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CO_2-ENHANCED AND HUMIDIFIED OPERATION OF A MICRO-GAS TURBINE FOR CARBON CAPTURE

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ABSTRACT

As greenhouse gas emissions are a key driver of climate change, sources of CO_2 must be mitigated, particularly from carbon-intensive sectors, like power production. Natural gas provides an increasingly large percentage of electricity; however its lower carbon intensity is insufficient to make proportional reduction contributions to circumvent 2°C global warming. The low partial pressure of CO_2 in its flue gas makes post-combustion capture more challenging – increasing the CO_2 in the exhaust assists in enhancing capture efficiency. This paper experimentally investigates the impact of the combination of humidified air turbines and exhaust gas recirculation to increase CO_2 partial pressures, with the aim of evaluating their effects on emissions and turbine parameters at various turndown ratios. It was found that CO_2 levels could be increased from 1.5 to 5.3 vol%, meaning more efficient post-combustion capture would be possible. CO_2 and steam additions increased incomplete combustion when used together at high levels for low turndown ratios (below 60%), with CO increasing from 49 to 211 ppm and CH_4 from 2.5 to 52 ppm; this effect was negated at higher power outputs. Turbine cycle humidification resulted in net improvements to the turbine efficiency, by up to 5.5% on a specific fuel consumption basis.

Keywords: gas turbine; CO_2 emissions; exhaust gas recirculation; humidified air turbine; post-combustion carbon capture.

Highlights:

- investigation of humidification and exhaust gas recycle on gas turbine performance
- incomplete combustion products (CO and CH_4) were only seen at low power outputs
- system temperatures were reduced by using steam and CO_2 injections
- combustor efficiency was reduced, whilst turbine efficiency improved
- augmented CO_2 levels and reduced gas volumes can improve capture performance

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ABBREVIATIONS AND NOMENCLATURE

C	specific heat capacity	PACT	Pilot-scale Advanced Capture Technology
CCS	carbon capture and storage	ppm	parts per million
EGR	exhaust gas recirculation	PT	pressure transducer
FR	flowrate	rpm	revolutions per minute
FTIR	Fourier transform infrared	SFC	specific fuel consumption
HAT	humidified air turbine	TC	thermocouple
LCP	Large Combustion Plant	UHC	unburnt hydrocarbons
mGT	micro-gas turbine	UKCCSRC	UK Carbon Capture Storage Research Council
NOx	oxides of nitrogen	η	turbine efficiency

1. INTRODUCTION

Due to the overwhelming evidence of climate change, it is necessary to mitigate greenhouse gas emissions. Average global temperatures were 0.87°C warmer in 2015 than 1951-1980 (GISTEMP.Team, 2016), which could have dramatic consequences, impacting ~660m people by 2030 (Global Humanitarian Forum, 2009). One of the largest static emissions sources is electrical power generation, accounting for 25% of greenhouse gases (IPCC, 2014). Whilst renewables are being deployed, it is necessary to find ways to decarbonise the conventional supply and address the remaining carbonaceous fuels that are likely to be utilised (Huisingh, et al., 2015), which can be achieved through carbon capture and storage (CCS).

1.1 Background

Whilst carbon capture has been demonstrated at scale for coal (SaskPower, 2016; NRG Energy Inc., 2017), research into CCS for gas-based power is ongoing, due to the differences in flue gas composition between these two fuels. Whilst coal generates relatively high CO_2 concentrations, natural gas, combusted under fuel-lean conditions, produces an exhaust with considerably lower levels, which is challenging for solvent-based capture that relies heavily on the concentration gradient between the flue gas and capture media. Furthermore, lean firing results in significant remaining O_2 in the flue gas, which can cause oxidative solvent degradation. This also means there are large volumetric flowrates of gas, necessitating capture plants with a substantial footprint. Consequently, gas turbine modifications have been sought to increase the partial pressure of CO_2 in the exhaust stream going to the capture plant to improve overall plant efficiency.

1.1.1 Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) recycles a proportion of the exhaust to the front end of the process to increase the CO_2 content of the oxidiser and thus the flue gas. This can increase the capture process efficiency, however, it can also reduce combustor performance, due to the reduction in peak temperatures, especially at the turbine inlet (Mansouri Majoumerd, et al., 2014). Optimising the EGR ratio is therefore of great importance to ensure the maximum CO_2 concentration is reached with minimal impacts on system performance. The energy requirements for cooling and recycling the flue gas also need to be considered, especially when applied to large-scale implementation. Several modelling and simulation studies quantify the impacts of EGR and find the ideal recycle ratio for different system setups; showing net efficiency gains for the whole integrated process (Li, et al., 2011a; Li, et al., 2011b; Mansouri Majoumerd, et al., 2014). EGR displaces air in the combustor, lowering oxygen availability; this depletion is the limiting factor, where incomplete combustion products, such as CO and unburned hydrocarbons (UHC) increase at inlet O_2 levels below 16% (ElKady, et al., 2009; Evulet, et al., 2009). Blowout has been seen to occur experimentally below 14% (Ditaranto, et al., 2009). There have been few experimental studies in this area, but these show stable operation is possible with high levels of EGR (Røkke and Hustad, 2005; ElKady, et al., 2009; Evulet, et al., 2009; Jansohn, et al., 2011). Recycling 25% of the flue gases has been shown to increase flue gas CO_2 levels to 8%, with 35% recycle giving exhaust emissions containing over 10% (ElKady, et al., 2009; Evulet, et al., 2009). This is dependent upon the fuel-air mix, with Li, et al. (2011b) showing 10% CO_2 is only achieved with 55% EGR. Best, et al. (2016) experimentally investigated the whole system impacts of EGR, considering the effects on turbine and capture performance. This showed a reduction in turbine efficiency but an increase in CO_2 levels, and thus a net capture process efficiency gain.

1.1.2 Humidified Turbine Cycles

Humidified air turbines (HAT) use water/steam injections before combustion, with air displaced by water; when condensed out, the CO_2 is then a relatively larger proportion of the total exhaust, enabling more efficient capture (Rao and Day, 1996; Jonsson and Yan, 2005). De Paepe, et al. (2012) found humidification improved efficiencies by up to 2.4%, however their humidification percentage was not quantified and emissions were not published. Mansouri Majoumerd, et al. (2014) looked at both HAT and EGR separately through validated modelling, but did not investigated their combined impacts; they found improvements in efficiency with steam, but a reduction with EGR. In conventional turbines, the pressure ratio and turbine inlet temperature are the biggest factors driving turbine performance. The rate of moisture injection is a strong influence and the addition of steam increases the specific heat capacity (C) of the working fluid, implying greater heat transfer through the recuperator is achievable, increasing efficiency (Horlock, 1998; Li, et al., 2011a). Steam addition also increases the mass flow through the turbine, augmenting its specific power output (Jonsson and Yan, 2005). If steam is added post compression, the additional mass flow through the turbine (for which the compressor has not had to do work for) can improve system performance through greater power generation. HAT has been used historically to improve turbine efficiency and reduce emissions. Older low-NOx combustors used water for temperature control (Jonsson and Yan, 2005), since it acts as a diluent, reducing system temperatures. Although the addition of steam may appear to improve the power output, this does not take into account the energy of rendering the steam (Wan, et al., 2010). If water is added, efficiency gains would be reduced due to the energy required to convert the water into steam via evaporation. The addition of high levels of steam to create humidified air can cause combustion instabilities, shown by higher levels of UHCs and CO (Day, et al., 1999). Using appropriate levels of humidification, it is possible to reduce NOx without significantly increasing incomplete combustion; suggestions range from 5 to 14 vol% (Takahashi, et al., 2002; Li, et al., 2011a; De Paepe, et al., 2012; De Paepe, et al., 2013; Wei and Zang, 2013).

1.1.3 Combining CO_2-Enahnced and Humidified Cycles

HAT can improve turbine efficiency through increased mass flow post-compression, reducing compressor work. It may therefore be possible to negate some of the reduced turbine efficiency experienced with EGR by combining it with HAT. However HAT has its own detrimental impact on combustion, and hence all the benefits must be balanced. It may be the case that for the turbine utilised here, there may be a limited impact on combustion due to the lean fuel-air mix (Nikpey Somehsaraei, et al., 2014), hence HAT may provide significant performance/efficiency benefits. Simultaneously, as previously seen, CO_2 enhancement can have limited impacts on combustion whilst providing significant capture efficiency gains (Best, et al., 2016). However in a combined cycle gas turbine with significantly leaner air mixes, both EGR and HAT may have significantly larger implications on the combustor, and thus cause flame instabilities and lean blowout issues. These methods will however also address the other challenges posed by CCS on natural gas.

