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Effect of the CO_2 enhancement on the performance of a micro gas turbine with a pilot-scale CO_2 capture plant

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Highlights:

- A validated process model of the micro gas turbine is presented.
- A validated CO_2 injected micro gas turbine model is presented.
- EGR is evaluated as mean to enhance the CO_2 content and reduce amount of flue gas.
- Effect of CO_2 enrichment on the pilot-scale CO_2 capture plant is evaluated.
- Effect of CO_2 enrichment on the thermodynamic properties of turbo machinery is assessed.

Abstract

Gas turbines are a viable and secure option both economically and environmentally for combined heat and power generation. Process modelling of a micro gas turbine for CO_2 injection and exhaust gas recirculation (EGR) is performed. Further, this study is extended to assess the effect of the CO_2 injection on the pilot-scale CO_2 capture plant integrated with a micro gas turbine. In addition, the impact of the EGR on the thermodynamic properties of the fluid at different locations of the micro gas turbine is also evaluated. The micro gas turbine and CO_2 injection models are validated against the set of experimental data and the performance analysis of the EGR cycle results in CO_2 enhancement to 5.04 mol% and 3.5 mol%, respectively. The increased CO_2 concentration in the flue gas, results in the specific reboiler duty decrease by 20.5 % for pilot-scale CO_2 capture plant at 90 % CO_2 capture rate for 30 wt. % MEA aqueous solution. The process system analysis for the validated models results in a much better comprehension of the impact of the CO_2 enhancement on the process behaviour.

Keywords: Micro gas turbine; Process modelling; CO_2 injection; Exhaust gas recirculation; Specific reboiler duty.

Nomenclature

CCS	carbon capture and storage
CDT	compressor discharge temperature
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
DLN	dry low NO_x
EGR	exhaust gas recirculation
H	head
m	mass flow rate
MGT	micro gas turbine
N	rotational speed
P	pressure
PACT	Pilot-scale Advanced Capture Technology
r	pressure ratio
R	universal gas constant
R&D	research and development
T	temperature
TIT	turbine inlet temperature
TOT	turbine outlet temperature
UHC	unburned hydrocarbons
z	compressibility factor
γ	ratio of specific heats (c_p/c_v)
δ	pressure ratio
θ	temperature ratio

Subscripts

cr	corrected
in	inlet
out	outlet
ref	reference condition

1.1. Introduction

The energy trend across the globe is changing due to the overwhelming concern regarding emission of greenhouse gases from the power generation sector (IEA, 2012). The contribution of the conventional power generation system, including coal- and natural gas- power generation, is in the gradual transition stage towards more sustainable systems, as towards low or zero carbon emission emitters. However, natural gas-fired power plants are a secure and viable option both economically and environmentally as it results in less oxides of carbon, nitrogen and sulphur in comparison to coal-fired power plants. Increased urbanization results in an escalated power demand and thus have led to a shift to natural gas-fired power plants around the globe to meet both the increasing demand and reduced emissions targets. In addition, post-combustion carbon capture technology needs to be integrated with a natural gas-fired power plant to reduce the carbon emissions with the most mature technology, the amine absorption system. However, the integration of the natural gas-fired power plant with amine-based carbon capture results in a major energy penalty due to the low CO_2 concentration in the exhaust gas from a natural gas-fired power plant. Literature reports various innovations to the natural gas-fired power generation system (Heppenstall, 1998; Poullikkas, 2005); however, most of them deal with efficiency enhancement rather than the enriching of the exhaust gas with CO_2. However, exhaust gas recirculation (Earnest, 1981) is the one of the innovative solutions in dealing with the low CO_2 concentrations in the exhaust gas from natural gas-fired power plants.

The benefits of the EGR system are well known as it enhances the CO_2 concentration of the exhaust gas and reduces the exhaust gas flow rate (Ali et al., 2014; Ali et al., 2015b). Both of these benefits results in the reduced penalty on the integration of the amine-based carbon capture system with the natural gas-fired power generation plant in EGR mode. The specific flue gas flow rate of a gas turbine system is much higher at about 1.5 kg/MW in comparison to a steam boiler system at about 0.95 kg/MW and EGR can considerably reduce the flue gas flow rate, thus resulting in a lower load on the amine-based CO_2 capture system when integrated (Jonshagen et al., 2010). The decrease in the mass flow can be accounted for by the changing temperature at the compressor inlet since the recycled stream is at a higher temperature, and to achieve the same combustor temperatures, a lower amount of cooler air is required (Li et al., 2011a). The application of the EGR results in the increased MACH numbers at the inlet and outlet tips of the compressor rotor due to the changes in the thermodynamic properties of the fluid stream (Jonshagen et al., 2010) however, this increase will not pose severe issues to the turbo machinery (Jonshagen et al., 2011). In addition, the increase in the CO_2 concentration in the working stream of the gas turbine, due to the EGR, results in the change of the thermodynamic properties of the fluid stream, both in the turbo machinery and the combustion section of the gas turbine (Ali et al., 2015b). Also, the recycled stream results in a higher water content at the combustor inlet, which can be controlled by the condenser present in the recycle loop (Ali et al., 2015a). Further, the injection of the recycle stream can be done at various locations in the gas turbine, resulting in different control algorithms due to the imbalance on the shaft (Ali et al., 2015a). An important consideration for EGR operation is that the maximum amount of the exhaust gas to be circulated is still undefined, as with an increase in the EGR, the combustion kinetics, stability, and emissions issues arise. The increase in EGR causes O_2 starvation at the combustor inlet with issues in terms of flame stability and increased emissions of unburned hydrocarbons (UHC) and CO, when O_2 concentration falls to 14 mol% at the combustor inlet (Ditaranto et al., 2009; Evulet et al., 2009). Moreover, the experimentation with a DLN F-class gas turbine combustor shows the stable operation for EGR up to 35 % (ElKady et al., 2009). Hence, the recommended O_2 concentration at the combustor inlet should be higher than 16 mol% to have a stable combustion operation in the gas turbine system with EGR (Bolland and Mathieu, 1998; Ditaranto et al., 2009; ElKady et al., 2009; Evulet et al., 2009). Further, modifications that are recommended in the literature for an EGR applicability include; changes in the premixedness, control system and variation in the design of the pilots for the burners to reach higher levels of the EGR percentage (ElKady et al., 2009). Technical modifications to the combustor design may result in more oxidant injection or a pure oxygen stream with different distribution levels which will result in a higher EGR percentage and much higher CO_2 levels in the flue gas. In addition, the guarantee issues from the gas turbine manufacturers should be the priority for the safe operation and redesign of the combustor and/or the whole gas turbine structure.

Work has been performed regarding the effect of the EGR on the performance of gas-fired power plants integrated with post-combustion capture systems with emphasis on the energy penalty and reduction in cost of the combined system (Belaissaoui et al., 2013; Biliyok et al., 2013; Biliyok and Yeung, 2013; Botero et al., 2009; Canepa and Wang, 2015; Canepa et al., 2013; Jonshagen et al., 2011; Jonshagen et al., 2010; Li et al., 2011a; Li et al., 2011b; SipÃķcz and Assadi, 2010; SipÃķcz et al., 2011; Sipöcz and Tobiesen, 2012; Yu et al., 2013). However, most of the work was performed on commercial-scale natural gas-fired power plants operated with EGR and then its integration with a post-combustion capture plant.

This paper focuses on the micro gas turbine which is a low emission, reliable and efficient combined heat and power generation system that competes with the combined heat and power reciprocating engines. Further, the micro gas turbine (MGT) is a good and accessible option for research purposes and the performance outcomes can provide recommendations for the commercial-scale gas turbines. However, the CO_2 concentration in the exhaust gas of the micro gas turbine is much lower, it ranges from 1.5 to 1.8 mol% while the commercial-scale natural gas-fired turbines have CO_2 concentrations in the range 3.8 to 4.4 mol% (Canepa et al., 2013; Li et al., 2011a; Li et al., 2011b; Sipöcz and Tobiesen, 2012). Regarding MGT, the impact of the EGR on the emissions and performance for different kinds of fuel by analysing through CFD modelling, is reported in the literature (Cameretti et al., 2009; Cameretti et al., 2013). It is important to note that some work on the effect of the EGR on the performance, and sensitivity analysis of the ambient temperature for the MGT with EGR have been reported in the literature (Akram et al., 2013; Ali et al., 2014; Ali et al., 2015b; Majoumerd et al., 2014; Nikpey et al., 2014). Further, the literature reports the varying optimum EGR from 40 to 55 % through different process modelling tools.

