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EXHAUST GAS RECIRCULATION AND SELECTIVE EXHAUST GAS RECIRCULATION ON A MICRO-GAS TURBINE FOR ENHANCED CO_2 CAPTURE PERFORMANCE

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ABSTRACT

Power generation from natural gas continues to gain interest due to its lower carbon intensity than other fossil fuels; coupling this with carbon capture and storage would enable a considerable decarbonization of the energy supply to meet stringent emissions reduction targets. This paper experimentally explores exhaust gas recirculation (EGR) and selective exhaust gas recirculation (S-EGR) through CO_2 injections to the compressor inlet of a micro-gas turbine. EGR/S-EGR reduces the volume of flue gas to be treated, whilst increasing CO_2 levels and limiting O_2; these improve capture performance and minimize the capture plant reboiler duty, therefore increasing overall plant efficiency. The effects of CO_2-enhanced operation are quantified across the whole operating envelope, in terms of mechanical impacts, detailed emissions analysis and overall efficiency. The addition of CO_2 altered the specific heat capacity and density of the oxidizer, lowering engine speeds and system temperatures – more so for higher EGR/ S-EGR ratios. This also resulted in higher concentrations of incomplete combustion species (e.g. CO and CH_4) compared to the baseline, but only at low turndown ratios. It was assumed that lower flame temperatures reduced the formation of thermal NOx (oxides of nitrogen), which has since been verified by computational fluid dynamics modelling of the combustor.

Keywords: micro-gas turbine; (selective) exhaust gas recirculation; recycle ratio; CO_2 capture.

INTRODUCTION

CO_2 is the most prominent greenhouse gas in the atmosphere and increasing greenhouse gas concentrations are now having a pronounced impact on the global climate. It is important therefore to reduce the amount of this gas that is released from various sources – power generation from fossil fuels, for example, which is highly carbon intensive. As a result, stringent carbon emission reduction targets are now in place to tackle climate change, for instance through COP 21 (Climate Action, 2015), and whilst these attempt to reduce carbon emissions from all carbon-intensive industries, several relate specifically to energy generation. Various means are now being used and/or investigated to decarbonize the energy supply. This includes the use of nuclear power, low-carbon fuels/energy sources (namely renewables, such as biomass, solar, wind and hydro) and carbon capture technologies.

Although there are various approaches to carbon capture, post-combustion techniques have the benefits of being able to be retrofitted to existing power stations and included in new build facilities. This applies to both coal and gas. Interest in power generation from natural gas continues to grow due to its high efficiencies and lower carbon intensity than coal. Coupling this with carbon capture and storage (CCS) would therefore enable a considerable decarbonisation of the energy supply needed to meet increasingly stringent emissions reduction targets. Solvent-based, post-combustion CO_2 capture is well-understood and has been extensively researched, however, from gas turbines it will still need to overcome a number of challenges, which can be outlined as follows:

- low CO_2 concentrations/partial pressures in the flue gas (resulting in high liquid-to-gas ratios and inefficient capture, causing high energy penalties)
- high flue gas O_2 concentrations (which can initiate substantial oxidative solvent degradation)
- and high flue gas flowrates (large capture plants are required to deal with such flowrates, resulting in significant plant footprints and increased costs)

A range of ways in which these issues can be mitigated have been investigated – these include exhaust gas recirculation (EGR) and selective exhaust gas recirculation (S-EGR); humidification of the gas turbine cycle; supplementary firing cycles; and externally-fired cycles (e.g. Bolland and Sæther, 1992; Evulet, *et al*., 2009; ElKady, *et al*., 2009; Li, *et al*., 2011a,*b*, 2012). These all aim primarily to increase the concentration of the CO_2 in the flue gas that is sent for capture, consequently improving the efficiency of the capture plant.

EGR – Review of Applications and Implications

Exhaust gas recirculation is where a proportion of the flue gas exiting the gas turbine is recycled back to its inlet; usually the flue gas requires cooling to condense out any moisture and to reduce negative impacts on compressor efficiency. Under selective EGR conditions, the flue gases are passed through a separation system, such as a membrane, which removes the CO_2 from the flue gas and selectively recycles only this portion back to the system inlet. The degree of recirculation is known as the EGR or recycle ratio. The motivations behind the implementation of EGR and/or S-EGR systems on natural gas-fired gas turbines are to address the challenges outlined above, thus this section provides a brief review of the various impacts this can have on turbine performance and explores the effects this has on post-combustion carbon capture.

Post-combustion CCS, although not yet commercially available on a large scale, works well for coal-based flue gas, since the concentration (and partial pressure) of the CO_2 in the gas is quite high; often 12-15% (Bouillon, *et al*., 2009; Oexmann and Kather, 2009; Merkel, *et al*., 2010; Sanpasertparnich, *et al*., 2010; Zhao, *et al*., 2012). The process is less efficient and effective however for natural gas-based power generation. The level of CO_2 in the flue gas from gas turbines on an industrial scale is relatively low; several studies report values in the region of 3-5% (e.g. Bolland and Sæther, 1992; Blomen, *et al*., 2009). This means that the separation of CO_2 from the rest of the flue gases can be inefficient due to the high energy requirements needed to remove such a low concentration of gas (with a low partial pressure) from the large volume of flue gas (Peeters, *et al*., 2007). Increasing the level and partial pressure of the CO_2 in the flue gas from gas turbines would therefore greatly benefit capture plants.

Recycling a proportion of the flue gas from the exhaust stream back into the system could be used to increase the back-end concentration of CO_2 in the flue gas. All studies in this field have shown that the use of EGR increases the CO_2 concentration in the flue gases generated from combustion processes, often significantly, which can subsequently aid carbon capture methods, particularly when coupled with amine-based absorption. There are very few research papers however concerning experimental studies of the use of EGR on natural gas-fueled gas turbines, particularly for enhancing post-combustion CCS using amine-based scrubbing technologies.