1.2 Aims and Objectives

This paper explores the possibility of combining EGR (CO_2 injection to the compressor inlet) and HAT (steam injection at the compressor outlet) on a mGT, with the purpose of evaluating the impacts on turbine operation and assessing the improvements to post-combustion capture through the resultant increase in flue gas CO_2 levels. This article explores the relative impacts of each process separately and then in combination, compared to a baseline. The effects on emissions as an indicator of incomplete combustion, characterised by CO and UHC, and on a range of turbine parameters are quantified, including engine speed, fuel consumption and efficiency. Whilst others have simulated the impact of these processes, e.g. Taimoor, et al. (2016), this is the first paper to experimentally investigate the combination of both techniques.

2. EXPERIMENTAL METHODOLOGY

The UK Carbon Capture Storage Research Centre's (UKCCSRC) Pilot-scale Advanced CO_2 Capture Technology (PACT) Facilities are the national specialist research and development facilities for combustion and carbon capture. The core site houses combustion rigs and a solvent-based, post-combustion carbon capture plant. Comprehensive analytical facilities are available to monitor the impacts of changing the operating regimes, including numerous turbine parameters and thorough exhaust gas characterisation.

2.1 Turbec T100 PH Gas Turbine

The PACT facility currently houses two natural gas Turbec T100 PH micro-gas turbines (mGT). Each has an electrical power generation capacity of up to 100 kW, with an electrical efficiency of 30%, and both have combined heat units that can recover a further 165 kW of thermal power, improving overall system efficiencies to ~80% (Turbec, 2009). This is a simple Brayton cycle, operating with the addition of a recuperator before the combustion chamber. This paper utilised the Series 1 mGT, which has been extensively modified to include both CO_2 pre-compression and steam post-compression, as depicted in Figure 1, to simulate EGR and HAT. The single-stage centrifugal compressor compresses ambient air, and CO_2 when injected, to pressure ratios of up to 4.5:1. This can then have steam added at this point, before passing through the recuperator and then to the combustor. The recuperator increases the oxidiser temperature to improve the electrical efficiency, exchanging heat with the exhaust gases from the turbine outlet; the efficiency of which is enhanced by both the steam and CO_2 addition, which increase C. The lean pre-mixed natural gas flame in the combustor is swirl-stabilised to give low emissions of CO, UHC and NOx. The products expand through the turbine to near atmospheric pressure and drive the single shaft for the compressor and generator. After passing through the recuperator, the exhaust gases go through a counter-flow water-gas heat exchanger. However in this experimental set up, to maintain high exhaust temperatures and reduce the possibility of condensate from the HAT process, the heat exchanger was drained and the exhaust gas remained hot.

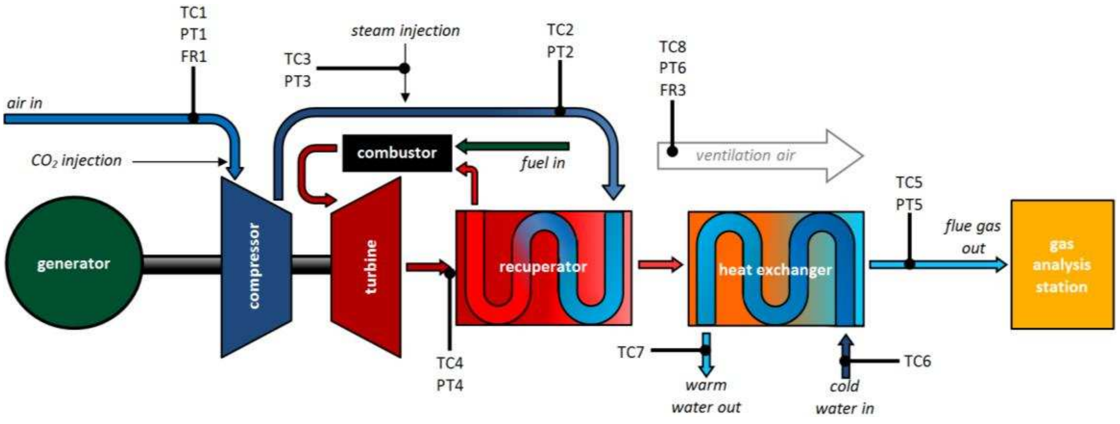


Figure 1: Schematic of the components of the Turbec T100 mGT system at PACT, including the modifications for CO_2 and steam injection, and thermocouples (TC), pressure transducers (PT) and flowrate monitors (FR).

2.2 Experimental Conditions

Three key parameters were varied for the tests conducted; the steam and CO_2 levels across various turn down ratios. Steam injection varied between 0 and 40 kg/hr, CO_2 enhancement from 0 to 125 kg/hr and power outputs between 50 and 70 kW. The test matrix was designed accordingly and the 44 permutations of the conditions tested are outlined in Table 1. All tests were carried out over a minimum of 15 minutes of continuous stable operation as recommended by ISO 2314 (BSI, 2010) and each condition was repeated at least twice, with data averaged for each.

2.3 Data Acquisition

All testing was carried out at the PACT Core Facilities, using the modified Series 1 mGT. The experimental set-up involved extensive monitoring systems for various gas turbine parameters and flue gas species. Firstly, the gas turbine parameters were assessed with the instrumentation added in-house throughout the turbine to ensure full systems monitoring and more comprehensive characterisation of the cycle (Figure 1). Data were collected using a Compact RIO-9022 Real-Time controller, displayed and recorded with a custom LabView program. K-type thermocouples were installed for additional temperature measurements in °C. Pressures (in bar g) were measured using Rosemount pressure transmitters, with errors up to 0.065% of the calibrated range, equivalent to 0.8 mbar for PT1, PT3 and PT5 and 7.5 mbar for PT2, PT4 and PT6. The instrument errors (Table 2) and standard deviations (Table 3) are too small for precise depiction on graphs and hence error bars are not plotted. Secondly, internally-monitored data using the Turbec manufacturers' instrumentation was recorded (via WinNAP software), which monitors the following parameters:

- air inlet temperature (°C)
- turbine inlet (calculated) and outlet temperatures (°C)
- power output and set point (kW)
- turbine speed (rpm and % maximum of 70,000)

Table 1: Test matrix outlining the conditions used.

						STEAM ADDITION (kg/hr)									
	0					**20**					**40**				
CO$_2$ ADDITION (kg/hr) →	0	50	75	100	125	0	50	75	100	125	0	50	75	100	125
POWER (kW) ↓															
50	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
55	✓				✓	✓				✓	✓				✓
60	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
65	✓				✓	✓				✓	✓				✓
70	✓				✓										

Most species in the flue gas were measured using a Gasmet DX4000 FTIR, Fourier transform infrared spectroscopy. This included the main combustion gases, such as CO_2, H_2O, CO and speciation of UHCs, as well as NOx. In this study, oxygen was monitored using a paramagnetic oxygen transducer in a ServoFlex Mini Multi-Purpose 5200 analyser. The fuel flow (in m^3/hr) was measured using a Quantometer turbine flow meter, with a maximum relative error of 0.63% as obtained from factory calibration (Table 2).

Table 2: Instrument standard errors for the devices used with the mGT.

INSTRUMENT	**INSTRUMENTAL ERROR**	
	%	**unit**
Quantometer	0.63	-
K-type thermocouples	0.40	1.5°C
Rosemount pressure transmitters 2051CDC2A	0.07	0.8 mbar
Rosemount pressure transmitters 2051TG2A	0.07	7.5 mbar

Table 3: Maximum standard deviation errors for the instruments used with the mGT.

INSTRUMENT	**MAXIMUM STANDARD DEVIATION**	
	baseline	**EGR & HAT**
GASMET DX4000 FTIR		
CO (ppm)	17.3	17.3
CH_4 (ppm)	3.9	6.0
CO_2 (vol%)	0.02	0.02
NOx (ppm)	1.3	1.2
TURBEC T100		
Engine speed (rpm)	59	139
Power (kW)	0.5	0.5
Temperatures (°C)	0.6	0.6
ADDITIONAL INSTRUMENTATION		
Pressures (mbar)	0.01	0.01
Temperatures (°C)	0.5	11.6

2.4 Emission Corrections and Data Reporting

All emissions are reported on a dry basis. NOx results were corrected to the industrial standard of emissions reporting and EC Large Combustion Plant (LCP) Regulation standards at 15% O_2, 101.3 kPa and 273.15 K (European Commission, 2006). Correcting NOx to 15% O_2 however may not be appropriate, since the O_2 in the exhaust will be lower than in turbines that do not utilise EGR or steam addition; the lower O_2 results mean NOx appear to be higher (ElKady, et al., 2009). A better comparison is on the basis of the fuel combusted and net power output from the turbine, giving a NOx emissions index (g/kg of fuel and g/kWh, corrected to 15% O_2). The mGT however does not fall under the EC LCP regulations, as the efficiency is below 35%, where NOx is limited to $50\eta/35$ (η is turbine efficiency, giving 34 mg/m^3 here). Local air quality standards, such as those of the Greater London Authority (AMEC, 2013), do apply to small mGTs though, and therefore imposes a 5 g/kWh limit, which the turbine achieves under normal operating conditions.