1.2. Novelty

In this paper, the EGR has been investigated by injecting CO_2 to the MGT inlet which is further integrated with the amine-based CO_2 capture plant. The performance evaluation of MGT and amine-based CO_2 capture plant for CO_2 enriched working stream will result in a better understanding of the effect of the EGR and assist in reaching the optimum conditions for operation.

Due to the limited literature found in this field, an extensive study needs to be performed on the effect of the CO_2 on the performance of the MGT, along with the effect on the amine-based CO_2 capture plant. Studying the behaviour of the MGT, along with CO_2 injection in full detail, is necessary to fully comprehend the optimum performance of the MGT in the innovative mode of the EGR operation. Hence, this study focuses on the evaluation of the impact of these parameters on the performance of the MGT and amine-based CO_2 capture plant for CO_2 injected and/or EGR operated MGT. The impact of the CO_2 enrichment on the thermodynamic properties of the working stream at different locations of the MGT is also investigated to assess the behaviour of the innovative EGR cycle.

This paper is structured as follows. In Section 2, the process description along with the modelling strategy is described in detail and also the methodology is presented. In Section 3, the validation of the MGT for base case and CO_2 injection is presented along with the set of comprehensive data and then the modelling of the MGT with EGR is presented. Further, the effect of the EGR on the thermodynamic properties of the working stream at different locations of the MGT is evaluated. In addition, the impact of the CO_2 injection on the pilot-scale CO_2 capture plant is also evaluated. Finally, in Section 4, comprehensive conclusions are drawn from the detailed investigation.

2. Process Description, Modelling Strategy and Methodology

2.1. Process Description

The Turbec T100 Series 1 micro gas turbine is available at the UKCCS Research Center Pilot-scale Advanced Capture Technology (PACT) facility located in Sheffield, UK. The Turbec MGT is a combined heat and power machine with a capability of 100 kW_e of electrical power and 165 kW_{th} of thermal power. The MGT compromises of a centrifugal compressor, a radial turbine and a high speed generator, all mounted on the same shaft. The lean premixed emission type combustor is fired with natural gas, and this result in low NO_x, CO and UHC. There are two heat exchangers in the MGT to enhance either the electrical or total efficiency of the MGT. The first heat exchanger is a recuperator, which preheats the compressed air, and the second heat exchanger is a gas-liquid heat exchanger to generate thermal power by heating the water. The components of the MGT are shown in Figure 1.

The air at ambient conditions of the temperature and the pressure is compressed to a pressure ratio of 4.5:1 through the compressor, and then passed through the recuperator for preheating through the exhaust gases of the turbine. The preheated compressed air is mixed with the natural gas in the combustor. The combustion products at a turbine inlet temperature (TIT) 950 ^oC expands through the turbine with the turbine outlet temperature (TOT) to remain fixed at 650 ^oC and at near atmospheric pressure. Thus, the turbine drives both the compressor and the generator as all are on the same shaft. The exhaust gases pass through the recuperator which boosts the electrical efficiency by preheating the compressed air. Then, the exhaust gases are used to generate the thermal output in terms of hot water by heating the water in the gas-liquid heat exchanger.

The exhaust gas from the MGT is split; one part of the exhaust gas is forwarded to the pilot-scale CO_2 capture plant and the other is sent to the chimney to be vented in to the atmosphere. The pilot-scale CO_2 capture plant is capable of capturing 1 ton per day of CO_2 based on MEA as aqueous solvent. The pilot-scale CO_2 capture plant is based on liquid absorption of CO_2 from flue gas and equipped with a flue gas desulphurization unit; however, for the present case it is bypassed. The pilot-scale CO_2 capture plant consists of absorber, stripper and water wash columns; the heat exchangers as cross heat exchanger, reboiler, condenser, lean amine cooler; the pumps for lean and rich amine solvent circulation; and the solvent tanks for fresh and spent solvents. The components of the pilot-scale CO_2 capture are shown in Figure 1. The columns are filled with random INTALOX Metal Tower Packing (IMTP25). The plant is equipped with thorough instrumentation to record the performance of the plant. More details can be found in the literature (Akram et al., 2016).

The flue gas enters the bottom of the absorber in which it interacts with the amine solvent flowing down from the top. The treated gas is washed-off of any traces of the amine solvent in the water wash column before emitting it to the atmosphere. The rich amine solvent from the absorber bottom is pumped through the cross heat exchanger and then entered the stripper column for the solvent regeneration. The CO_2 rich stream is released from the stripper top while the regenerated solvent flows down to the bottom for recirculation.

The CO_2 is injected at the compressor inlet of the MGT from the CO_2 storage vessel. The pressure of the CO_2 stream is slightly higher than atmospheric at the compressor inlet in order to ensure better mixing of the CO_2 stream with the air. The CO_2 injection stream is displayed in Figure 1 and the flow rate of the CO_2 can be varied from 0 to 125 kg/hr to check the performance at different enrichment levels.

2.2. Process Simulation Strategy

The combined heat and power model of the MGT and pilot-scale CO_2 capture plant are developed in Aspen HYSYS® V8.6. The property package for the estimation of the thermodynamic properties for the gas turbine section is the Peng-Robinson equation of state. The minimization of the total Gibbs free energy is used as a criterion for the chemical equilibrium in the combustor to estimate the composition of the components of the flue gas. The details of the thermodynamics of the Brayton cycle can be found in the literature (Ali et al., 2014) and therefore not repeated in this paper. Further, the property package used for the model developed for the CO_2 injection in MGT, as well as the MGT model with EGR, is the Peng-Robinson equation of state. The MGT model and the MGT model with CO_2 injection are validated with extensive experimental data and the MGT model with EGR is developed after satisfactory validation of the above two models. The property package for the pilot-scale CO_2 capture plant model is the Acid Gas property package based on Electrolyte NRTL. The details of the thermodynamic property package, chemistry, chemical equilibrium and kinetic reactions and their respective data, and correlations for mass transfer, pressure drop and interfacial area can be found in the literature (Akram et al., 2016).

2.2.1. Base Case Model

The base case model of the MGT is developed in the steady-state at the ISO conditions (ISO, 1997) with the power output 100 kW_e and at the rotational speed 70000 rpm. The composition of the natural gas, along with the net calorific value, is shown in Table 1. The composition of the air is shown in Table 2 with relative humidity 60 %. The TOT is fixed by varying the fuel flow rate to the inlet of the combustor, and is kept constant at 645 ^oC. For TOT, the value of 645 ^oC is chosen instead of 650 ^oC (Turbec, 2000) as the mean value of the TOT measured was 645 ^oC during the experiments, with a maximum mean standard deviation of 1.23 for both with and without CO_2 injection. Instead of constant isentropic efficiency of the compressor and the turbine in the MGT model, characteristic maps have been used in the MGT modelling to reduce the number of assumptions that have to be made for the estimation of the isentropic efficiencies of the compressor and the turbine. The characteristic maps help in the reduction of the number of variables required to set the degree of freedom of the model to zero, as compared to the previously reported MGT models (Ali et al., 2014; Ali et al., 2015b). The details of the characteristic maps can be found in Section 2.2.2.

