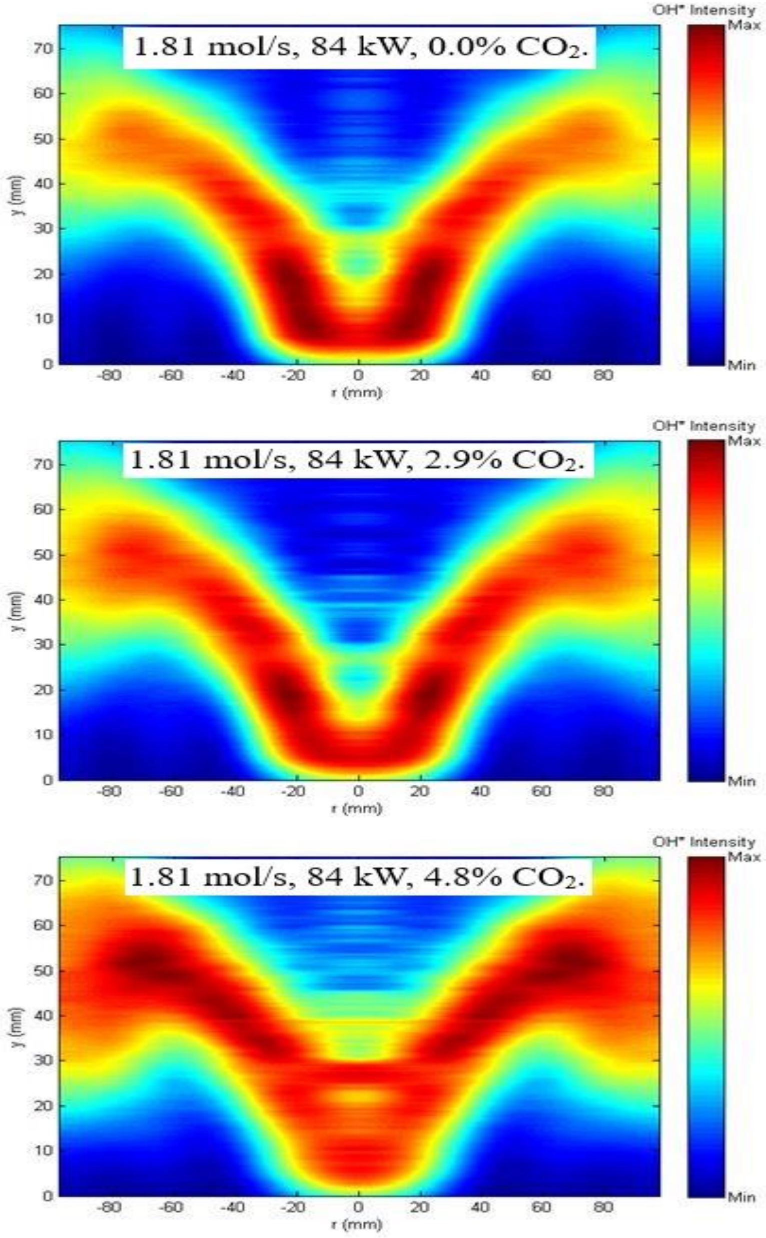
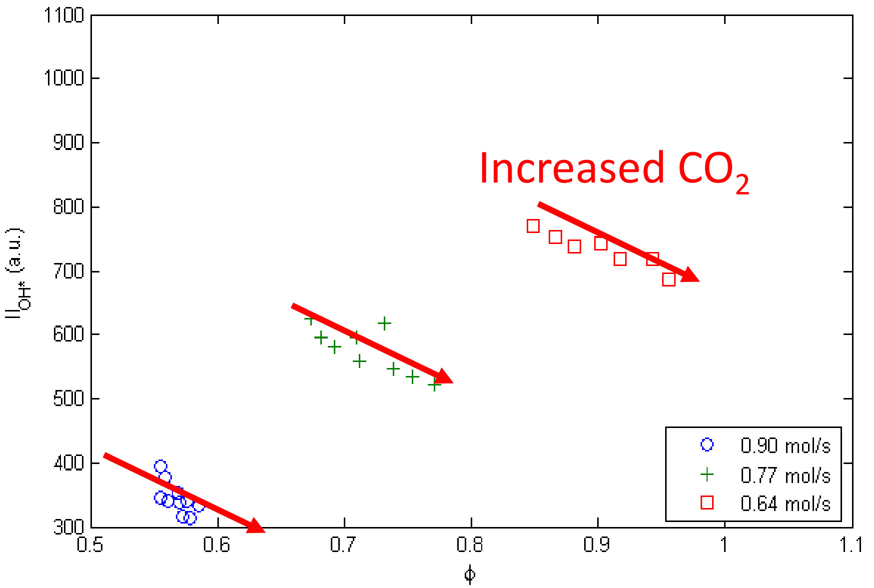


Abel inverted chemiluminescence images at 84 kW, 2.2 bar$_a$ and 1.81 mol/s total flow for three CO_2 concentrations in the inlet premix.