Emissions of CO and UHCs, measured with the FTIR, were used as an indicator of combustor performance. Turbine efficiency was calculated using the net calorific value of the fuel, its flowrate and the power output.

3. RESULTS AND DISCUSSION

The modified mGT was utilised for these tests, with its additional capabilities for steam and CO_2 to simulate the processes of HAT and EGR. During the commissioning phase, the turbine power electronics were damaged by water ingress from the condensation of the injected moisture. After its replacement, the heat exchanger was drained to prevent condensate back flow into the turbine housing, due to the higher exhaust gas temperatures. Condensate was not seen at the new bleed spots, with no moisture observed within the turbine housing. The baseline and CO_2-enhanced results have been discussed previously in much detail by Best, et al. (2016); the results are briefly reported here for comparative purposes.

3.1 Baseline Performance

The results for the baseline tests are summarised in Table 4. Whilst fuel consumption increases with power output, the specific fuel consumption decreases, resulting in improved efficiencies at higher load factors. There is a notable increase in performance with turndown ratio, with the lowest efficiency and highest emissions at 50 kW. As the power output increases, the efficiency improves, with better combustion at ≥60 kW, particularly CO, which highlights incomplete combustion. Since the system operates under very fuel-lean conditions, there is no issue with oxygen availability; thus the fuel-oxidiser mixing is likely to be inadequate here, resulting in lower temperatures within the combustion zone. Furthermore, with high levels of both O_2 and NOx present at low turndown ratios, this indicates insufficient diffusion, combined with a lower pressure ratio that suggests longer residence times. Higher NOx emissions at 70 kW are expected, due to the hotter temperatures throughout the system than for low load factors. Additional assessments of baseline performance were considered by Best, et al. (2016).

3.2 mGT Performance using CO_2 Injections for EGR Operation

Various turndown ratios were employed with CO_2 enhancements of up to 125 kg/hr; the results are summarised in Table 4. The use of CO_2-enhanced operation slowed turbine speeds compared to the baseline, due to the denser CO_2 enabling the same mass throughput at lower volumetric flowrates. System temperatures were notably reduced compared to the baseline, due to the higher C of the added CO_2. The turbine inlet temperature, for example, was ~10°C lower for the EGR tests. In terms of emissions, NOx decreased for the comparative CO_2 tests, as thermal NOx formation is favoured by higher temperatures; the temperatures throughout the system were lower when operating with EGR. CO was notably increased by CO_2 injections, but only for baseload operation (50 kW), as demonstrated in Table 4. Low emissions levels were reported for power outputs ≥60 kW. The higher levels of CO_2 injection at high turndown ratios resulted in considerably more CO_2 in the exhaust gas, which would benefit post-combustion capture performance. Further details of the analysis of CO_2-enhanced operation can be found in Best, et al. (2016); the results all corroborate the assessments of previous work (e.g. ElKady, et al., 2009; Evulet, et al., 2009).

Table 4: Summary of baseline and CO_2-enhanced performance of the mGT (after Best, et al. (2016)).

VARIABLE	0 kg/hr CO_2 INJECTION			75 kg/hr CO_2 INJECTION			125 kg/hr CO_2 INJECTION		
	50 kW	60 kW	70 kW	50 kW	60 kW	70 kW	50 kW	60 kW	70 kW
TURBINE PARAMETERS									
Fuel flowrate (m^3/h)	23.8	27.3	30.6	23.4	27.0	30.2	23.6	26.9	30.3
Specific fuel consumption (kg/kWh)	0.38	0.36	0.35	0.37	0.36	0.34	0.37	0.35	0.34
Engine speed (rpm)	59,784	62,476	64,886	58,372	61,384	63,857	58,481	61,247	63,707
Turbine efficiency (%)	21.36	22.33	23.07	21.98	22.89	23.86	21.89	22.94	23.76
TEMPERATURES AND PRESSURES									
TC2 compressor outlet temp (°C)	161	174	186	153	167	180	154	167	180
PT2 compressor outlet pressure (bar)	2.2	2.5	2.8	2.2	2.5	2.8	2.2	2.5	2.8
Turbine inlet temperature (°C)	883	898	913	872	888	905	873	888	904
Turbine outlet temperature (°C)	643	644	643	641	641	642	641	641	642
FLUE GAS COMPOSITION									
O_2 (vol%, dry)	19.0	19.0	19.0	17.9	18.0	17.9	17.8	17.7	17.6
CO (ppm, dry)	49	1	2	154	3	4	132	5	4
NOx (O_2 corrected, g/kWh)	1.63	1.19	1.56	1.72	0.33	0.95	1.65	0.59	0.75
CO_2 (vol%, dry)	1.5	1.5	1.6	3.6	3.6	3.5	5.0	4.9	4.7

3.3 mGT Performance using Steam Injections for HAT Operation

With the addition of steam post-compression, it is expected that the CO_2 concentration would increase on a dry basis in the exhaust, since steam is displacing the air; this is observed in Figure 2. There is a good correlation of higher CO_2 in the exhaust with steam addition with the volume percentage fractionally larger due to the HAT process after the water has been condensed out (emissions converted to a dry basis), supporting the conclusions of Li, et al. (2011a) and De Paepe, et al. (2012), among others. This trend is observable at all power outputs. Figure 3 shows the impacts of steam injection on engine speed. As with the use of CO_2-enhanced operation above, steam also results in a denser oxidiser and thus the same mass throughput for the system can again be achieved at a lower volumetric flow, slowing turbine speeds by ~2000 rpm, as also found by De Paepe, et al. (2012). Whilst steam injection overall had a significant impact on the rotational speed of the engine, there was much less difference between the two steam injection cases tested compared to the baseline.

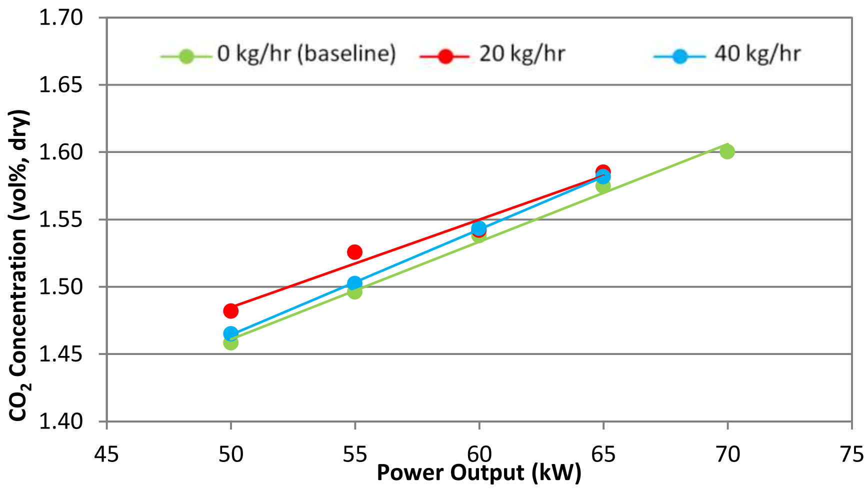


Figure 2: CO_2 level measured in the exhaust at various levels of humidification for different power set points.