The experimental research has largely been quite focused, looking primarily at the inadvertent and unwanted impacts of using recirculation and how these can be dealt with – experimentally quantifying the impacts of EGR and low-oxygen air on the performance of gas-fueled turbines (De Paepe, *et al*., 2012). This includes investigations of combustion/flame instabilities and the formation of pollutants, due to the decreases in oxygen levels in the combustor. If the O_2 levels become too low, the flame can become unstable, due to the narrow flame stability limits, and could even be extinguished (Røkke and Hustad, 2005; ElKady, *et al*., 2009). EGR results in lower combustion temperatures and this, coupled with the lower oxygen levels present, can therefore reduce NOx (NO and NO_2) formation (Røkke and Hustad, 2005; Evulet, *et al*., 2009); these same factors may lead to an increase in CO and unburned hydrocarbons (UHC), although this is not always the case if the excess air available is sufficient (ElKady, *et al*., 2009; Evulet, *et al*., 2009; Jansohn, *et al*., 2011). Complete burn-out of the fuel with minimal emissions and high CO_2 levels in the flue gas can be achieved if the operating conditions are appropriately chosen, even with relatively high recycle ratios. The proportion of nitrogen in the outlet gases is also increased, along with CO_2, as the EGR ratio increases (Evulet, *et al*., 2009). Investigations have found that there is frequently little variation in the amount of CO produced or in the combustion efficiency when the EGR ratio is altered, within certain limits (Jansohn, *et al*., 2011). This is predominantly due to the fact that very lean combustion conditions are often used and EGR (at 40-50%) generally does not reduce the O_2 concentration in the combustor near or below the stoichiometric ratio. The overall consensus on EGR from both the experimental and theoretical studies considered below, is that a maximum recirculation rate (the recycle ratio) of 40-50% should be used.

Process simulations and modelling investigations have generally explored more complex issues relating to EGR and are able to compare extensively the various different systems and configurations available, both technically and economically, to gain a detailed insight into their performance. The key findings of these theoretical studies on EGR echo those of the preliminary experimental investigations and have been published by a range of authors (Bolland and Sæther, 1992; Bolland and Mathieu, 1998; Aboudheir and ElMoudir, 2009; Botero, *et al*., 2009; Jansohn, *et al*., 2011; Sipöcz, *et al*., 2011; Li, *et al*., 2011*a*,*b*, 2012; Sipöcz and Tobiesen, 2012). As expected, they report that EGR significantly increases the CO_2 concentration in the flue gas, whilst simultaneously decreasing its volumetric flowrate and oxygen content. These result in a lower thermal requirement of the reboiler for solvent regeneration in the CCS unit and thus greater overall energy outputs and efficiencies can be achieved, with lower costs and smaller energy penalties.

Despite these distinct advantages, however, the addition of a carbon capture process has clear detrimental impacts on the power output, efficiency and costs of energy generation; EGR mitigates these to some extent and appears to be better, technically and economically, than other options at present (Li, *et al*., 2011*a*). Treating flue gas with a higher concertation of CO_2 would result in more efficient capture with a considerably reduced energy penalty by decreasing the thermal requirements of the capture plant for solvent regeneration; the greater concentration of CO_2 enables the thermal requirements of the capture unit to be much lower and can therefore reduce the energy needed for this. Moreover, the smaller volume of gas that requires treatment would mean that a smaller capture plant could be installed. Both of these factors would result in lower capital and operating costs of the CCS system, as well as a smaller plant site footprint (Sipöcz, *et al*., 2011; Sipöcz and Tobiesen, 2012).

Aims and Objectives

Whilst a number of studies have investigated EGR and S-EGR on gas turbines for improved capture performance, very little empirical data is available. The focus, as noted in the preceding section, has been on process simulations for performance assessments and techno-economic analyses. Therefore, experimental work at the UK Carbon Capture and Storage Research Centre's (UKCCSRC) Pilot-scale Advanced CO_2 Capture Technology (PACT) National Core Facilities for combustion and carbon capture technology research explores exhaust gas recirculation and selective exhaust gas recirculation technologies on a micro-gas turbine to reduce the volume of flue gas to be treated, and to increase CO_2 and limit O_2 levels in the flue gas – addressing the key challenges outlined above. The aim of this is to improve capture performance and minimize reboiler duty, therefore increasing the overall plant efficiency. Here, a Turbec T100 PH Series 1 micro-gas turbine was modified to explore the impacts of a wide range of EGR and S-EGR ratios; achieved through CO_2 injections to the compressor inlet. The effects of CO_2-enhanced operation are quantified across the whole operating envelope of the turbine, in terms of mechanical impacts on the turbine, detailed emissions analysis and overall efficiency.

NOMENCLATURE

CCS – carbon capture and storage
CFD – computational fluid dynamics
EGR – exhaust gas recirculation
NOx – oxides of nitrogen (NO and NO_2)
PACT – Pilot-scale Advanced CO_2 Capture Technology
S-EGR – selective exhaust gas recirculation
TOC – total organic carbon
UHC – unburned hydrocarbons
UKCCSRC – UK Carbon Capture and Storage Research Centre

MATERIALS AND METHODS

Experimental Set-Up and Test Conditions

The Turbec T100 PH Micro-Gas Turbine

The PACT Core Facilities houses two Turbec T100 PH micro-gas turbines. For these tests, the Series 1 turbine was used, which has been modified for CO_2 injections to the compressor inlet. This has enabled CO_2-enhanced operation of the gas turbine, which simulates the effects of EGR/S-EGR. The turbine is of a combined heat and power design and produces energy via natural gas combustion – up to 100 kW of electrical power (exported to the grid) and up to 165 kW of heat in the form of hot water. The centrifugal compressor has a maximum pressure ratio of 4.5:1 at maximum load. The lean, pre-mixed combustor ensures low emissions and feeds the combustion gases to the radial turbine. With its modular and compact design, it can generate power at high electrical efficiencies (~30%) and the use of a flue gas recuperator, to pre-heat the combustion air, combined with the integrated flue gas heat exchanger further improve the overall efficiency (~77%).