The base case model results are summarised in Table 3 and the results are presented for two developed models, one with constant isentropic efficiency of the compressor and turbine and the other in which characteristic maps are implemented. The model result without maps is the simplified model in which the efficiency of the compressor and turbine of the MGT is fixed. Further, in order to satisfy the degree of freedom of the components of the model, more specifications in terms of the temperature and/or pressure are required to solve the case. In addition, the rotational speed is a parameter that cannot be accounted for in MGT model without maps. The detailed model includes the characteristic maps as explained in Section 2.2.2. The inclusion of the characteristic maps reduces the number of specifications in the model, and allows the rotational speed to be accounted for. Instead of efficiency, temperature and/or pressure; only the rotational speed is specified to solve the model.

The model results with characteristic maps are in good agreement with the manufacturer's reference data (Turbec, 2000) as indicated in Table 3, and the already published results of the model developed for the MGT through different process modelling tools (Ali et al., 2014; Ali et al., 2015b; De Paepe et al., 2012; Delattin et al., 2008; Kautz and Hansen, 2007; Majoumerd et al., 2014; Nikpey et al., 2014; Nikpey Somehsaraei et al., 2014; Parente et al., 2003). The comparison of the present model results with the previously published model results are presented in Table A. 1 in Appendix A. The model is then tested against the set of experimental data for various power outputs in order to increase the model robustness.

2.2.2. Characteristic Maps

Characteristic maps indicate the performance of the machine in terms of the mass flow rate, pressure ratio or head and isentropic efficiency at various rotational speed levels of the machine. These are available for the Series 2 of the Turbec T100 series, and are incorporated into the MGT model. They assist in the estimation of the isentropic efficiency in the MGT model for each operating point, by specifying either the rotational speed or the pressure ratio of the MGT and the other parameters are estimated. They are mostly presented in terms of the non-dimensional and corrected parameters, which assists in the reduction of the number of variables required to specify the operating point of the system. These corrected parameters can be converted to the normal ones by the following equations (Boyce, 2012; Cumpsty, 2003; Hunecke, 1997; Saravanamuttoo et al., 2001):

$$N_{cr} = \frac{N}{\theta} \tag{1}$$

$$\dot{m}_{in,cr} = \frac{\dot{m}_{in}\sqrt{\theta}}{\delta} \tag{2}$$

where N is the rotational speed, $\dot{m}$ is the mass flow rate, θ is the temperature ratio defined by equation (3) and δ is the pressure ratio defined by equation (4). The subscript "cr" indicates the corrected values of the parameter, and "in" indicates the parameter at the inlet of the compressor.

$$\theta = \frac{T_{in}}{T_{ref}} \tag{3}$$

$$\delta = \frac{P_{in}}{P_{ref}} \tag{4}$$

where T is the temperature, P is the pressure and the subscript "ref" indicates the reference condition which depends on the vendor specification. More details of the performance maps can be found in (De Paepe et al., 2012; Nikpey Somehsaraei et al., 2014). However, Aspen HYSYS uses the head in terms of the pressure ratio for the inclusion of the characteristics maps into the model. The pressure ratio is converted into the head, by the following equation:

$$H = \frac{\gamma}{\gamma-1} zRT_{in}\left[\left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \qquad (4)$$

where H is the head, the amount of energy required to boost the gas from one pressure level, P_{in} to a higher pressure level, P_{out}; γ is the ratio of the specific heats (c_p/c_v); c_p is the specific heat at constant pressure; c_v is the specific heat at constant volume; z is the compressibility factor; R is the universal gas constant; and T_{in} is the inlet temperature.

Due to the injection of the recirculated exhaust gas at different locations in the MGT, the operation of the MGT might be outside the operating envelope of the characteristic maps for both compressor and turbine. As the injection at different locations results in an imbalance of the shaft, due to the difference in the flow rate through the compressor and turbine section of the MGT, the operating point of the MGT may move away from the surge curve. This deviation can be estimated through the surge margin and is defined by the equation (Walsh and Fletcher, 2004):

$$\text{Surge margin} = \left[\frac{r_{\text{at surge}}}{r_{\text{operating point}}} - 1\right] \times 100 \quad (5)$$

where r is the pressure ratio at constant flow rate.

2.2.3. CO_2 injection and/or EGR Modelling

Due to the low concentration of the CO_2 in the exhaust gas from the MGT, as indicated in Table 3 which implies that the exhaust gas of the MGT needs to be enhanced in terms of the CO_2 concentration. The most viable method is through either injection of CO_2 at the compressor inlet or through exhaust gas recirculation in which part of the exhaust gas is split through the splitter; dried through the condenser and recirculated back to the compressor inlet of the MGT. A schematic of the MGT with EGR is shown in Figure 2. The recycle loop consists of the splitter, condenser, booster fan and filter. The condenser acts in two ways: to decrease the temperature of the recycled stream and to remove the water from the recycled stream depending on the temperature specified. The temperature of the recycled stream is maintained at 15 ^{o}C at the compressor inlet. The recycled stream can only be injected back into the system if its pressure is slightly higher than the live pressure of the stream where it is injected, and this is achieved by the booster fan which increases the pressure from the condenser pressure back to the live pressure of the stream. The slightly higher pressure of the recycled stream allows better mixing of the recycled stream with the air. The filter assists in the removal of any of the solid contaminants present in the recycle stream. The amount of the exhaust gas recirculated can be defined by the following expression:

$$\text{EGR ratio} = \frac{\text{Amount of recirculated exhaust gas}}{\text{Amount of exhaust gas}} \quad (5)$$

In addition, the thermodynamic properties of the working stream for the EGR are investigated at different locations of the MGT, namely:

i. Compressor inlet.
ii. Compressor outlet/recuperator air side inlet.
iii. Combustor outlet/turbine inlet.
iv. Turbine outlet/recuperator gas side inlet.

The thermodynamic properties investigated include; mass density, heat capacity and isentropic co-efficient ($\gamma = c_p/c_v$); to better apprehend the effect of the EGR on the performance of the MGT for recycling the exhaust gas other than just injecting CO_2 in the MGT.

2.3. Methodology

This paper deals with process modelling and simulation analysis of the MGT integrated with a pilot-scale amine-based CO_2 capture plant. The experimental data obtained through the PACT facility is used only to validate the MGT base case and the MGT with CO_2 injection models. Similarly the experimental data of the pilot-scale amine-based CO_2 capture plant is used to validate the model of the pilot-scale amine-based CO_2 capture plant as presented in (Akram et al., 2016). However, the exhaust gas recirculation to the MGT is analysed only through modelling and simulation in Section 3.3, after testing the MGT against extensive validation in Sections 3.1 and 3.2. Further, the integrated case of the MGT with the pilot-scale amine-based CO_2 capture plant is analysed through modelling and simulation for varying rates of CO_2 injection as presented in Section 3.4. In conclusion, the effect of CO_2 enhancement on the performance of the MGT integrated with pilot-scale amine-based CO_2 capture plant is analysed in this paper.

3. Results and Discussion

3.1. MGT model validation

The base case model is validated against the set of experimental data obtained for the Turbec T100 Series 1 of the MGT through the PACT core facility and the electrical power output is varied from 50 to 80 kW_e to access different operational modes. These experimental results are performed with substantial additional instrumentation other than the default instrumentation of the MGT in order to better comprehend the behaviour of the MGT at different power outputs. The modelling is performed for each power output to evaluate the performance for each operational scenario and the results obtained from the modelling are compared with the mean values of the experimentally measured data points. The measured versus modelled results for some of the selected parameters are given in Figure 3. The mean percentage absolute deviation for the model results for all the quantities investigated, such as the compressor discharge temperature (CDT), turbine inlet temperature, compressor discharge pressure, flue gas composition for CO_2 and O_2 and power output, in comparison to the measured values are: 1.02, 3.54, 1.97, 1.75, 4.72 and 0.02 %, respectively. Figure 3 shows that the model results are in good agreement with the experimental data.

3.2.MGT model validation with CO_2 injection

The CO_2 concentration at the exhaust of the MGT is low, in the range 1.51 to 1.69 mol% as illustrated in Figure 3 (c) and this will cause a major energy penalty when integrated with the CO_2 capture system. This drawback is avoided either by injecting CO_2 into the MGT or by recycling the exhaust gas back to the gas turbine, which results in the enrichment of CO_2 for improved CO_2 capture efficiency. The steady state model developed is extended to study the effect of CO_2 enrichment.