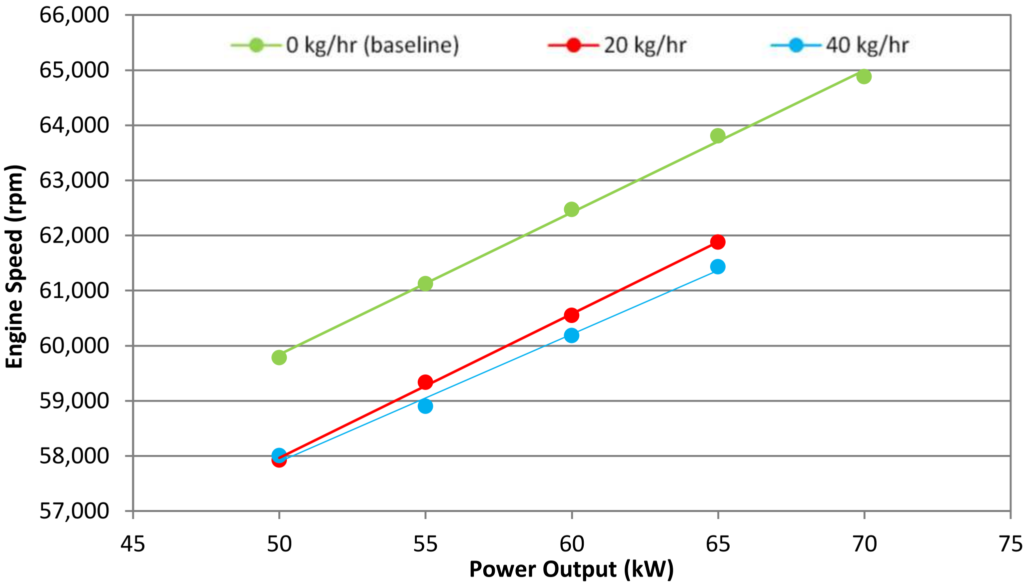


Figure 3: Engine speeds at various levels of humidification for different power set points.

3.4 mGT Performance using Steam and CO_2 Injections for HAT and EGR Operation

The use of steam and CO_2 injections combined were then assessed. The impacts of changing these primary variables on system temperatures, emissions and overall efficiency are considered.

3.4.1 Impacts on System Temperatures

A number of system temperatures were monitored for the mGT, as outlined in Section 2.3. Both steam and CO_2 have the ability to alter the *C* and their impacts are considered here.

Cold-side Recuperator Inlet: Figure 4 outlines the temperatures recorded at TC2 – the compressed oxidiser at the cold-side inlet to the recuperator, which included the steam and/or CO_2, where used. The baseline tests, with no steam or CO_2, had the highest temperatures. This is consistent for all power outputs, but temperatures here increase as the load factor increases; the highest temperature for the highest power output. The impact of simulated EGR reduced the temperatures here consistently for all power outputs by ~7°C. The use of steam however was shown to have a greater impact. Temperatures for all power outputs when using steam injection were lower than for both the baseline and CO_2-enhanced cases; the maximum difference seen was 44°C. The temperatures recorded when using 40 kg/hr steam are slightly higher than the 20 kg/hr cases as the steam temperatures required to obtain the higher flowrates were greater.

Turbine Inlet and Outlet: Figure 5, which outlines the turbine inlet temperatures for power outputs of 50 and 60 kW for a range of cases, reveals that this is greatly impacted by the power output. Those for 50 kW (Figure 5a) are much lower than those for 60 kW (Figure 5b). Furthermore, the use of both HAT and EGR affect these temperatures. As the level of CO_2 injection increases, temperatures decrease due to the alterations in the *C* of the flue gas. The addition of steam also increases the *C* and thus these temperatures were also found to be lower across all power outputs. Overall, the temperatures at the turbine inlet were up to 15°C lower. As can be seen for Figure 5, the temperature appears to be less affected and more consistent with the addition of CO_2 to an already steam-enhanced system – there are smaller differences between the baseline and steam cases with high levels of CO_2. This is probably because the *C* is already higher here, and the combined addition of steam is a less radical change. The turbine controls a number of parameters to ensure a turbine outlet temperature of ~645°C is maintained. Whilst steam and CO_2 altered this temperatures, it was by relatively small amounts (<5°C). The CO_2 additions resulted in lower temperatures at higher levels of injections, however there were no trends seen for steam injections.

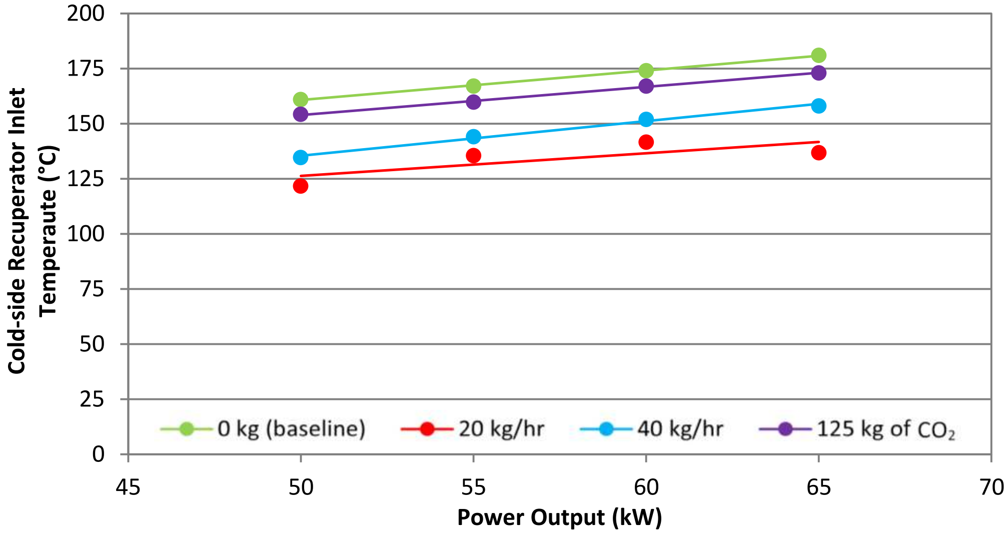
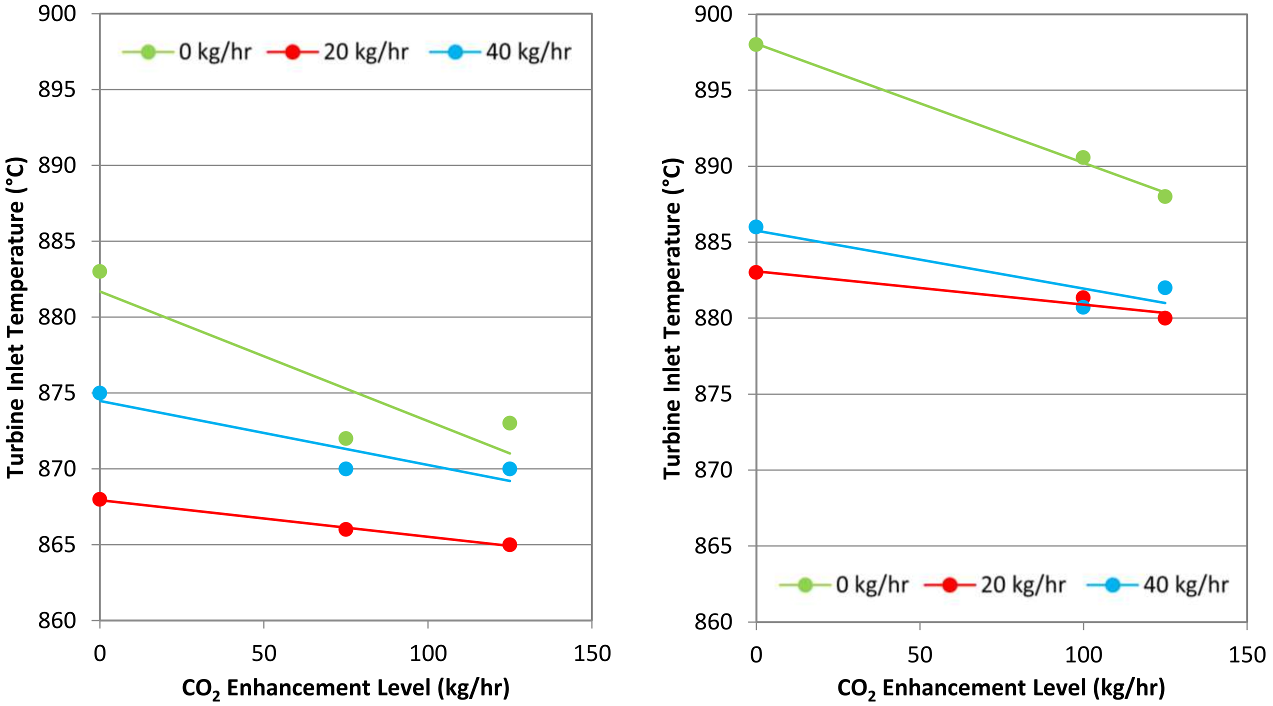


Figure 4: Impacts of steam and CO_2 injections (separately) on the temperature at TC2.