Conditions for the Test Campaign

The conditions used for these tests focused on two key variables – the power output (50-80 kW) and the CO_2 flowrate (0-175 kg/hr). A range of turbine loads and CO_2 injection flowrate combinations were tested, with data collected for the parameters outlined below. This represented different levels of EGR/S-EGR depending on the power output; recycle ratios of up to 356% were tested. Full characterization of the baseline (no CO_2 injection – thus a recycle ratio of 0%) was completed in addition to the EGR and S-EGR tests for comparative purposes.

Each test condition was allowed to fully stabilize before measurements were taken, where the test period lasted for at least 15 mins, to comply with ISO 2314 (ISO, 2009). As atmospheric conditions can impact on the results, specifically temperatures, the tests were repeated at different times of the day to ensure consistency throughout the campaign, covering a variety of ambient conditions.

Fuel Composition

The natural gas fuel was comprised primarily of methane (90.6 mol%), with smaller proportions of other hydrocarbons – including ethane (5.1 mol%) and propane (1.3 mol%), among others. The incombustible portions of the gas – the CO_2 and N_2 – made up less than 2.5% of the fuel. The gross calorific value of the natural gas that was fired was 39.6 MJ/m^3 (net calorific value 35.2 MJ/m^3).

Systems Monitoring

Assessment of Gas Turbine Parameters

A series of turbine parameters were monitored and data logged at a frequnecy of 1 Hz. These included the calculated turbine inlet temperature (°C); turbine outlet temperature (°C); power generated by the turbine (kW); and the engine speed (rpm). The Series 1 engine has also been modified to include a range of additional data-logged instrumentation, incorporating a number of thermocouples (±0.4% error), pressure transducers (±0.07% error) and flow meters (±0.63% error) at key locations to assess temperatures (°C), static pressures (bar g) and flowrates (kg/min or m^3/hr). Temperatures and pressures were monitored at the following locations: compressor inlet and outlet; flue gas diffusion zone (between the turbine and the recuperator); and in the exhaust duct. The air, fuel and flue gas flowrates were also measured.

Emissions Analysis

A GasMet FTIR DX4000 Analyzer and associated conditioning system was used to determine the levels of primarily CO_2, CO and various unburned hydrocarbon species (CH_4, C_2H_6, C_2H_4, C_3H_8, C_6H_{14} and total organic carbon) in the flue gas. A number of other gaseous species were also quantified in this manner, including water vapor, SO_2, NO, NO_2, NH_3 and total NOx as NO_2. This uses Fourier transform infrared, a form of spectroscopy, to assess gaseous compounds by the differences in their absorbance of the infrared radiation. The residuals (the difference between expected and actual absorption of IR for a gas species and concentration) were within limits specified, and were all less than 0.0002 AU.

The bulk composition of the flue gas was determined with the FTIR, however, this is unable to analyze for O_2, due to the unburned content in the flue gas (i.e. the hydrocarbon species above), which can impact readings. Consequently, a different analytical technique was used for O_2 assessments – paramagnetic transducers in a ServoMex ServoFlex MiniMP 5200 Analyzer (±0.2% error).

EXPERIMENTAL RESULTS

Overview of Baseline Tests

An initial test campaign analyzed the changes in the gas turbine parameters and emissions for the baseline – across power outputs of 50-80 kW without any CO_2 enhancement (i.e. an EGR ratio of 0%). The results are summarized in Table 1, quantifying the variability in performance over a range of turndown ratios. At baseload (50 kW), emissions of both CO and UHC were higher, indicating poorer combustion compared to higher power outputs (60+ kW), where temperatures and pressures were greater, as measured around the compressor and turbine. As shown, the engine speed, fuel consumption and flue gas flowrates also increased with power output. Oxygen levels decreased slightly with increasing power outputs, which correspond to equivalent increases in CO_2.

Impacts of EGR/S-EGR on Gas Turbine Parameters

Compared to the baseline tests, EGR/S-EGR operation achieved via CO_2 injections to the compressor inlet altered a number of gas turbine parameters, including the system temperatures, engine speed, fuel consumption and thus turbine efficiency, as outlined below.

The key temperatures that were altered were at the compressor outlet and at the inlet and outlet of the turbine. As a result, it is likely the combustor temperatures were also reduced, which is considered further below. Fig. 1 outlines the reductions in the compressor outlet temperature with CO_2 enhanced operation. When operating at 75 and 125 kg/hr of CO_2 enhancement, the compressed air temperature was reduced by 5-10°C consistently across all turndown ratios for the EGR cases. CO_2 has a higher specific heat capacity than air and thus this resulted in the lower temperatures seen at this location. The pressures recorded here were not affected. As with the baseline case, as the power output increased, the turbine inlet temperature also increased, for all conditions. The relationship between compression pressure and temperature is well known, and therefore the increasing pressures seen at the outlet of the compressor for the higher power outputs (see Table 1) is the reason for the increases in temperature here.

The turbine inlet and outlet temperatures also differed between the baseline and EGR/S-EGR tests. Fig. 2 shows a similar reduction in temperatures at the turbine inlet compared to the compressor outlet – by around 10°C consistently for all power outputs. The turbine outlet temperature however showed a different trend, as delineated in Fig. 3. For the baseline case, this temperature was the same for all turndown ratios tested – 645°C – kept constant by the turbine altering a range of parameters to ensure high efficiency, as shown in Table 1. The addition of CO_2 however again reduced the temperatures recorded here, by around 5°C across all power outputs, for all EGR/S-EGR conditions. The reasons for these reductions in turbine inlet and outlet temperatures are also due to the higher specific heat capacity of the CO_2 in comparison to the air baseline cases, and are therefore often more pronounced for greater degrees of simulated EGR and S-EGR.