The MGT model is also validated against the set of experimental data for CO_2 injection at the compressor inlet of the MGT at different part load conditions for varying injection rates of CO_2 injection. The CO_2 flow rate is varied for each part load condition from 0 to 125 kg/hr to access the behaviour of the CO_2 injection for different operational modes. The process modelling is performed for various CO_2 injection for each part load condition to evaluate the process performance of the different operational scenarios and the results obtained from the process modelling are compared with mean values of the experimentally measured data points. The measured versus modelled results for some of the selected parameters are shown in Figure 4. The mean percentage absolute deviation for the parameters investigated are within the acceptable range, such as the compressor discharge temperature (CDT), compressor discharge pressure, flue gas composition for CO_2 and O_2 and power output, in comparison to the measured values are: 1.81, 1.54, 2.73, 2.29 and 0.02 %, respectively. Figure 4 shows that the model results are in good agreement with the experimental data.

The minimum and maximum CO_2 concentration observed during the modelling of CO_2 injection in MGT is 1.48 and 5.04 mol% in comparison to the mean experimental values of 1.48 and 4.98 mol%, respectively for the power output of 50 kW_e. The minimum O_2 observed in the flue gas is 17.60 and

17.11 mol% for measured and simulated cases at the CO_2 injection rate of 125 kg/hr, respectively, with the O_2 content at the combustor inlet of 19.96 mol%. The O_2 content at the combustor inlet is much higher than the limited oxygen to be present at the combustor inlet as reported in the literature (Bolland and Mathieu, 1998; Ditaranto et al., 2009; ElKady et al., 2009; Evulet et al., 2009).

3.3.Effect of the EGR ratio

The more real application is to recycle the part of the exhaust gas back to the compressor inlet which is termed as EGR. The EGR ratio is varied to check its impact on the system performance through the splitter in the model to adjust the amount of the EGR ratio defined by Equation (5). The modelling is done at the ISO conditions and electrical power output is maintained at 100 kW_e and TOT is fixed at 645 ^oC. The location for the recycle and process conditions of the recycle stream is already optimised by the author (Ali et al., 2015a). The increase in the EGR ratio increases CO_2 in the exhaust gas with a decrease in O_2 concentration both at the combustor inlet and exhaust gas, as shown in Figure 5 (a). The decrease in O_2 concentration at the combustor inlet causes O_2 starvation, which will affect the combustion stability with higher UHC and CO emissions at the outlet. The decreasing trend of the O_2 at the combustor inlet and outlet is shown in Figure 5 (a). The modelling suggests that EGR $\leq$ 55 % should be maintained to remain within the oxygen levels recommended for efficient combustion (Ditaranto et al., 2009; ElKady et al., 2009; Evulet et al., 2009), and this results in CO_2 enrichment from 1.6 mol% in the base case MGT cycle to 3.5 mol% in the EGR cycle. Further, the EGR system results in the decrease of the total mass flow of the flue gas, which will influence the performance of the CO_2 capture system. The results of the EGR model at 55 % EGR are given in Table 4. The flue gas composition of the MGT with EGR for different EGR ratios is shown in Figure 5 (b). The increase in CO_2 composition in the exhaust gas is almost by a factor of 2.2 and is approximately the same as reported in the literature (Biliyok and Yeung, 2013; Jonshagen et al., 2010; Sipöcz and Tobiesen, 2012) for EGR equipped commercial scale natural gas-fired power plants. The electrical efficiency decrease is 7.6 % for the EGR cycle in comparison to the base case MGT cycle. This decrease is due to the power consumption by the booster fan in the recycle loop. However, the exhaust gas flow rate decreases by 55 % of the base case MGT cycle while the overall efficiency increases by 1.6 %.

The change in the composition of the stream affects the thermodynamic properties of the working stream, which affects the performance of the MGT. As defined in Section 2.2.3, the three thermodynamic properties are chosen to check the performance of the MGT for the changed composition of the working stream at different locations. The thermodynamic properties for different locations of the MGT are shown in Figure 6.

The mass density of fluid decreases with the increase of the EGR as shown in Figure 6 (a) at all locations due to the increased content of CO_2 in the fluid. However, this effect is more pronounced at higher temperatures and pressures. This effect also depends on the concentration of the other participating constituent's in the fluid at the particular location. As it is observed, for the EGR of 55 %, the mass density of the fluid increases by 5 and 0.2 % at the compressor inlet and turbine outlet, however, the increase is up to 22 and 20 % at the recuperator inlet and turbine inlet. The effect of the increased CO_2 content on the heat capacity of the fluid at different locations of the MGT is less pronounced. As, increase of 1.5 % is observed at the gas turbine inlet for the heat capacity, however, this increased heat capacity results in the higher heat duty of the recuperator and G/L heat exchanger. The effect of the EGR on heat capacity for different locations of the MGT is shown in Figure 6 (b). Further, the isentropic coefficient of the fluid at different locations of the MGT decreases with an increase of EGR as shown in Figure 6 (c). The increase of the isentropic coefficient is less pronounced and an average 0.5 % decrease is observed for the EGR percentage of 55 %. Thus, it can be concluded that the performance of the MGT for the EGR cycle can be better comprehended by understanding the behaviour of the fluid for the increased CO_2 content in the working fluid of the MGT.

3.4. Effect of CO_2 enrichment on the validated pilot-scale CO_2 capture plant

The process model of the pilot-scale CO_2 capture plant has already been validated against the set of experimental data from the PACT facility as reported in the literature (Akram et al., 2016). The performance of the pilot-scale CO_2 capture plant is reported for MEA for a 30 wt. % solvent with 90 % CO_2 capture rate. The slip stream of the exhaust gas of the micro gas turbine is enriched with CO_2 before entering the pilot-scale CO_2 capture plant. The CO_2 concentration in the flue gas entering the absorber varies from 5.5 to 9.9 mol%, thus representing the wider range of the EGR operation. The model results are in good agreement with the measured values as the mean percentage absolute deviation is within the acceptable range. The mean percentage absolute deviation for the rich and lean loading, rich and lean MEA concentration and specific reboiler duty are 2.4, 0.2, 1.9, 0.1 and 2.0 %, respectively.

The slip stream of the micro gas turbine is sent to the pilot-scale CO_2 capture plant for the removal of CO_2 from the flue gas. The CO_2 injection in MGT is varied from 0 to 125 kg/hr and its effect through slip stream on the performance of the pilot-scale CO_2 capture plant is investigated through modelling. The MGT with CO_2 injection is considered for integration with the pilot-scale CO_2 capture plant which also covers the CO_2 concentration range of the MGT with EGR, since, the maximum CO_2 concentration for CO_2 injection in the MGT results in 4.91 mol%, which is higher than the CO_2 concentration of 3.5 mol% observed during the MGT with EGR case. The flow rate of the flue gas entering the absorber is fixed at the value of 400 kg/hr and the CO_2 capture rate is fixed at 90 % and the solvent employed is MEA with 30 wt. % aqueous solution. The lean loading is fixed at 0.2 mol CO_2/mol MEA for all the cases. The solvent flow rate was estimated based on the 90 % CO_2 capture rate, and also it has been verified by the literature (Agbonghae et al., 2014). Further, the solvent flow rate varies from 404 kg/hr at no injection of the CO_2 to 600 kg/hr at CO_2 injection of 125 kg/hr.