(a)

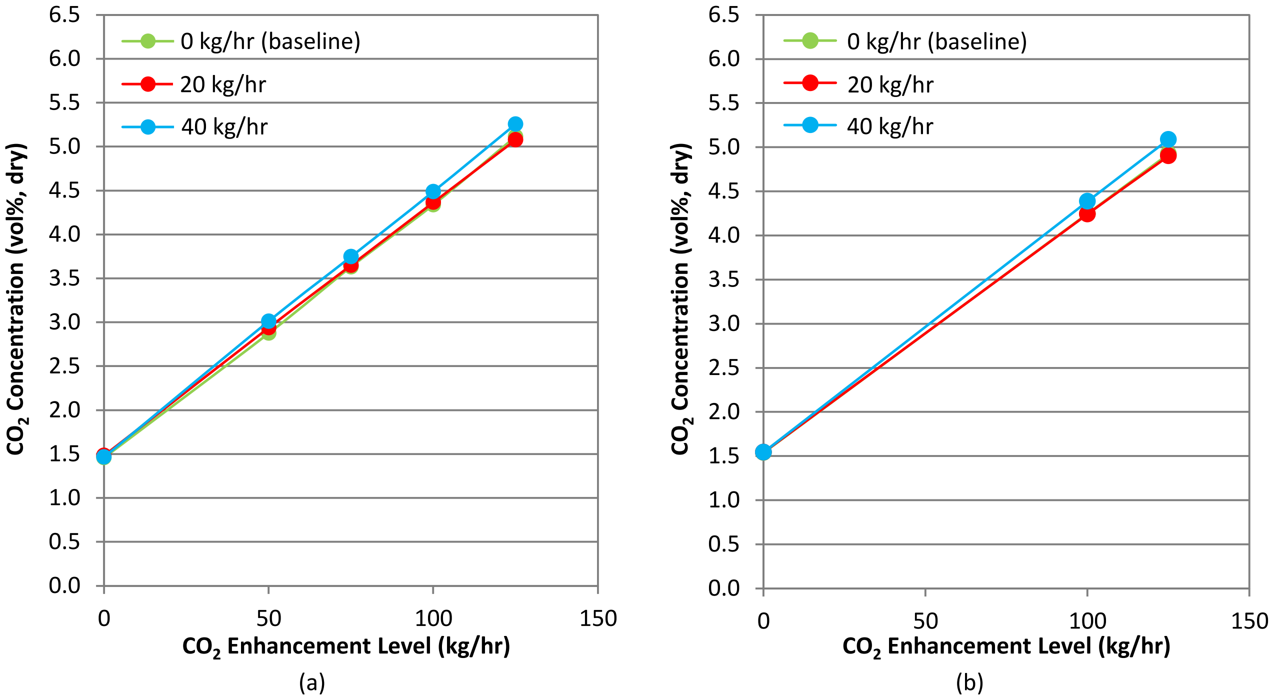
(b)

Figure 5: Impacts of steam and CO_2 injections on turbine inlet temperature, for (a) 50 kW; and (b) 60 kW.

3.4.2 Impacts on Emissions

Although low oxygen levels in the combustor cause unstable flames and blowout, the relatively fuel-lean conditions of the mGT ensure this is not an issue. Even with high levels of steam and CO_2 injections for low power outputs (40 kg/hr steam and 125 kg/hr CO_2 at 50 kW), where the oxidiser flowrates are lowest, the remaining O_2 in the flue gas was still 17.7 vol% on a dry basis. However flame speeds and temperatures are reduced due to the increased *C* under these conditions (De Santis, et al., 2016), and the combination of EGR and HAT further exacerbate this effect compared to when they are used individually. As previously considered in Best, et al. (2016), it has been shown that system modifications, such as EGR (and for HAT and/or EGR herein), have the greatest impact on emissions at the lowest turndown ratios. This is due to the slightly richer air-fuel ratio at the bottom of the turbines turndown ratio, with changes in the oxidiser composition from the steam and/or CO_2 injections having more effect and the mixing being more diffuse.

CO_2 Levels: With the additions of both CO_2 and steam, a linear CO_2 increase was seen, as observed in Best, et al. (2016) for the use of CO_2 injections alone. At 40 kg/hr steam enhancement with increasing CO_2 injection across the turndown ratios of 50 and 60 kW (shown in Figures 6a and 6b, respectively), the highest concentration of CO_2 was found, as would be expected; peak CO_2 concentrations of 5.3 vol%, dry were seen for the most extreme case at the lowest turndown ratio. This is a particularly strong trend and is consistent for both power outputs and across all levels of CO_2 enhancement. This quantifies the extent to which the CO_2 concentrations can be augmented by the combination of the HAT and EGR.



(a) (b)

Figure 6: CO_2 concentrations measured in the exhaust from the mGT at various levels of humidification for different levels of CO_2 enhancement for, (a) 50 kW and (b) 60 kW.

CO Emissions: Carbon monoxide levels were monitored in the exhaust as an indicator of incomplete combustion; Figure 7 outlines the impact of steam and CO_2 injections. Even with a small addition of steam, emissions of CO_2 increase dramatically for low power outputs (50-55 kW). Greater additions of steam result in higher CO emissions – with levels over 200 ppm. Furthermore, these are significantly affected beyond that of the simple EGR, as indicated by Table 4 and seen in Figure 7. For CO_2 injections alone, the peak CO concentrations in the flue gas were recorded as ~150 ppm. When combining both steam and CO_2 injections, the high levels seen with humidified operation alone are increased even further. Here, the highest CO levels were recorded for maximum steam (40 kg/hr) and CO_2 (125 kg/hr) injection rates at the lowest turndown ratio – 260 ppm for 50 kW. Elevated levels of CO were only seen for low power outputs (50-55 kW) and were much reduced by increasing the power output; by 65 kW, levels were below 5 ppm for all cases. This shows increased incomplete combustion occurs only at low load factors when mixing is insufficient and flame speeds are reduced, resulting in only partial fuel combustion. Therefore, the negative impacts of operating with high levels of EGR and HAT can be mitigating by increasing the power output of the turbine above baseload operation. Overall efficiencies are greater for higher power outputs, as shown in Table 4 and considered further below (Section 3.4.3).

Unburned Hydrocarbon Content: In addition to CO, emissions of methane were also monitored in the exhaust as an indicator of incomplete combustion, along with a number of other hydrocarbon species. A similar trend in CO and CH_4 emissions (Figures 7 and 8, respectively) can be observed. The use of EGR or HAT alone increased emissions compared to the baseline – 125 kg/hr CO_2 increased CH_4 levels from 2.5 to 22 ppm at baseload and 40 kg/hr steam increased CH_4 to 52 ppm. However, the combination of EGR and HAT further elevated the levels of CH_4 present, increasing the concentration to over 70 ppm. This clear evidence of increased incomplete combustion is most likely due to reduced flame speeds (De Santis, et al., 2016) and lower efficiencies. As with the results for CO above, increasing the power output rapidly improve efficiency (Table 4) and reduces the levels of CH_4 – with minimal emissions at 60+ kW for all cases. Emissions of other UHCs, such as ethane, showed a similar trend – increasing with the level of HAT and EGR used, but decreasing to minimal levels by 60 kW. This is where the temperatures would be higher and mixing improved, resulting in faster flame speeds and superior combustion efficiencies, minimising the levels of incomplete combustion products.