Table 1: Summary of the baseline results – gas turbine parameters and emissions from S1 testing.
at 288.15 K and 101.325 kPa

VARIABLE		50 kW	60 kW	70 kW	80 kW
Fuel Consumption (m^3/hr)*		22.9	26.3	30.0	35.7
Flue Gas Flowrate (kg/min)		30	32	35	41
Engine Speed (rpm)		59,112	61,963	65,029	69,667
Compressor Outlet Temperature (°C)		160	171	183	202
Compressor Outlet Pressure (bar)		2.22	2.49	2.78	3.12
Turbine Inlet Temperature (°C, calculated)		881	897	917	948
Turbine Outlet Temperature (°C)		645	645	645	645
Flue Gas Species (dry basis)	**O_2 (vol%)**	18.5	18.4	18.3	18.2
	CO_2 (vol%)	1.4	1.5	1.6	1.7
	CO (ppm)	22.4	2.2	1.8	0.0
	Total NOx (ppm)	12.9	13.9	12.3	10.2

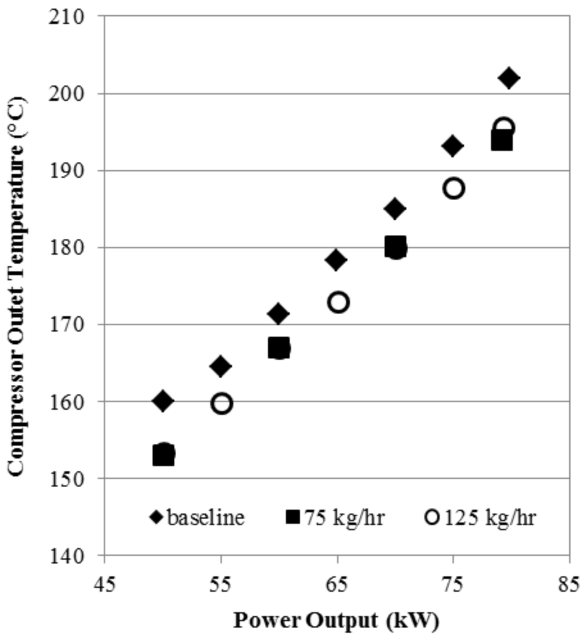


Figure 1: Changes in the compressor outlet temperature with power output for different levels of CO_2 enhancement.

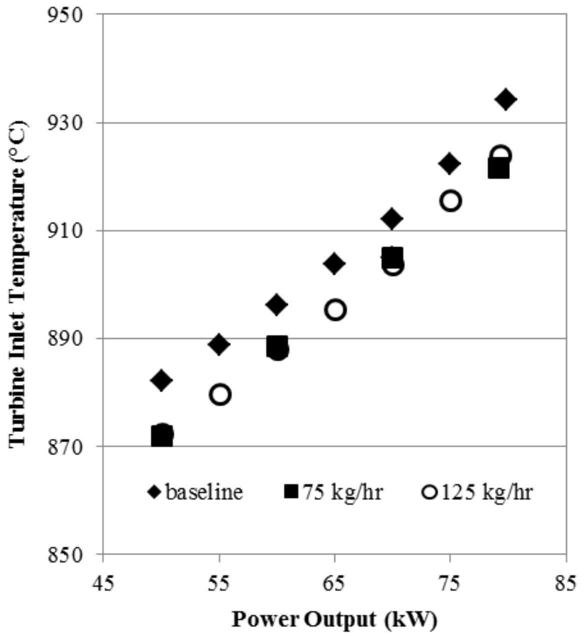


Figure 2: Alterations in the calculated turbine inlet temperature with power output for different levels of CO_2 enhancement.

The engine speed, detailed in Fig. 4, increased significantly as the power output increased, where the maximum flow of both fuel and air through the system were seen, when the compressor and turbine rotate more quickly. For the CO_2 injection tests however, the highest speed recorded was much lower, but still for the highest power output. As seen, the engine speed was consistently slower when CO_2 was included in the combustion air and this trend was seen for all CO_2-enhanced cases. The reason for this is the increased density of CO_2 in comparison to air, which means the same mass flowrate through the system can be achieved with a smaller volumetric throughput and therefore the engine speed can be reduced.

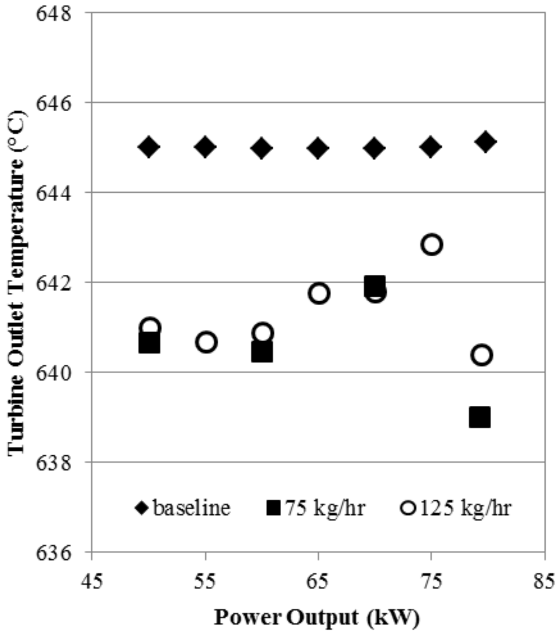


Figure 3: Differences in the turbine outlet temperature with power output for different levels of CO_2 enhancement.

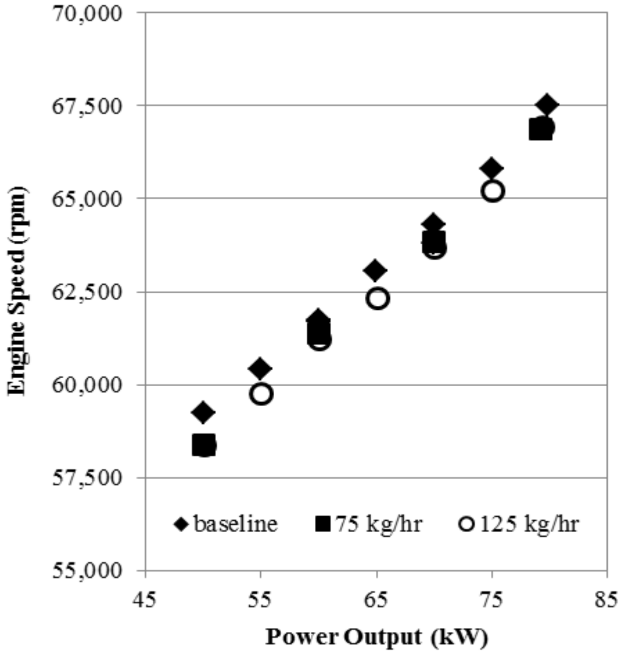


Figure 4: Variations in the engine speed with power output for different levels of CO_2 enhancement.