The effect of the CO_2 enrichment is clear from the results as shown in Figure 7 and Figure 8. The effect of the CO_2 injection on the specific reboiler duty is shown in Figure 7 and it is observed that the specific reboiler duty decreases with an increase in the CO_2 concentration in the flue gas. The CO_2 concentration increases by a factor 3.5 times in comparison to the CO_2 concentration without injection, which results in the specific reboiler duty decrease by 20.5 % for CO_2 injection at the rate of 125 kg/hr. The effect of the CO_2 injection on the specific reboiler duty along with CO_2 content in flue gas for the pilot-scale CO_2 capture plant coupled with MGT is shown in Figure 7. The specific reboiler duty decreases from 10.2 to 8.1 GJ/tCO_2 for CO_2 concentration increase from 1.42 to 4.91 mol%, respectively. This results in a drop of 5.9 % in the specific reboiler duty per unit percentage increase in CO_2 concentration, based on a linear fit equation. Also the drop in specific reboiler duty was observed experimentally for the similar pilot-scale CO_2 capture plant (Akram et al., 2016; Akram et al., 2015). The drop of 7.1 % per unit percentage increase in CO_2 concentration was observed when the CO_2 concentration was increased from 5.5 to 9.9 mol% (Akram et al., 2016). Similarly, the drop of 7.5 % per unit percentage decrease in the CO_2 concentration was observed when the CO_2 concentration was increased from 4.5 to 11.5 mol% (Akram et al., 2015). In addition, the drop of only 2.9 % per unit percentage decrease in CO_2 was observed when the CO_2 concentration increases from 5.46 to 13.37 mol% with a decrease in the specific reboiler duty from 5.01 to 3.85 GJ/tCO_2, respectively (Notz et al., 2012). Also, the specific reboiler duty of 8.3 GJ/tCO_2 at 4.5 mol% CO_2

concentration in the literature (Akram et al., 2015) through experimentation validates the estimated specific reboiler duty of 8.1 GJ/tCO_2 at 4.91 mol% CO_2 concentrations in the present paper. Further, the present sharp drop in specific reboiler duty is in line with the literature reported trend (Li et al., 2011a) and higher than the reported drop (Ali et al., 2016) in the specific reboiler duty for a commercial-scale natural gas fired power plant coupled with a CO_2 capture plant with EGR.

The specific reboiler duty decreases due to the higher partial pressure of the CO_2 at the higher CO_2 injection rate of 125 kg/hr. Since, the flowrate of the flue gas remains constant, the amount of the CO_2 in the constant flue gas increases and this results in a large driving force resulting in more CO_2 to be absorbed by the solvent and then regenerated at lower specific reboiler duty. Therefore, the higher CO_2 partial pressure results in a higher driving force with a higher CO_2 loading in the solvent, hence favouring the capture reaction (Li et al., 2011a). Since, the present pilot-scale CO_2 capture facility is of 8 m packing height with a random type packing, the specific reboiler duty estimated for such a low range of the CO_2 concentration is the same as that predicted in the literature (Akram et al., 2016; Akram et al., 2015; Mangalapally et al., 2009; Morken et al., 2014; Notz et al., 2012; Thimsen et al., 2014) for similar kinds of facilities, but keeping in mind their variable operating conditions including the L/G ratio, packing height, absorber inlet temperatures, lean solvent loading and strength and stripper pressure.

With the increase in CO_2 composition, amine loading increases and also the difference between rich and lean loading increases. This indicates that the amount of the CO_2 absorbed also increases. The increased loading results in lesser steam being required in the stripper, so the regeneration in the stripper is becoming easier with the reduced energy requirement in the reboiler for the increased CO_2 composition. The increased rich loading results in the increased cyclic capacity and with it the specific reboiler duty decreases. The rich amine loading increases by 42 % for maximum CO_2 injection of 125 kg/hr. The effect of the CO_2 injection on the rich loading along with CO_2 content in flue gas for the pilot-scale CO_2 capture plant coupled with MGT is shown in Figure 8.

In conclusion, the power generation system with CO_2 enhancement integrated into a CO_2 capture system will suffer a small reduction in efficiency as reported in the literature. The US Department of Energy Report (NETL, 2010) reported a number of case studies for different commercial-scale gas turbines with and without EGR being coupled to a CO_2 capture system. They found approximately 0.5 % point improvement in efficiencies when EGR is applied. Further, NGCC with a CO_2 capture system results in 8.1 % reduction in the total thermal energy consumption in the reboiler of the CO_2 capture plant when EGR is applied (Li et al., 2011b). It is found that the efficiencies are always higher by 2 to 3 % points than without the EGR system (Canepa et al., 2013).

4. Conclusions

This study has investigated the effect of CO_2 injection and EGR on the behaviour of the MGT coupled with the pilot-scale CO_2 capture plant. The following conclusions can be made:

- The process system analysis assists in better understanding of the process details of the system under consideration. The detailed analysis, modelling and simulation outcomes are an accurate demonstration for the evaluation of the optimized micro gas turbine EGR mode configuration with pilot-scale CO_2 capture plant.
- The increase in CO_2 composition in the exhaust gas is almost a factor 3.5 and 2.2 times for CO_2 injection in MGT and EGR, respectively. The CO_2 injection results in the CO_2 concentration increase to 5.04 mol% from 1.48 mol%, which will benefit on its integration with pilot-scale CO_2 capture plant.

- The EGR results in the CO_2 concentration enhancement to 3.5 mol% from 1.6 mol% in the base case with a 55 % decrease in the exhaust gas flow, which will benefit its integration with the carbon capture system.
- The increased CO_2 content due to EGR, affects the thermodynamic properties of the fluid at different locations of the MGT.
- The enhancement of the CO_2 concentration due to the injection of CO_2 in MGT results in lower specific reboiler duty by 20.5 % for the pilot-scale CO_2 capture plant.

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Appendix A

Table A. 1: Comparison of the present model with the published MGT models using different process simulation software's.

	Parente et al., 2003	Kautz and Hansen, 2007	Delattin et al., 2008	De Paepe et al., 2013	Majoumerd et al., 2014	Ali et al., 2015	Manufacturer Data (Turbec, 2000)	Present Model
Electrical power [kW_e]	101	100	100 KJ/kg	100	100	100	100	100
Thermal output [kW_{th}]	N/A	N/A	N/A	186.7	170	153.3	165	165
Electrical efficiency [%]	27.8	30	30.8	30.7	31	32.1	30	30.2
Overall efficiency [%]	N/A	N/A	N/A	57.3	84	81.2	80	79.9
CO_2 in flue gas [mol%]	N/A	N/A	N/A	N/A	1.6	1.6	N/A	1.6
O_2 in flue gas [mol%]	N/A	N/A	N/A	N/A	N/A	17.3	N/A	17.5
Flue gas flow rate [kg/s]	N/A	0.79	0.8	0.735	0.771	0.7	0.80	0.8
Fuel consumption [kW]	44 MJ/kg	333	N/A	8.13 g/s	321	312	333	331
Rotational speed [rpm]	N/A	N/A	100%	69679	69675	N/A	70000	70000
Pressure ratio	N/A	4.5	4.3	4.6	4.4	4.5	4.5	4.5
Turbine inlet temperature [^oC]	950	950	930	925.4	948	945	950	948
Turbine outlet temperature [^oC]	N/A	650	640	645	650	644	650	645
Compressor discharge temperature [^oC]	N/A	214	N/A	210.1	N/A	216.9	N/A	212.4
Software Used	In-house Code	Aspen Plus	Aspen Plus	Aspen	IPSEpro	Aspen HYSYS	N/A	Aspen HYSYS

Table 1: Natural gas composition and calorific value.

Component	Mole Percentage
CH_4	90.6
C_2H_6	5.1
C_3H_8	1.3
i-C_4H_{10}	0.2
n-C_4H_{10}	0.2
CO_2	1.4
N_2	1.1
Net Calorific Value (kJ/mol)	897.3

Table 2: Air composition.

Component	Mole Percentage
N_2	77.3
O_2	20.7
Ar	0.9
CO_2	0.03
H_2O (relative humidity, %)	60

Table 3: Performance of the MGT base case model at ISO conditions.