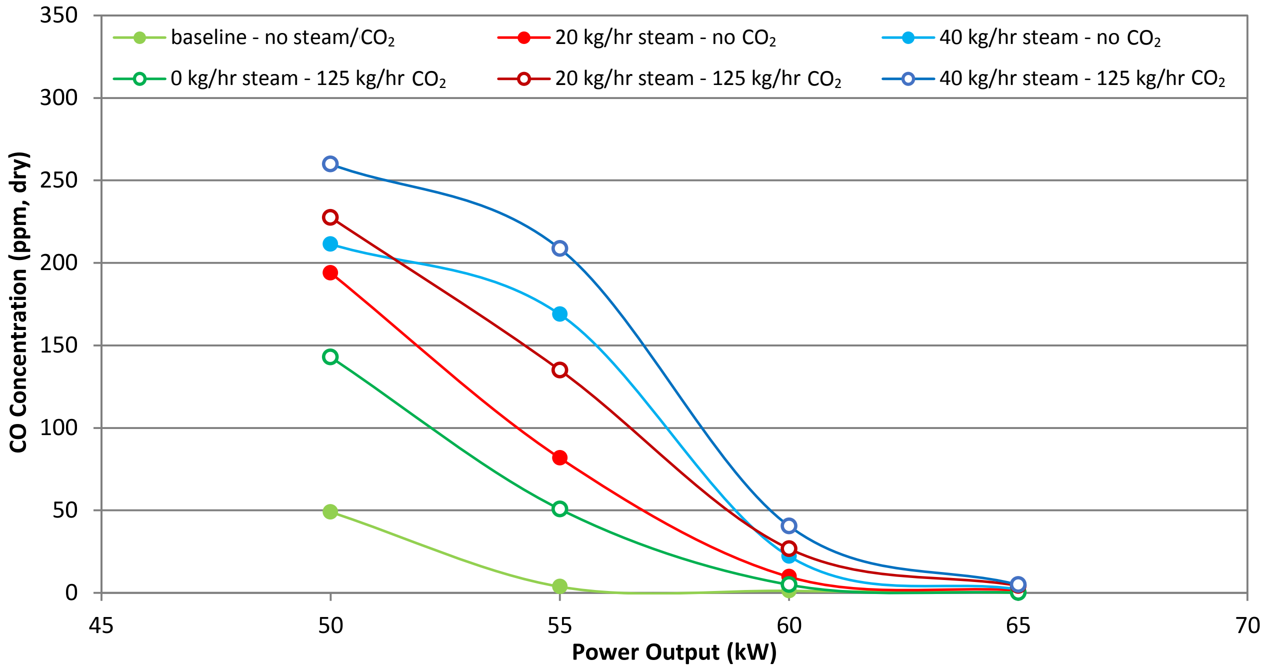


Figure 7: CO concentrations as an indicator of incomplete combustion, comparing various levels of humidification at different power settings, for 0 and 125 kg/hr CO_2 injection.

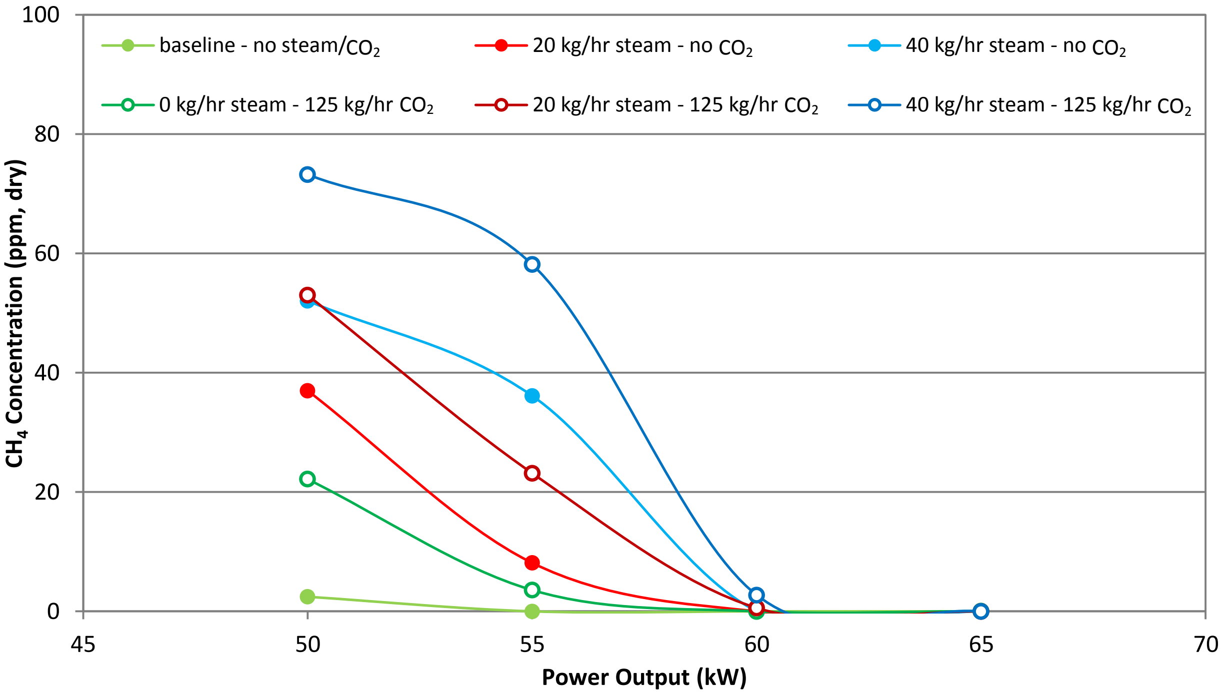


Figure 8: CH_4 concentrations at various levels of humidification at different power settings, for 0 and 125 kg/hr CO_2 injection.

NOx Emissions: The NOx Emissions Index was calculated based on the experimental data from the FTIR using the method outlined in Section 2.4. As previously investigated in Best, et al. (2016), NOx can be reduced by CO_2 injections, due to the alterations in C of the working fluid, limiting thermal NOx formation (De Santis, et al., 2016). From Figure 9, it can be seen that there was much overlap in the results herein, particularly at higher turndown ratios that are likely to be used in power stations. Despite the fact that both process modifications increase the C of the oxidiser, and thus have the ability to reduce system temperatures, as reported in Section 3.4.1, the impact was not clearly seen here in terms of reductions in NOx levels for the combined steam and CO_2 cases compared to the baseline. Emission levels were similar for all tests at 65 kW. There was little variation in the turbine outlet temperature monitored, and this may impact NOx formation despite the changes in oxidiser composition. Kinetic modelling of these variations may enable further insight here, specifically in terms of the variations in combustion/flame temperatures, flame stability and emissions between the different operating conditions.

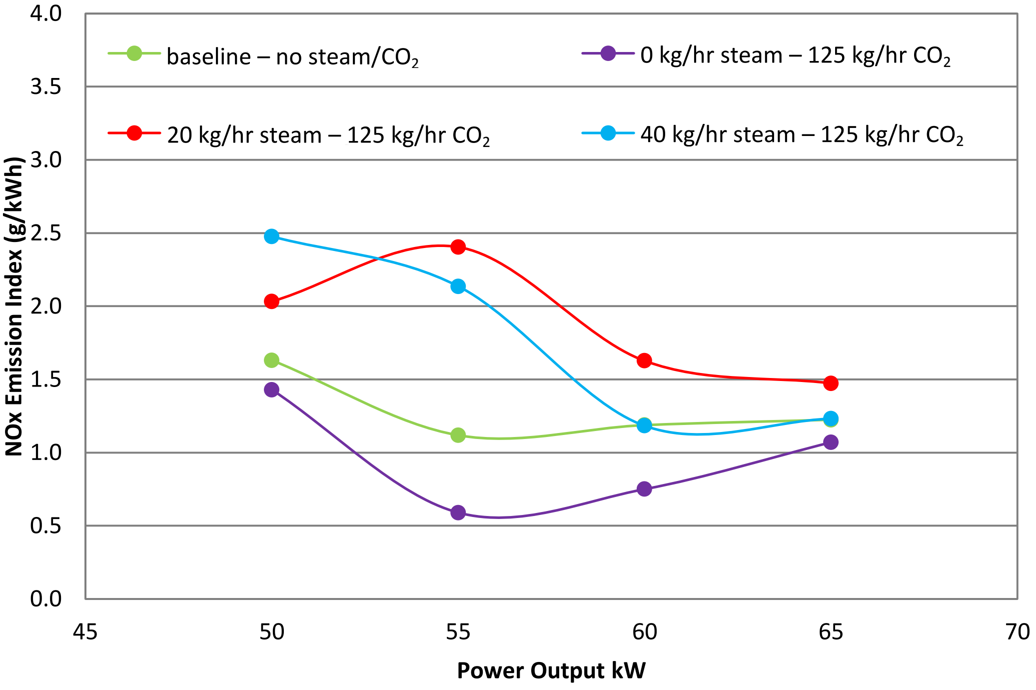


Figure 9: NOx Emissions Index for various levels of humidification at different power settings, for baseline and 125 kg/hr CO_2 injection.

3.4.3 Turbine Parameters and System Efficiency

A number of turbine parameters were monitored and from these, a range of key performance indictors can be established, such as the specific fuel consumption and the overall system efficiency.