The fuel consumption for the baseline cases, as outlined in Table 1, increased as the power set-point increased, as more fuel is required to generate more energy. When CO_2 was included with the inlet air stream, there was a slight increase (~4%) in fuel consumption for comparable power outputs. For baseload operation at baseline conditions, fuel consumption was 22.9 m^3/hr; at this power output when CO_2 injection was included (150-175 kg/hr), this increased to around 23.8 m^3/hr. At high power outputs of ~80 kW however, there was little difference in the fuel flowrates between the baseline and CO_2 injection conditions.

Based on this data, namely the power output and fuel consumption, the turbine efficiency can be calculated. Overall it was seen that as the power output increases, the efficiency increases, peaking at 24.1% for 70-80 kW (Fig. 5). The addition of CO_2 does not alter the shape of this trend, but efficiencies decrease when CO_2 is included in the oxidizer, as shown for all cases, most notably for low turndown ratios at high CO_2 flowrates (21.5% for 50 kW with 175 kg/hr of CO_2).

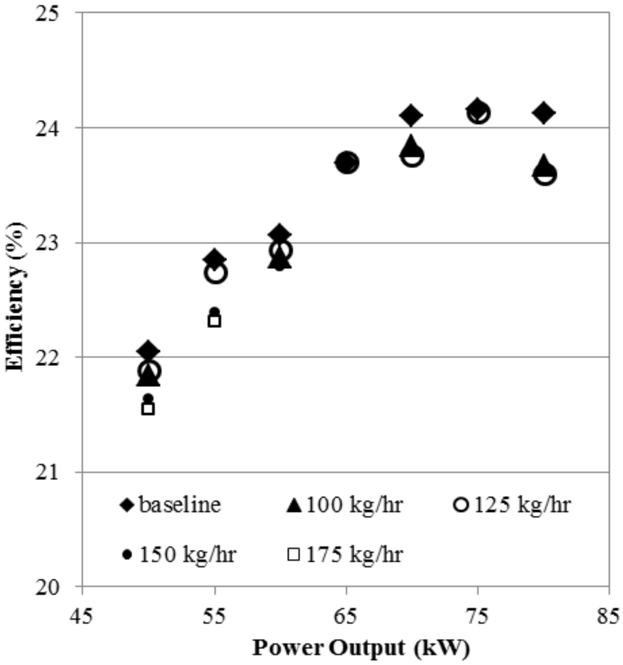


Figure 5: Changes in efficiency with power output and CO_2 enhancement.

Impacts of EGR/S-EGR on Emissions

The FTIR determined the bulk composition of the flue gas, with paramagnetic transducers used for oxygen levels, all reported on a dry basis. As shown in Table 1, the CO_2 concentration increases linearly but very little with power output over the baseline tests with no EGR/S-EGR (from 1.4 vol% at baseload, 50 kW, to 1.7 vol% at 80 kW). The use of simulated EGR and S-EGR however augments this, with high levels of enhancement resulting in the highest concentrations of CO_2 – 5 vol% was seen for baseload power (50 kW) at 125 kg/hr of injection, as seen in Fig. 6, and increasing the enhancement further at baseload power (to 150 and then 175 kg/hr at 50 kW) resulted in flue gas CO_2 concentrations of 5.6 and 6.3 vol%, respectively. These were at the maximum level of CO_2 enhancement possible and at minimal power output (lowest air flowrates and thus least dilution); therefore this was where the highest flue gas concentration recorded, at an equivalent of a recycle ratio of 356%. As shown in Fig. 6, as the power output increases and simulated EGR/S-EGR is operating at the same level of injection, the amount of CO_2 in the flue gas is reduced with increasing power output due to the larger volumes of air and fuel used to generate more power at high engine speeds; thus the CO_2 included in the oxidizer is more diluted.

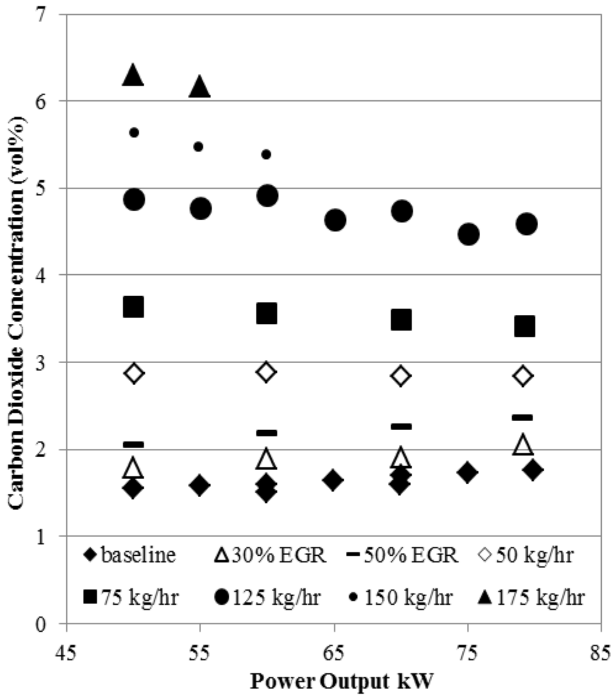


Figure 6: Changes in the CO_2 concentration with power output and CO_2 enhancement.