Parameter	Manufacturer data (Turbec, 2000)	Model results without maps (Ali et al., 2015b)	Model results with maps
Electrical power [kW_e]	100	100	100
Thermal output (hot water) [kW_{th}]	165	153	165
Electrical efficiency [%]	30	32.1	30.2
Overall efficiency [%]	80	81.2	79.9
CO_2 in flue gas [mol%]	N/A	1.6	1.6
O_2 in flue gas [mol%]	N/A	17.3	17.5
Flue gas flow rate [kg/s]	0.80	0.7	0.8
Fuel consumption [kW]	333	312	331
Rotational speed [rpm]	70000	N/A	70000
Pressure ratio	4.5	4.5	4.5
Turbine inlet temperature [^oC]	950	945	948
Turbine outlet temperature [^oC]	650	644	645

Table 4 Performance of the EGR cycle at ISO conditions.

Parameter	Model results
Electrical power [kW_e]	100
Thermal output (hot water) [kW_{th}]	185
Electrical efficiency [%]	28
Overall efficiency [%]	81
CO_2 in flue gas [mol%]	3.5
O_2 in flue gas [mol%]	13.8
Flue gas flow rate [kg/s]	0.4
EGR percentage [%]	55
Rotational speed [rpm]	70000
Turbine inlet temperature [^oC]	922
Turbine outlet temperature [^oC]	645

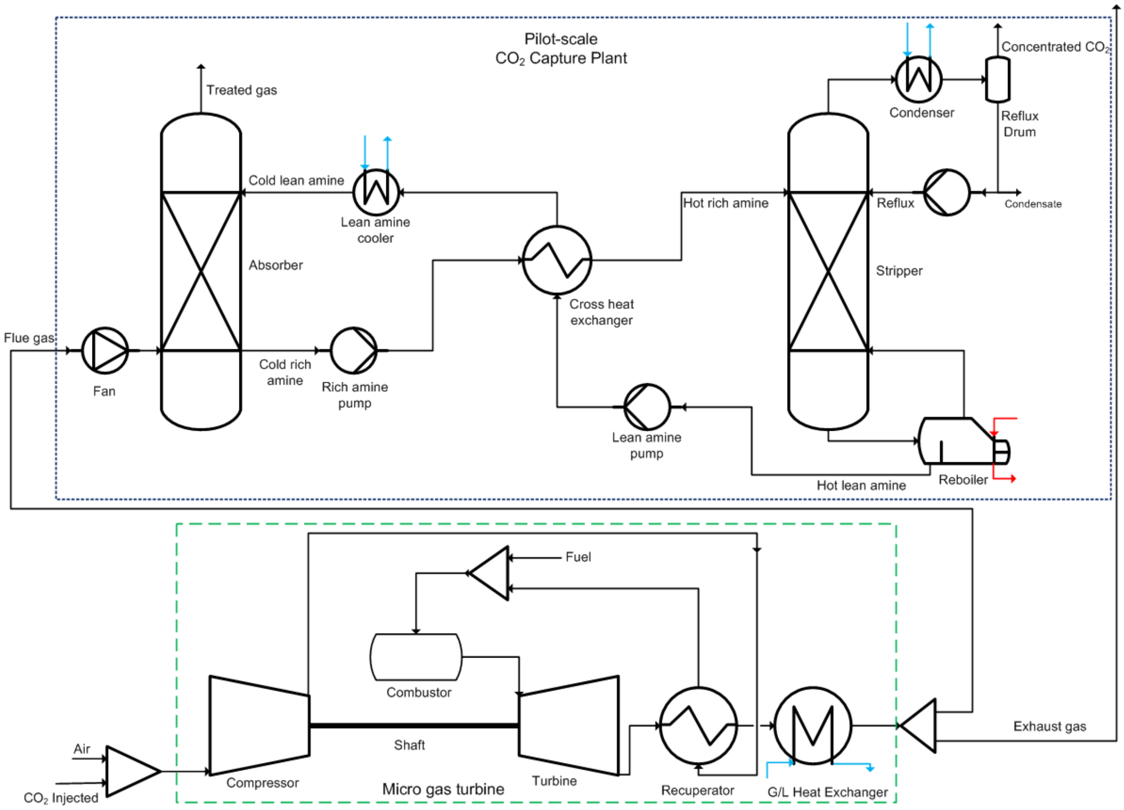


Figure 1: Schematic of the micro gas turbine with CO_2 injection coupled with the pilot-scale CO_2 capture plant.

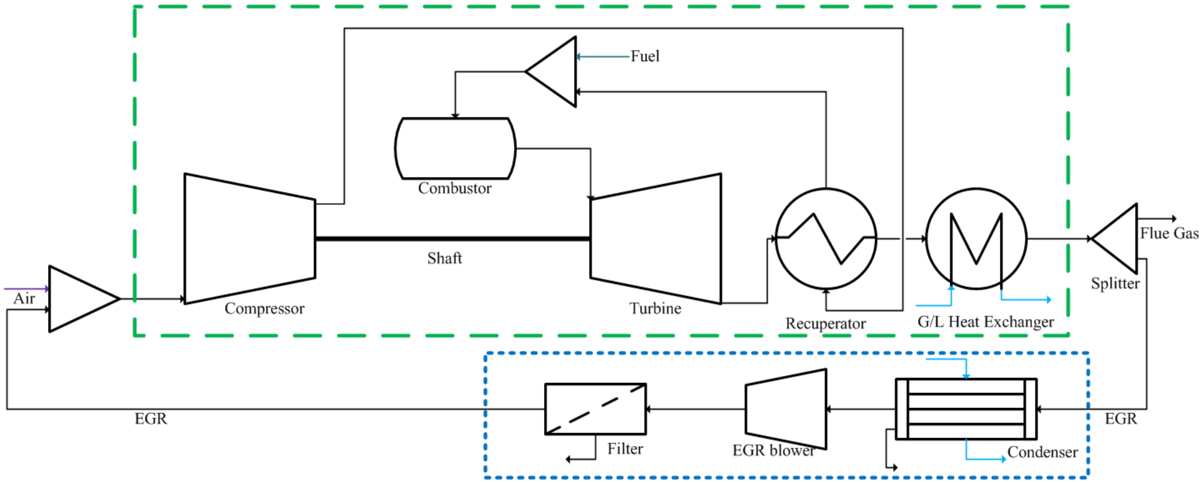


Figure 2: Schematic of the micro gas turbine with exhaust gas recirculation.

(a)

(b)

(c)