Engine Speed: Figure 10 delineates the impacts of steam and/or CO_2 additions on the mGT engine speed, which both have notable implications. As outlined for HAT and EGR individually, the use of either of modification reduces the engine speed significantly, since a lower volumetric flowrate through the system is achieved for the same mass flow, due to the increased density of the steam and CO_2. CO_2 additions decreased the turbine frequency by up to 1600 rpm (in line with previous results published by Best, et al. (2016)), whereas humidification reduced the turbine frequency by up to 1850 rpm. This reduction is ~2.9%, similar to the savings in specific fuel consumption of 3.2% at 50 kW with 40 kg steam addition considered in the subsequent section. When these processes are combined, further reductions in engine speed were observed; Figure 10 clearly shows that the highest flowrates of steam impacted the most on this parameter when used in conjunction with simulated EGR. The largest decrease in turbine engine speed (of ~2500 rpm) was observed at 40 kg/hr steam addition with high levels of CO_2 enhancement.

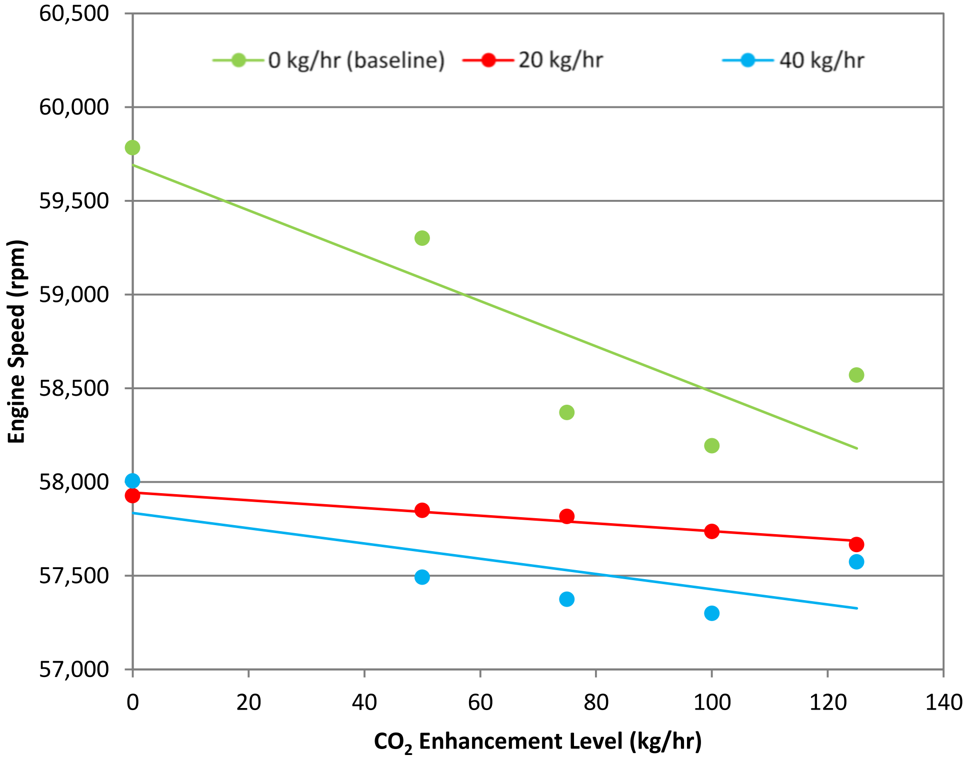


Figure 10: Turbine engine speed for various levels of humidification and CO_2 injection at 50 kW.

Specific Fuel Consumption (SFC) and Efficiency: With the addition of CO_2, it would be expected that the combustor would experience reduced efficiency due to the increased *C* and reduced O_2 availability, caused by the displacement of air with CO_2. In Best, et al. (2016) and ElKady, et al. (2009), this is shown to occur, and was replicated here by the presence of increased levels of CO and CH_4 (Figures 7 and 8). These emissions strongly evidence the reduction in complete combustion and lower flame temperatures. In terms of SFC and overall system efficiency however, the trends are quite different. Figure 11 shows that the baseline tests – with no steam or CO_2 – had the highest SFC per unit energy generated across all power outputs. Furthermore, Figure 12 reveals the baseline cases had the lowest efficiency. The efficiency takes into consideration a number of factors, including the power generated and fuel flowrate. The efficiency improves with power output, as seen in Figure 12a and 12b for 50 and 60 kW, respectively. The use of CO_2 injection alone improves the SFC and efficiency slightly for all power settings. The same trend is seen for the addition of just steam, although the changes seen with this are more prominent. These observed improvements may be due to the reduced engine speeds, for the reasons considered in the preceding section, which appear to outweigh the apparent losses in combustion performance indicated in the emissions at low turndown ratios. With the addition of both steam and CO_2 though, there appears little difference in the results for SFC between these and the steam only cases. It would appear that whilst HAT improves the SFC beyond that of the baseline turbine performance, the impact of this alone is so strong that in combination with CO_2 enhancement little difference is seen. The improvements noted at 20 and 40 kg/hr steam injection alone is 3-5% better than the baseline over the operating envelope tested. Figure 12 also reveals that whilst CO_2 and steam separately improve the efficiency of the system (as found by Li, et al. (2011a) and De Paepe, et al. (2012) for EGR and HAT, respectively), there is little change in the efficiencies when both are utilised; this is noted not only for power outputs of 50-60 kW, as shown in Figures 12a and 12b, but also for the other turndown ratios investigated. This is the maximum efficiency achievable under these conditions and whilst steam addition has improved this compared to the baseline and EGR-only cases, greater levels of steam injection appear to have little impact and the efficiency cannot be improved further; the maximum efficiency has already been attained for these conditions.

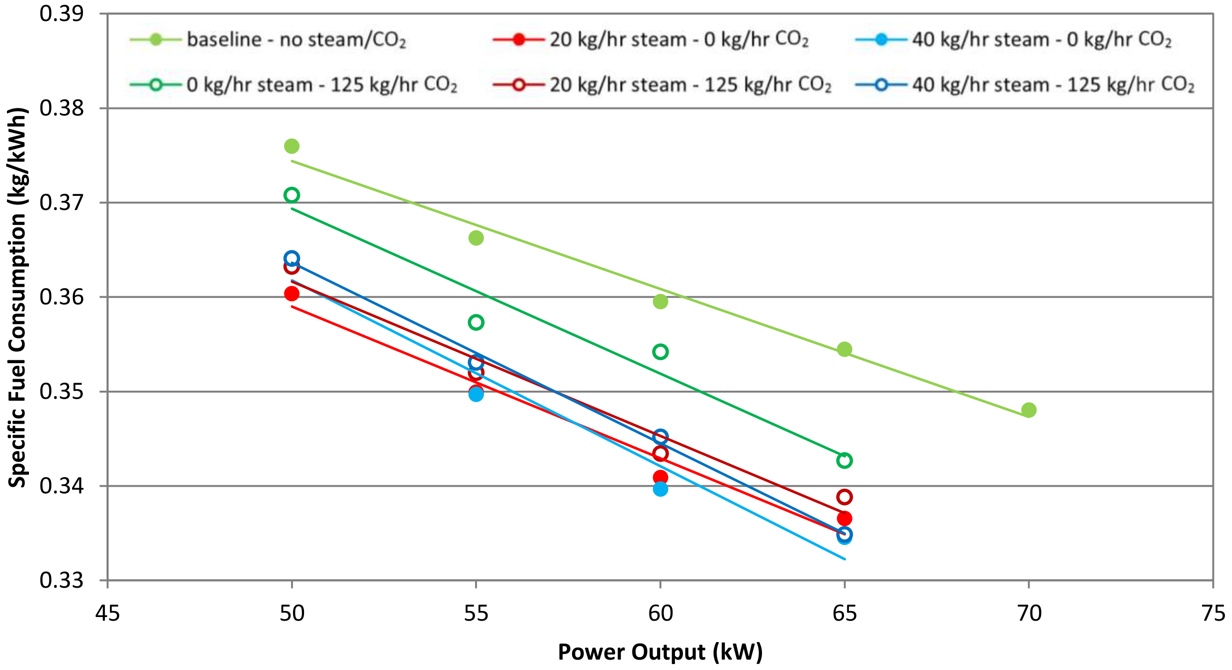
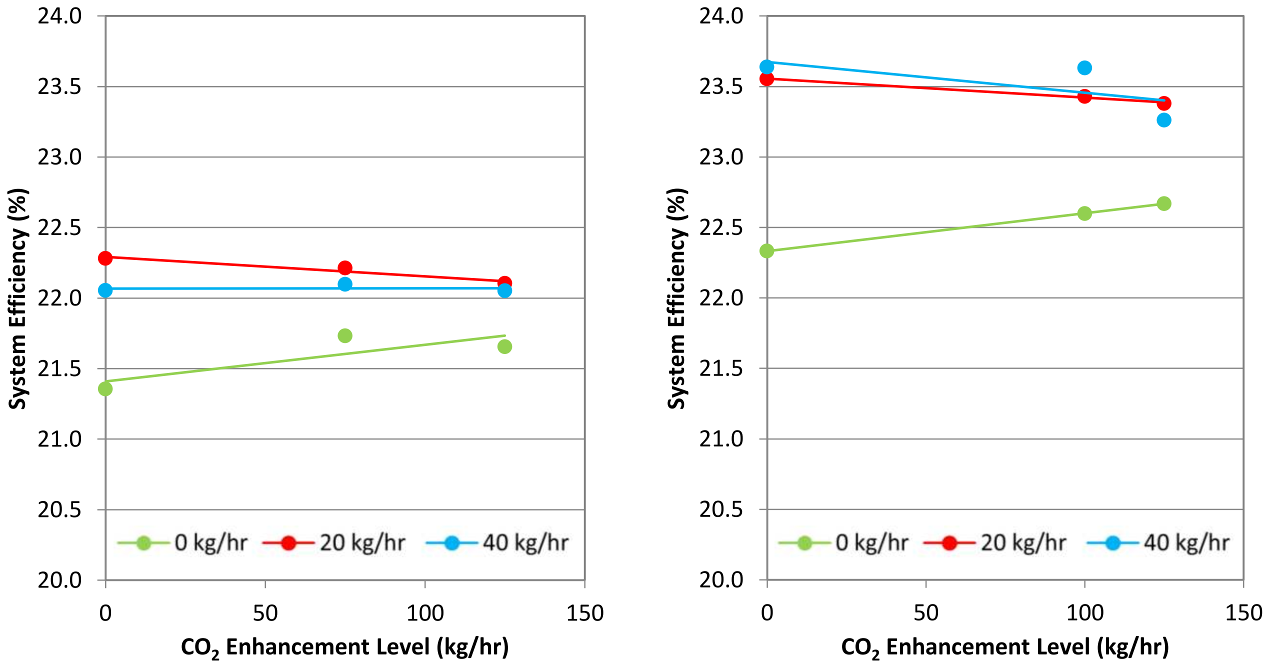