For the baseline tests (0 kg/hr of CO_2 enhancement), the O_2 concentration varied very little over the power outputs tested, decreasing from 18.50 vol% at 50 kW to 18.17 vol% for the highest power output tested, as seen from Table 1 and Fig. 7. When operating under the various CO_2-enhanced conditions, the oxygen concentration again changed very little for each level of augmentation and power output, but was consistently below 18 vol%, due to the change in the carbon dioxide levels in the flue gas. Furthermore, the higher the level of enhancement, the less oxygen present in the flue gas, and this seemed a more dominant influence than the power set-point. At 175 kg/hr of CO_2 injection at baseload, oxygen levels in the exhaust were 17.6 vol% (Fig. 7).

Products of incomplete combustion – primarily CO, but also a range of unburned hydrocarbons including methane, ethane, hexane and others – were detected by FTIR in the flue gas of the S1 gas turbine during the baseline tests and the EGR/S-EGR experimental campaign. CO is shown in Fig. 8, with methane in Fig. 9. During the baseline tests, at low power settings, the CO levels were elevated at over 20 ppm, which would indicate poorer combustion. As the power output increased to 60 kW and beyond, minimal emissions of CO (~2 ppm) were detected in the flue gas, thus the combustion had improved. Above 75 kW, almost no CO was present, which would suggest that the combustion efficiency was at a peak here (also indicated by Fig. 5). The addition of CO_2 to the combustion air was seen to have considerable impacts on emissions generation, as noted by the increase in CO levels in the exhaust, shown in Fig. 8 for a range of enhancement levels. CO concentrations at baseload were significantly higher. Without CO_2 injection, CO levels were around 22 ppm here, whilst enhanced CO_2 operation increased these to well over 100 ppm – and even up to ~170 ppm in some cases. For baseload operation, by 55 kW, the CO levels had dropped to almost nothing. For high CO_2 enhancement flowrates, however, there were still elevated levels of CO, around 50 ppm as shown, for this power output. It was not until the power output had increased further – to 60+ kW – that the CO levels reached minimal levels, where higher pressure ratios improved diffusion.

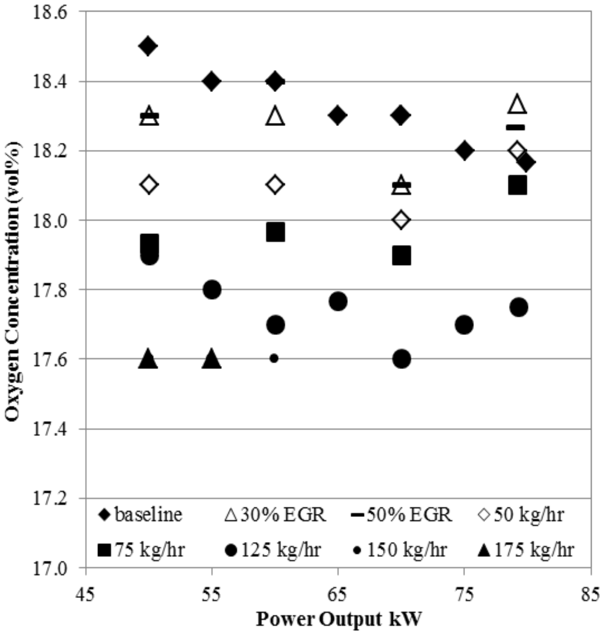


Figure 7: Reductions in the oxygen with power output for different levels of CO_2 enhancement.

A range of other incomplete combustion products were also monitored. The correlation for methane levels (Fig. 9) in the flue gas was similar to the one for CO (Fig. 8) and it was the most predominant of all UHC species in the flue gas. Although significant impacts on combustion were seen at the lower power outputs (50-55 kW), once higher power outputs were achieved, the CH_4level was minimal. The concentrations of the other species were all very low, indicated by Table 2, although these tended to be higher when operating under CO_2-enhanced conditions compared to the baseline. In addition to UHCs, emissions of total organic carbon (TOC) were also recorded by the FTIR for these tests, also reported in Table 2. There was no correlation between the TOC content and power output; the readings varied between 0.8 and 4.5 mgC/Nm^3 for the baseline, with an average of 1.37 mgC/Nm^3. Elevated TOC concentrations were recorded for the tests with high levels of CO_2 injection – with readings in excess of 15 mgC/Nm^3 seen for injection levels at 75 kg/hr and above.

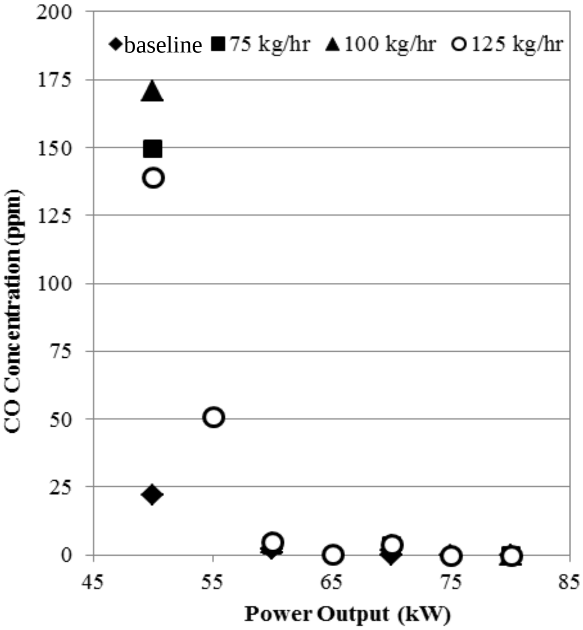


Figure 8: Alterations in CO concentrations with power output for different levels of CO_2 enhancement.