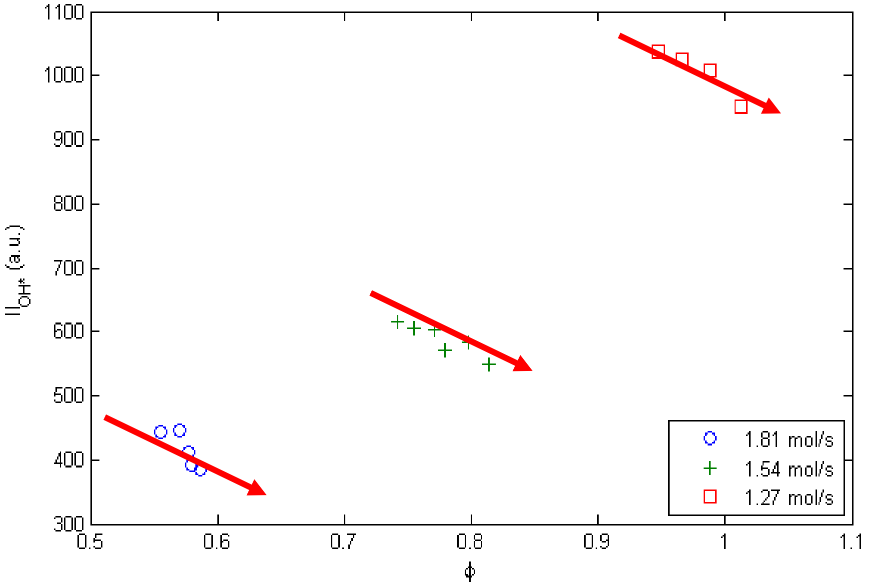
Chemiluminescence Results

- At the higher operating power and pressure, results show a similar trend for CO_2 addition with downstream migration of heat release and expanded outer recirculation zones.
- The total molar flow rate has doubled between the two operating conditions, but bulk flow velocity should be approximately maintained due to the change in reactant density.
- Consequently, the effect on the flow-field was minimal.

Abel Averaged Chemiluminescence Results



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.

- 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.

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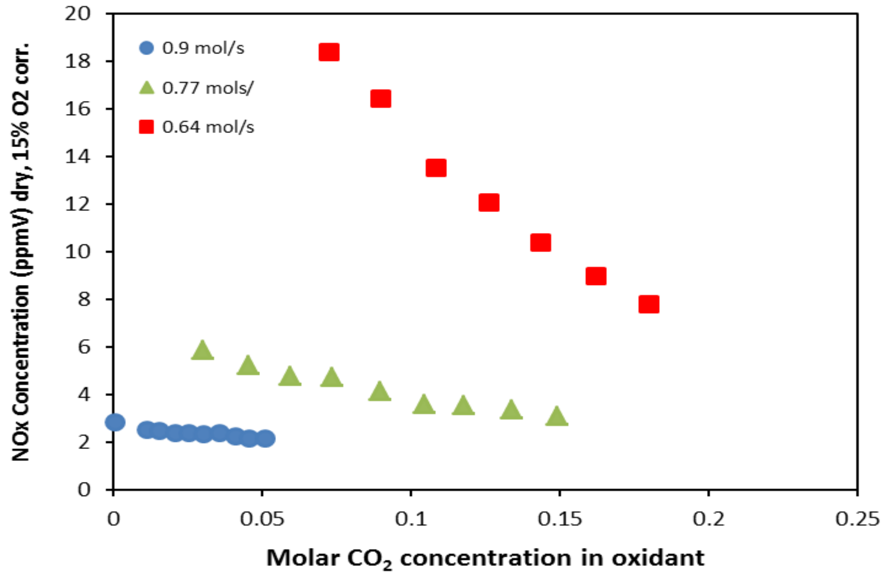
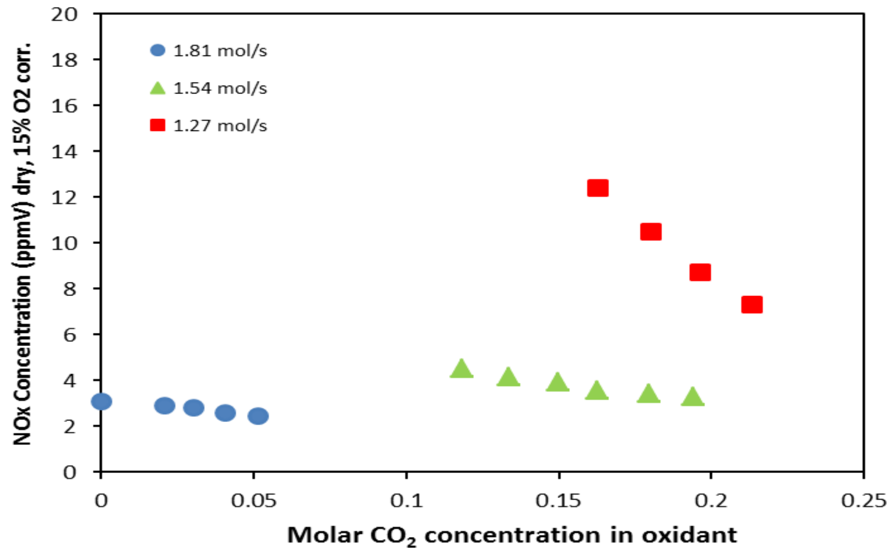
Measured NO_X