Figure 11: Specific fuel consumption for various levels of humidification at different power settings, for 0 and 125 kg/hr CO_2 injection.



(a)

(b)

Figure 12: Calculated efficiencies for various levels of humidification at different levels of CO_2 injection up to 125 kg/hr for, (a) 50 kW and (b) 60 kW.

3.5 Impact of EGR and HAT on Gas-CCS Performance

Although several previous studies have investigated the use of EGR or HAT, as outlined in Section 1.1, none have combined these process modifications to assess their collective impacts; thus it is difficult to drawn direct comparisons. Where relevant in the above sections (Sections 3.5 through 3.4), the new data presented here has been compared to that previously published, and they concur with the main findings where similar trends were observed (e.g. ElKady, et al., 2009; Evulet, et al., 2009; Li, et al., 2011a; De Paepe, et al., 2012). Further investigation however is required into the combination of different process modifications, including humidification, EGR, supplementary firing, etc. to fully assess the potential of gas turbine improvements that could be applied positively in gas-CCS scenarios. These could augment overall efficiencies, as well as increase the CO_2 concentrations for enhanced capture performance. In addition to the implications for the mGT here, upscaling the technology would also result in further factors to be considered for commercial-scale combined cycles. When operating with real EGR, for example, cooling the recycled stream sufficiently will be vital to ensure optimal performance, maintaining high efficiencies in the compressor. Additional intercooling here though, between compressor stages, may not be appropriate for combined HAT and EGR operation, since this may result in the condensing of moisture at inappropriate locations depending on when the moisture is introduced to the cycle. Other adaptations to this system could potentially further improve efficiencies, such as the use of selective EGR (Merkel, et al., 2013) or a supercritical bottoming cycle (Li, et al., 2011a). In terms of the micro-turbine here, to improve efficiencies would entail significant overhaul (renewal/reconditioning) of the compressor and turbine seals and blades.

Solvent-based, post-combustion capture is an energy intensive process, due to the regeneration of the capture solvent – large amounts of energy are required to break the bonds between the CO_2 and the solvent, releasing it for compression. As gas turbines have a low partial pressure of CO_2 in the flue gas that is treated, this means more energy is required per tonne of CO_2 captured; increasing the partial pressure of CO_2 reduces this energy consumption (Akram, et al., 2016). Combining the options of EGR and HAT has been shown to increase the CO_2 concentration in the flue gas more than either of these technologies on their own (Figure 6). These increases equate to reductions in specific reboiler duty – for the 50 kW case here, an increase in CO_2 from 5.1 vol% without steam to 5.3 vol% with steam under EGR conditions could mean a drop in specific reboiler duty of over 0.1 MJ/kg CO_2 captured (Akram, et al., 2016). This would mean a saving in energy consumption of over 1%, in addition to the reduction in SFC of the turbine of 3%. At 60 kW, similar improvements are noted – with CO_2 increasing from 4.9 to 5.1 vol% with 40 kg/hr steam addition, again reducing the specific reboiler duty by over 0.1 MJ/kg CO_2 captured (Akram, et al., 2016), whilst turbine SFC is reduced by 4%. These reductions in reboiler duty may appear to be modest but on the larger scale can add up to significant energy and thus cost reductions. These are even more pronounced when the compared to a baseline of no EGR or HAT. When operating with real EGR at scale, this would result in reduced volumes of flue gas to the capture plant, further minimising costs (Li, et al., 2011a).

Whilst these tests have been conducted at a pilot-scale for economic reasons, scaling-up these technologies will be required for the widespread deployment of CCS from natural gas. Their deployment can have much larger benefits, in terms of reducing energy consumption and lowering the costs of capture at larger scales. There may however be some negative consequences of the use of EGR/HAT under certain operating conditions and thus these need to be highlighted to ensure such process modifications are deployed under the correct circumstances. As seen from the discussion on emissions (for both CO and CH_4 in Section 3.4.2), elevated concentrations of incomplete combustion products were noted for low turndown ratios when high levels of simulated EGR and HAT were used in combination; these however rapidly decreased as the power output increased. Gas turbine plants are utilised for their high degree of flexibility, enabling load following and rapid response times to ramping requirements. Moreover, these are often used for baseload power and thus do not often run at full output, generating electricity at relatively low levels compared to their maximum capacity. If systems operate under such conditions with high levels of EGR and HAT though, this could cause potential problems with emissions compliance. Increasing the power output has been shown to mitigate these issues, however this may impact on grid supply and stability. Furthermore, the ramping behaviour of the turbines would also necessitate a flexible capture strategy to deal with the variations in the power output and thus in the exhaust gas flowrates received by the capture plant.

4. CONCLUSIONS

Decarbonising conventional power is vital to limit climate change and gas-CCS could significantly address this issue. There are challenges associated with this, however modifications, such as EGR and HAT, can optimise the process. These were experimentally researched here with a mGT, to assess their collective impacts, through CO_2 and steam injections, evaluating the effects on emissions and turbine parameters at various turndown ratios. It was found that CO_2 levels in the exhaust could be substantially increased when using both methods, more so than when used individually; enabling more efficient capture. Peak CO_2 concentrations of 5.3 vol% were recorded for the most extreme levels of steam and CO_2 augmentation. Other benefits included net improvements to the turbine efficiency, by up to 5.5% on a SFC basis, indicating an offset in the reduction in turbine efficiency caused by EGR. This is due to the higher density working fluid, which results in lower engine speeds (reduced by up to ~2500 rpm) for high levels of EGR and HAT. Since the engine is working less hard to achieve the same throughput, efficiencies are improved.

Some negative consequences were seen under certain conditions and it would be advisable to avoid these when operating at large-scale. Incomplete combustion increased at low load factors, but was rapidly negated as power outputs increased. Emissions were negligible above 60 kW – <3 ppm for UHCs and ~40 ppm for CO. This was due to poor fuel-oxidiser mixing, lower pressures and the higher *C* of the modulated working fluid, which reduces system temperatures, flame speeds and reaction rates. Measured temperature differences of up to 44°C were seen, however greater differences in combustion temperatures (70°C or more), particularly in the flame region, have been predicted (De Santis, et al., 2016).

Whilst turbine cycle humidification alone has large impacts, the combination with EGR results in greater levels of CO_2 in the flue gas and thus reductions in reboiler duty, allowing more efficient capture. Furthermore, the efficiency gains will help offset the energy consumption for implementing these developments. The use of either/both of these process modifications could be a key enabling technology for the widespread deployment of efficient gas-CCS.

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