Lastly in this section, NOx emissions – both NO and NO_2 – peaked at lower power outputs (50-60 kW) for the baseline tests, primarily influenced by the levels of NO. The levels recorded for the simulated EGR tests were comparable to the baseline tests, with little apparent difference between the various levels of CO_2 enhancement. These data were then converted to a NOx Emissions Index, based on the amount of fuel utilized and the flue gas flowrate, giving emissions per unit power output (g/kWh). Fig. 10 highlights the impact of CO_2 enhancement, showing a consistent reduction in NOx with simulated EGR. This is most likely attributed to the increased heat capacity of the oxidizer, through the inclusion of a higher specific heat capacity component (the CO_2), which is thought to reduce the peak flame temperatures (evidenced by the reductions in other system temperatures, as discussed above) which can limit the production of thermal NOx, considered by Røkke and Hustad (2005) and Evulet, *et al*. (2009). The higher levels of CO_2 enhancement (representing greater recycle ratios) brought about the biggest reduction in the NOx Emissions Index.

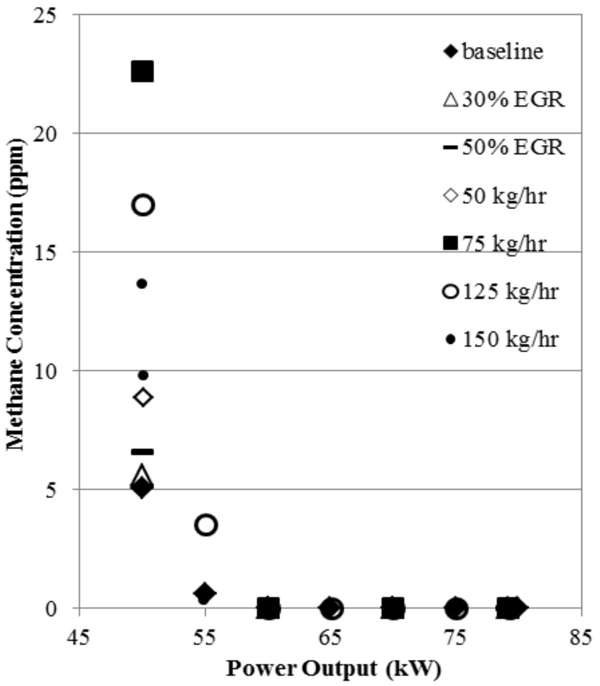


Figure 9: Changes to the unburned methane levels in the flue gas with power output for different levels of EGR.

Table 2: Average levels of unburned hydrocarbons in the flue gas from the gas turbine for different levels of CO_2 enhancement under baseload operating conditions (50 kW).

SPECIES	CO_2 INJECTION (kg/hr)			
	0	75	100	125
Methane – CH_4 (ppm)	4.9	21.9	28.0	21.6
Ethane – C_2H_6 (ppm)	1.1	1.2	1.4	0.9
Ethylene – C_2H_4 (ppm)	0.3	2.0	2.5	1.9
TOC (mgC/Nm^3)	4.5	17.0	9.0	12.1

Implications for Post-Combustion Capture

These tests have shown that EGR/S-EGR operating regimes increase the CO_2 concentration and reduce the amount of O_2 in the flue gas. When utilizing full EGR as opposed to simulated EGR, there would also be reductions in the volumetric flowrate of the exhaust to the capture plant. Akram, *et al*. (2016) investigated the implications of this on a solvent-based post-combustion capture process using 30 wt% monoethanolamine and flue gases with varying amounts of CO_2 – representing a range of recycle ratios from a gas turbine. They concluded that higher CO_2 concentrations in the flue gas resulted in: (i) higher lean and rich CO_2 loadings; (ii) a reduction in specific reboiler duty; (iii) reductions in the regeneration energy and solvent sensible heat; (iv) reductions in the desorption energy; and (v) increases in steam generation rates in the stripper. Considerable performance improvements should therefore be seen (due to the reduced reboiler duty and regeneration energy) by coupling EGR/S-EGR-based gas power with CCS, providing the combustion system is optimized to ensure sufficient O_2. Based on their data, the increases in CO_2 in this paper (to 6.3 vol%) through the use of simulated EGR/S-EGR would likely decrease the specific reboiler duty to ~7 GJ/t of captured CO_2 (from likely more than 10 GJ/t of CO_2 at concentrations of less than 3 vol% CO_2). Additional increases in the CO_2 levels through the use of higher S-EGR ratios would decrease this further.

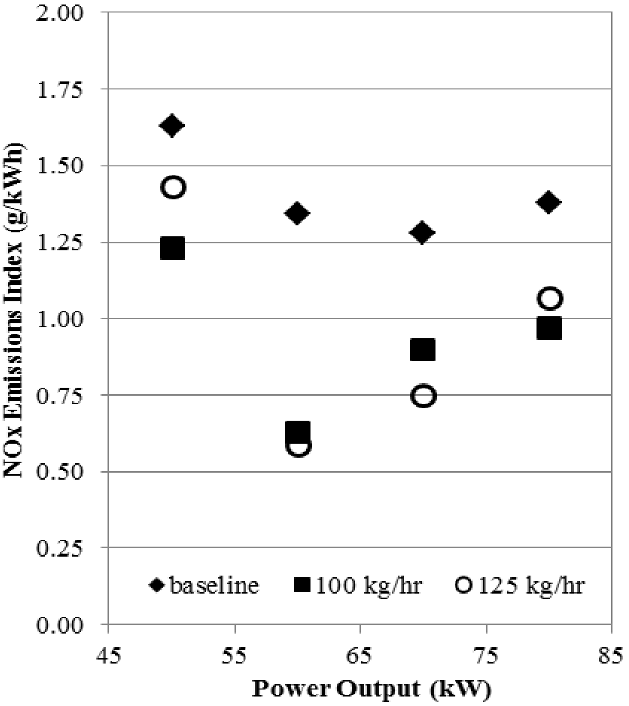
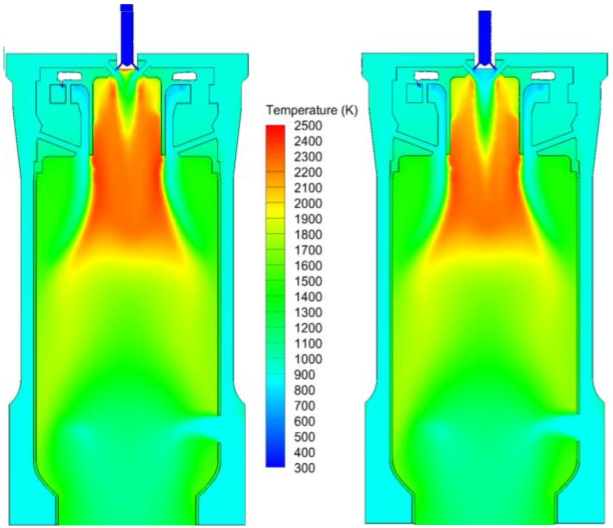


Figure 10: Reductions in the NOx Emissions Index with various levels of CO_2 enhancement at different power outputs.