- CO_2 addition is shown to reduce NO_x production for all conditions tested, with the plotted profiles demonstrating a similar relationship to AFT.
- This suggests that thermal NO_x production is dominant (as would be expected with CH_4-air combustion) and again cooler, leaner conditions provide the lowest concentrations.



Normalised (dry 15%O_2) NOx concentrations for each flow and CO_2 condition at 42 kW, 1.1 bar_a.



Normalised (dry 15%O_2) NOx concentrations for each flow and CO_2 condition at 84 kW, 2.2 bar_a.

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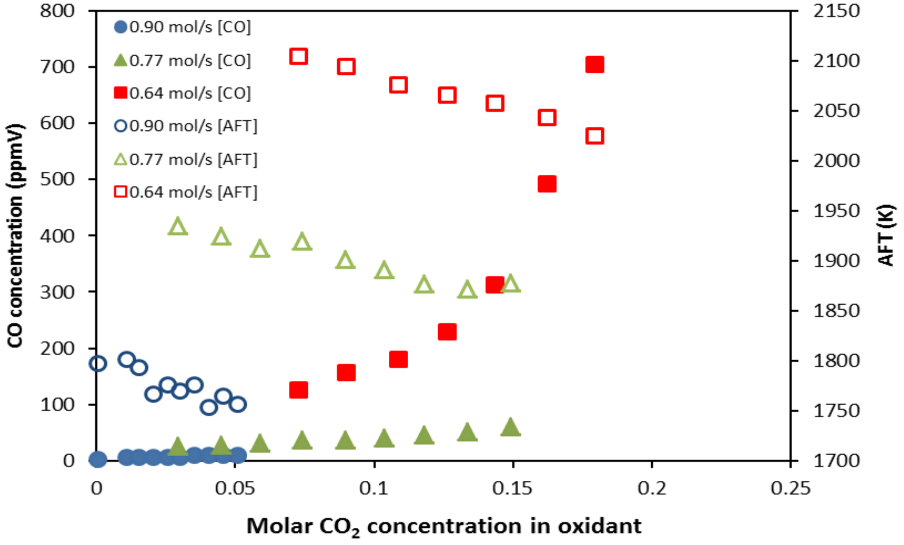
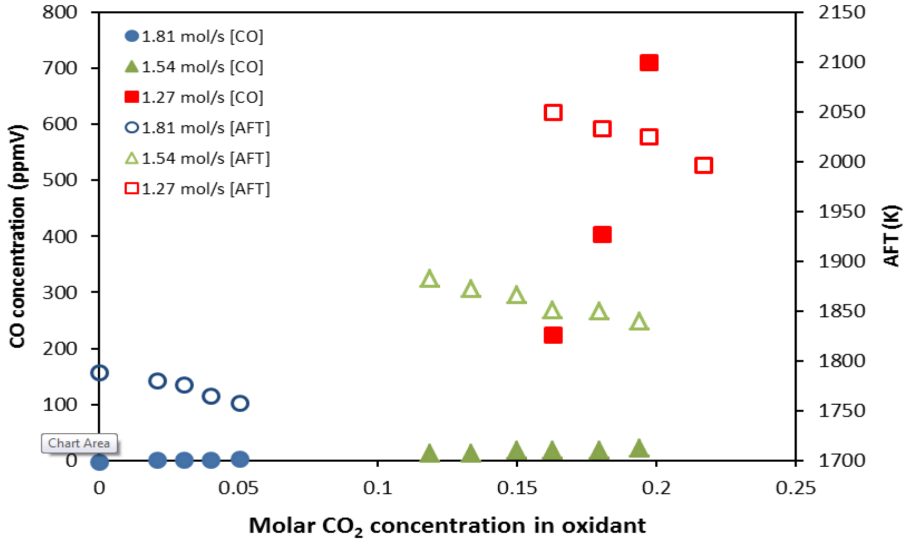
Measured CO



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$_a$.

- 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.

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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.

Conclusions

- 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.

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