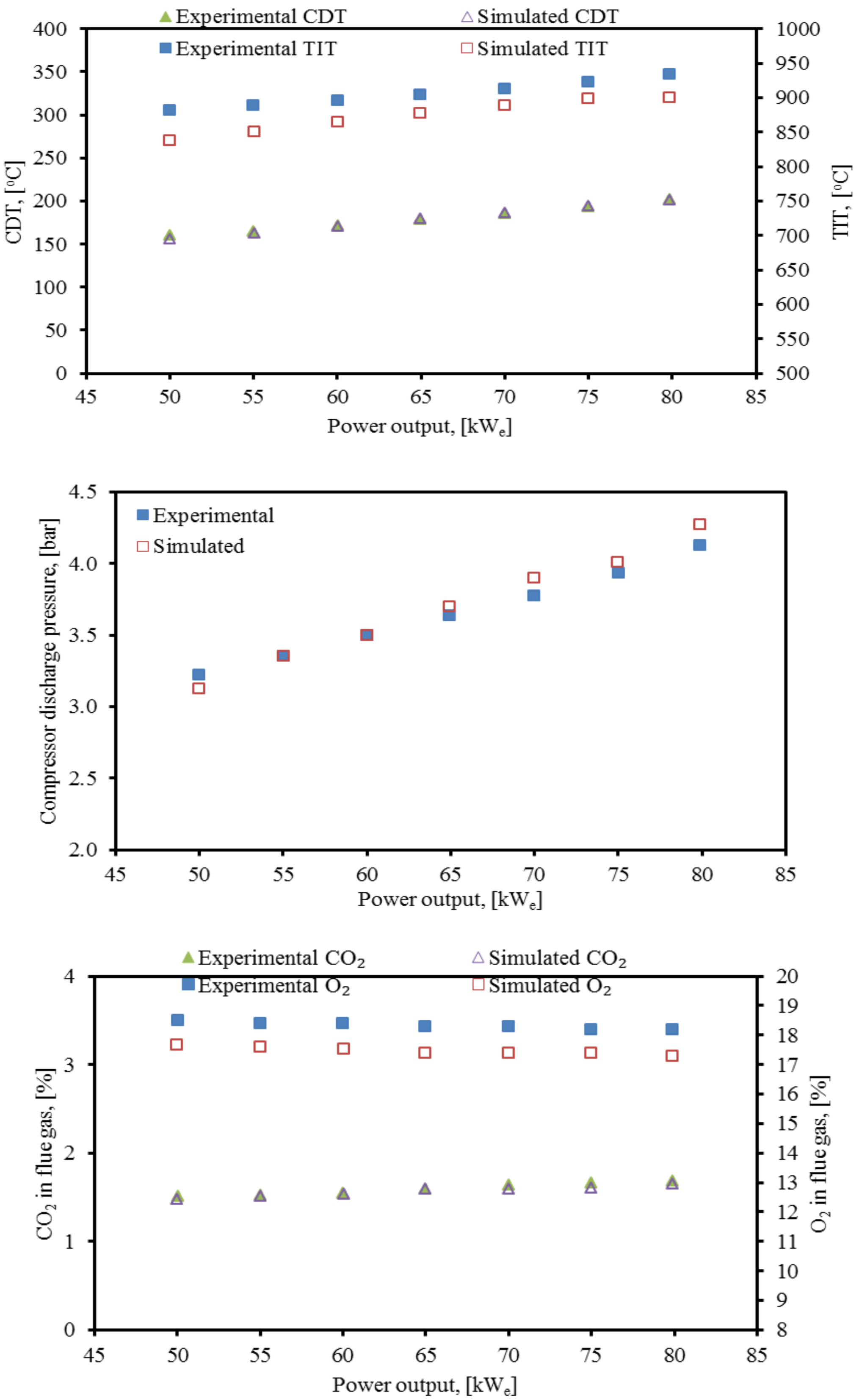


Figure 3: Measured and simulated results for MGT (a) Compressor discharge temperature and turbine inlet temperature; (b) Compressor discharge pressure; and (c) CO_2 and O_2 molar composition in the flue gas.

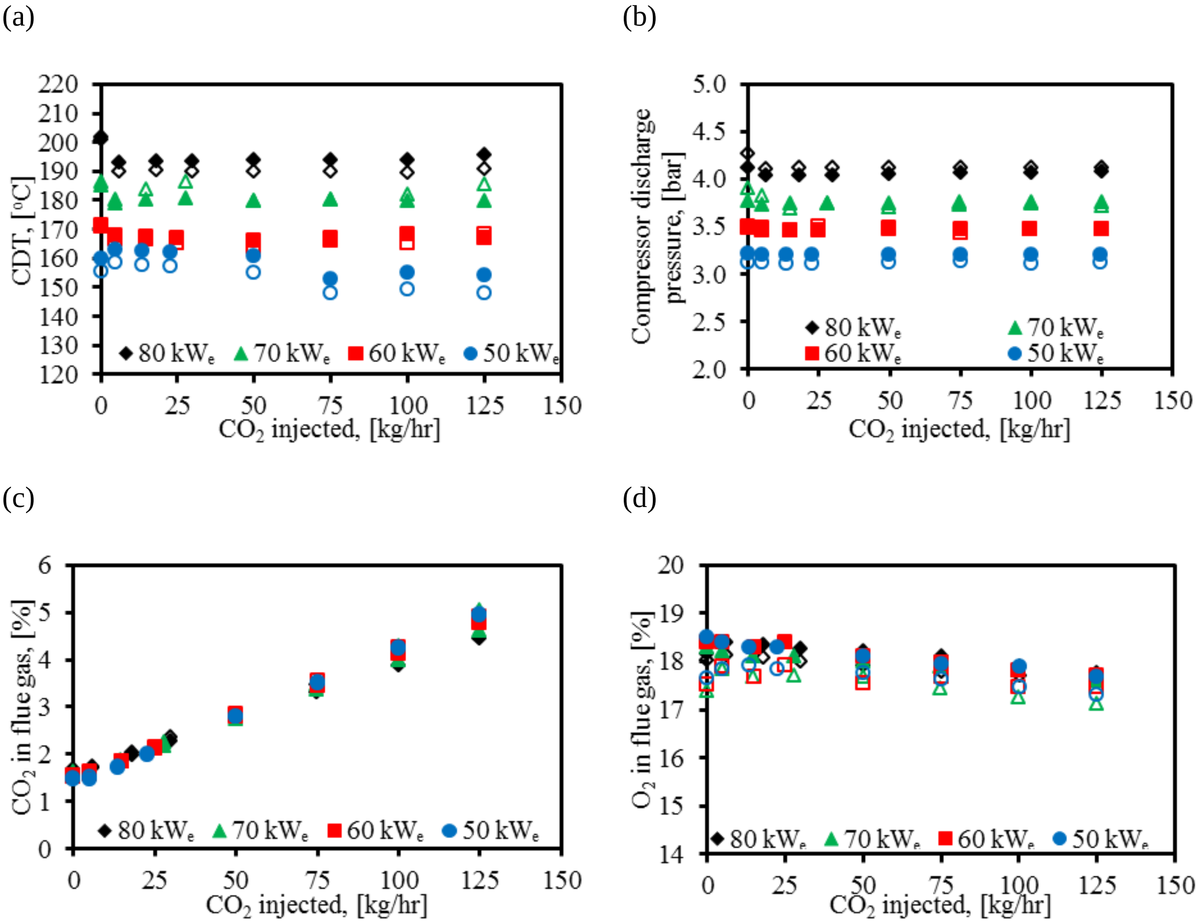
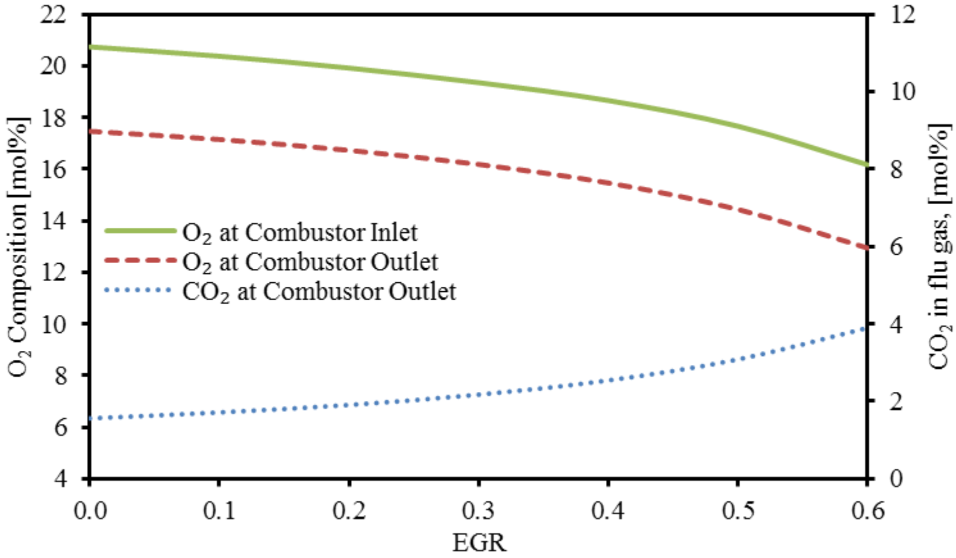


Figure 4: Measured (filled) as a function of the simulated (hollow) results for CO_2 injection in MGT (a) Compressor discharge temperature; (b) Compressor discharge pressure; (c) CO_2 molar composition in flue gas; and (d) O_2 molar composition in flue gas.