VALIDATED MODELLING

As discussed in the preceding section, NOx emissions peaked at low turndown ratios and the NOx Emissions Indexes calculated were consistently lower under EGR/S-EGR operation (Fig. 10). This is most likely attributed to increased CO_2 concentrations reducing peak temperatures, thus minimizing thermal NOx formation. Since flame temperatures could not be experimentally measured in the combustor, computational fluid dynamics (CFD) modeling has been employed to confirm that the presence of CO_2 in the oxidizer stream had an impact here, most notably in the flame region. The effects of CO_2 dilution on temperatures and laminar flame speeds were investigated in detailed adiabatic 1D laminar calculations for freely propagating flames, carried out with the GRI3.0 chemical mechanism (GRI, 2000), which consisted of 325 chemical reactions and 53 species. Laminar flames speeds were reduced by up to 25% when 4 vol% CO_2 was included in the oxidizer compared to the baseline air case; from 1.6 to 1.2 m/s at equivalence ratios of ~1. Increased CO_2 levels impacted on the combustion process due to thermal (lower temperature levels due to higher heat capacity – alteration of kinetic pathways promoted by high temperature) and chemical (due to chemical reactivity of CO_2 and its participation in elementary reactions) effects. Laminar flame speeds and adiabatic flame temperatures were considerably reduced by CO_2 additions across the entire flammability range. Temperature reductions and slower chain branching reactions associated with lower concentrations of radicals in the flame have been observed. In general, it was found that the thermal effects were more significant here; the chemical effects are boosted by higher initial temperatures and stoichiometric conditions (i.e. at higher combustion temperatures, corresponding to faster chemical kinetics).

Furthermore, CFD analysis of the Turbec combustor was performed in ANSYS Fluent 15.0, with a Flamelet Generated Manifold approach for chemistry tabulation and the realizable k-ε model for turbulence modelling. This takes into account conjugate and radiative heat transfer under steady-state operation (for more information, see De Santis, *et al*., 2016). Simulations were performed on a computational grid of ~6.25m elements (2.21m solid cells for conjugate heat transfer calculations). The radiative heat transfer equation was solved using the Discrete Ordinate technique. The weighted sum of grey gas model was employed to calculate the mixtures' optical properties, with coefficients from Smith, *et al*. (1982). Fig. 11 shows the effects of CO_2 on the temperature profile within the center plane of the modelled combustor. There is a large cool section and a clear temperature reduction in the flame region when 4 vol% CO_2 is included with the oxidizer (Fig. 11b), compared to the baseline case (Fig. 11a), where air is the oxidizer. The maximum in-flame temperature reduction caused by CO_2 dilution was ~70°C, in line with the reduction in the adiabatic flame temperatures observed in the 1D calculations. Due to the high sensitivity of thermal NOx production to temperature, these lower flame temperatures would significantly limit NOx generation.



(a) (b)

Figure 11: CFD contour plot of temperatures in the combustion chamber, based on experimental data, showing: (a) the baseline case using air; and (b) air plus 4 vol% of CO_2 in the oxidizer.

CONCLUSIONS

Coupling natural gas power with CCS will enable this fossil fuel to continue to be used in a low-carbon future. However, there are a number of challenges that need to be overcome when these technologies are integrated. Post-combustion capture on gas can be inefficient, due to the high energy penalties brought about by treating large volumes of flue gas with relatively low CO_2 concentrations and partial pressures; further issues are caused by the high percentage of oxygen remaining in the flue gas from fuel-lean combustion conditions. The purpose of EGR/S-EGR, investigated here, is to increase the levels of CO_2 in the flue gas to optimize post-combustion capture performance.

This paper addresses these key challenges by investigating conventional and selective EGR, through simulating these with CO_2 injections to the compressor inlet of a micro-gas turbine. Up to 175 kg/hr of CO_2 was injected, equating to recycle ratios up to ~350%. Detailed analysis of gas turbine parameters and flue gas emissions was completed to assess the impacts on turbine efficiency and performance, and to determine the implications for post-combustion capture.

Extensive temperature measurements enabled the impacts of the higher heat capacity CO_2 to be determined, quantifying the degrees to which the compressor outlet, turbine inlet and turbine outlet temperatures decreased – by up to 10°C in each case compared to the air-fired baseline. The inclusion of this higher heat capacity gas in the oxidizer was shown to have more significant impacts on the temperatures in the combustor, with validated CFD models revealing temperature decreases in the flame region of ~70°C. This consequently limited thermal NOx formation, more than halving the NOx Emission Index in some cases. CO_2, with its greater density, also slowed engine speeds, often by 1000 rpm or more. These effects were seen to a greater degree at higher levels of CO_2 enhancement (higher recycle ratios).

These results clearly show that turbines operating 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 of the turbine. Turbine performance at these lower power outputs could be considerably impacted by high recirculation ratios – producing higher levels of emissions that can negatively affect capture solvents, such as CO and UHCs, which cause degradation.

Experimental data such as this, which investigates the effects of EGR/S-EGR on key turbine and CCS variables, aids the improvement of capture performance, by aiming to increase capture efficiency and reduce the energy penalty through minimizing the reboiler duty. 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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