(a)



(b)

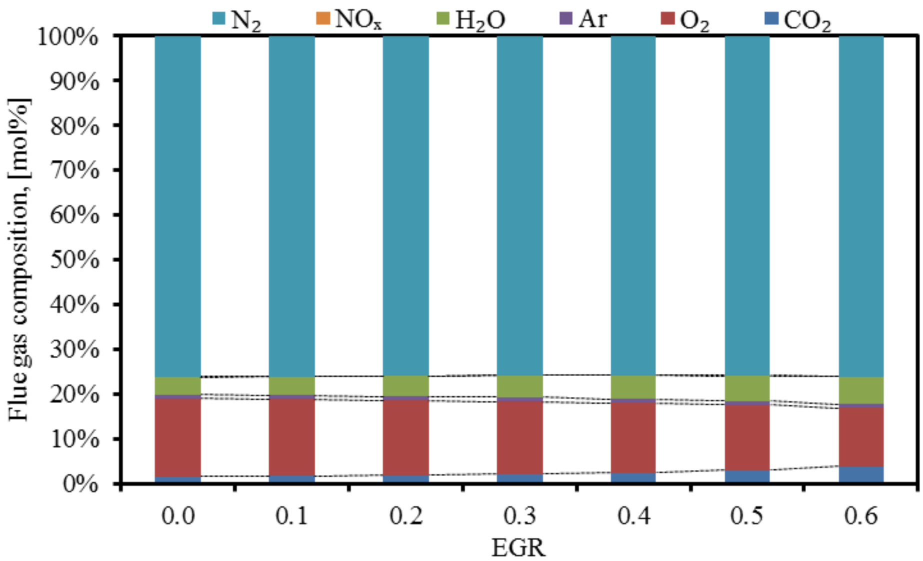
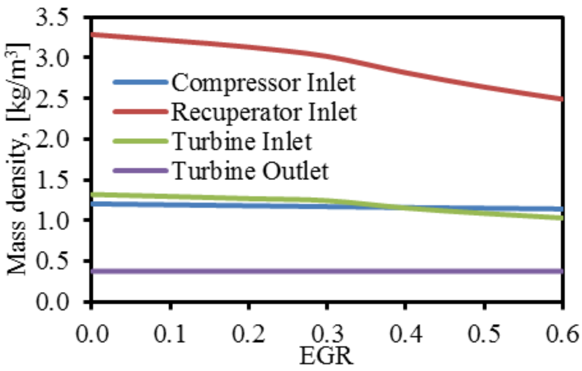
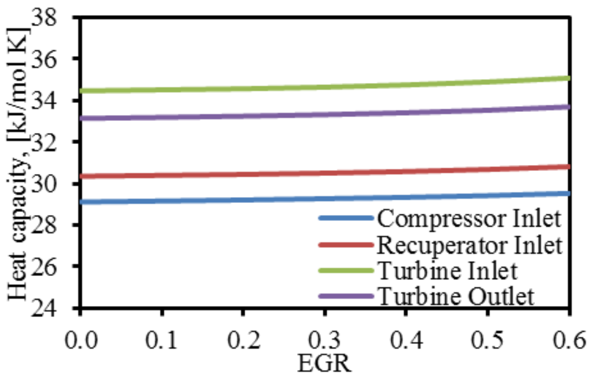


Figure 5: Effect of the EGR ratio on (a) O_2 and CO_2 molar composition at combustor outlet and O_2 molar composition at combustor inlet; and (b) Flue gas composition.

(a)



(b)



(c)

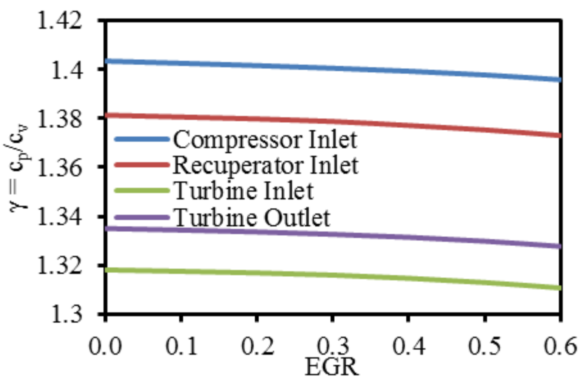


Figure 6: Effect of EGR on the thermodynamic properties of working stream at different locations of MGT (a) Mass density as a function of EGR; (b) Heat capacity as a function of EGR; and (c) Isentropic coefficient as a function of EGR.

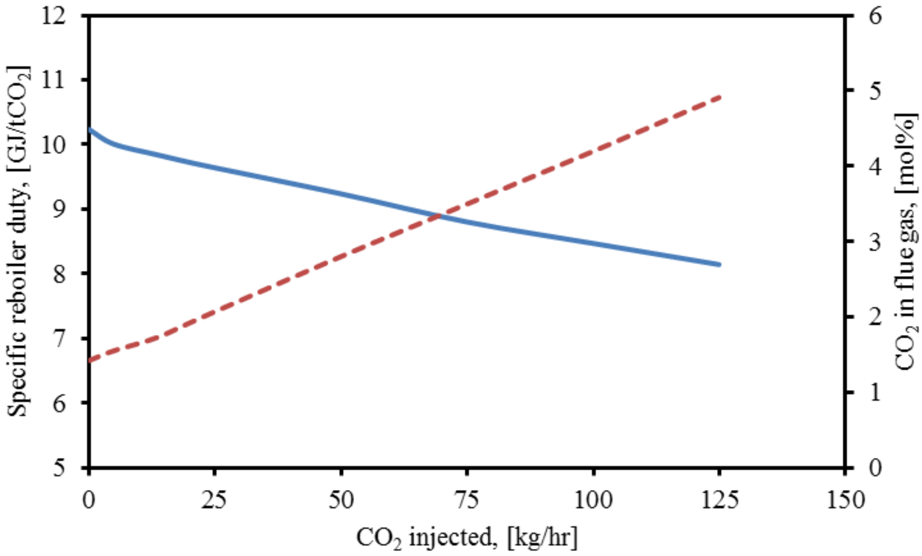


Figure 7: Effect of CO_2 injection on the specific reboiler duty (solid line) along with CO_2 in flue gas (dashed line) of the pilot-scale CO_2 capture plant.

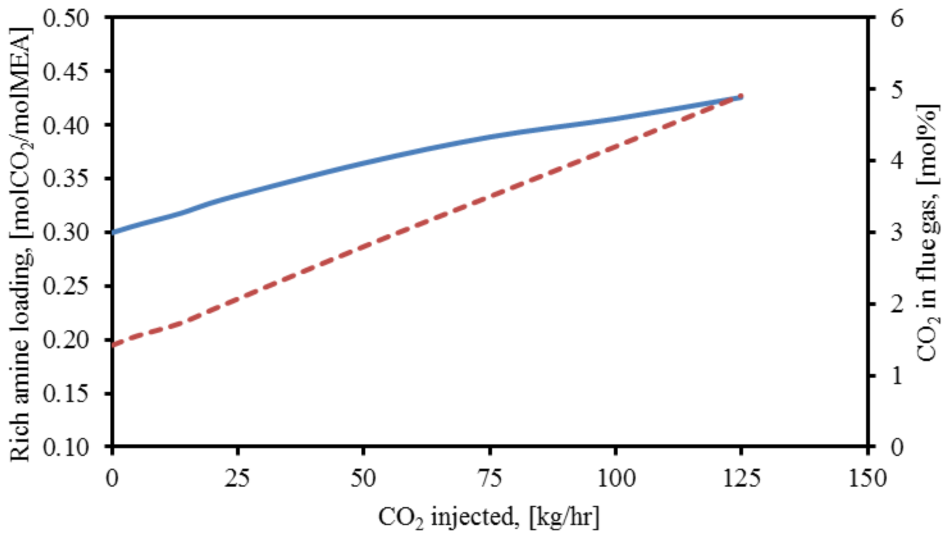


Figure 8: Effect of CO_2 injection on the rich amine loading (solid line) along with CO_2 in flue gas (dashed line) for the pilot-scale CO_2 capture plant.