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Carbon capture on a micro gas turbine: assessment of the performance

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Abstract

From all fossil fuel power production routes, the electricity produced with Gas Turbines (GTs) running on natural gas has the lowest CO_2 emissions. However, if we want to move towards full carbon clean power production, the CO_2 in the exhaust must be captured. The energy impact of a Carbon Capture plant (CC) applied to the micro Gas Turbine (mGT) still remains unclear because few quantitative analyses are available. The low concentration of CO_2 in the GT exhaust gas is disadvantageous from a CC point of view. Exhaust Gas Recirculation (EGR) is one of the technologies used to increase the CO_2 concentration in the GT flue gas. It is potentially an effective method to reduce the high energy-penalty caused by the carbon capture. A typical capture method is an absorber–stripper system where the absorbent is commonly a 30wt% aqueous monoethanolamine (MEA) solution. In this work, a Turbec T100 mGT coupled with a chemical-absorption plant is considered. The entire plant has been simulated using Aspen Plus®. Simulation results show that the specific reboiler duty is rather constant (around 4.3 MJ/kgCO_2) when varying the electrical power output of the mGT. The cycle performance is strongly affected by the thermal energy requirement for the stripping process, decreasing the global electric efficiency around 6.2 absolute percentage points. These results could be a starting point for future energy integrations between the mGT and the CC plant.

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Keywords: micro Gas Turbine (mGT); Carbon Capture (CC); Exhaust Gas Recirculation (EGR); Aspen Plus® simulations.

1. Introduction

The International Energy Agency (IEA) has recently announced the target of CO_2 neutrality by 2100 to

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limit the effects of climate change [1]. Carbon Capture, Use and Storage (CCUS) should be used globally in the transition period towards this fully renewable energy supply, to fulfil the need of energy and the need for a carbon clean economy. In addition, since electricity storage is still lacking, certain flexibility from the electricity production is still highly recommended [2]. In this context, Gas Turbines (GT) cycles are good candidates to achieve this flexible production. Although the CO_2 emissions from natural gas combustion are significantly lower than other fossil fuel power productions, the need to mitigate Greenhouse Gas (GHG) emissions is unavoidable. The necessity to abate CO_2 emissions will thus drive the deployment of Carbon Capture Use and Storage for GT. Chemical absorption using amine solvents is widely used and commercially mature for separating CO_2. For MonoEthanolAmine-based (MEA), the main disadvantages arise from the high amount of thermal energy needed to regenerate the solvent and extract the CO2, especially when its concentration in the exhaust gas is low. The CO_2 concentration can however be increased by performing Exhaust Gas Recirculation (EGR) on the GT [3]. Applying this technology, three main advantages can be achieved: lower NO_x emissions, lower exhaust mass flow rate and higher CO_2 concentration [4]. These last two consequences will result respectively in lower costs and lower efficiency penalties of the Carbon Capture (CC) plant.

The paper is organized as follow: the simulation approach is first presented. The plants considered and described in this paper are the mGT Turbec T100 present at the Vrije Universiteit Brussel (VUB) [5] and the Pilot-scale Advanced Capture Technology (PACT) facilities at the UK Carbon Capture and Storage Research Centre (UKCCSRC) [6]. The results of the simulations are presented, giving an overview of the impact of the CC on the global performance of the mGT.

2. Simulation Approach

The model of the mGT was coupled with the one of the CC unit as represented in Fig.1. The main specifications of the plants are summarized in Table 1. The complete mGT and CC plant analyses are available respectively in De Paepe et al. [7] and Agbonghae et al. [8]

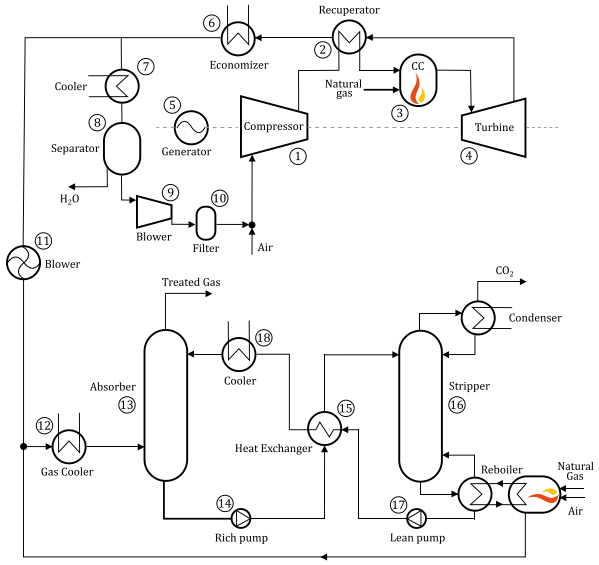


Fig.1: The fraction of the mGT flue gas which is not recirculated in the compressor inlet is transferred to the chemical absorption plant in which the CO_2 extraction takes place

Table 1. Main design specifications of the mGT and CC plant

mGT	Electrical Power Output	[kW]	100
	Thermal Power Output	[kW]	153
	Electrical efficiency	[%]	30
	Pressure Ratio	-	4.35
	$\%CO_2$ (Standard)	[%]	1.6
	Turbine Outlet Temperature	[°C]	645
	EGR ratio	-	0.62
	$\%CO_2$ (with EGR)	[%]	4.3
CC	Absorber dimensions	[m x m]	6 x 0.6
	Stripper dimensions	[m x m]	6 x 0.45
	Packing Type		IMTP
	Packing Size	[mm]	38

2.1. Turbec T100

The Turbec T100 is a single-shaft recuperative mGT (Fig.1). The air is first compressed in a variable speed radial compressor (1). The compressed air passes through a recuperator (2) where it is preheated by the exhaust gas coming from the turbine. The compressed air is further heated in the combustion chamber by burning natural gas (3). The combustion gases, which leave the combustor at nominal temperature of 950°C, expand over the turbine (4) to deliver the necessary power to drive the compressor. The remaining power on the shaft in converted into electrical power by a variable speed generator (5). Moreover, the Turbec T100 is also equipped with a gas-water heat exchanger, which recovers the remaining heat in the exhaust gas after the recuperator (6). The EGR stream is simulated by splitting part of the exhaust gas, cooling the exhaust down (7) to maintain a high compression efficiency, separating the condensed water (8), installing a blower (9) to provide the necessary pressure increase and, finally, adding a filter (10) before the compressor inlet.

2.2. PACT CC plant

The solvent-based CO_2 capture plant is composed of two columns, one packed absorber and one packed stripper (Fig.1). The flue gas is fed in the bottom of the absorber (13) by a blower (11), while the lean solvent enters at the top. As the liquid and the gas phases interact, the concentration gradient at the liquid/gas interface drives CO_2 to the liquid phase. Subsequently the rich solvent is pumped first into the rich-lean heat exchanger (15), where it is heated to higher temperature by the lean solvent from the stripper bottom. In the stripping column (16), the rich solvent is regenerated. The vapour at the desorber top is led into the condenser where most of the water is removed so that almost pure CO_2 is obtained. The heat duty of the stripper reboiler is supplied by pressurized hot water. The regenerated solvent, after being pumped into the rich-lean heat exchanger, is further cooled in an air-cooled plate cooler (18).
At the top of the absorber and stripper columns, wash columns are installed to remove entrained droplets of solvent carried over by the flue gas using demineralized water. The wash columns have a relatively low energy impact on the CC plant, so they have been neglected in this analysis.

2.3. Modelling

The dry mGT with the EGR channel has been modelled in Aspen Plus v8.8® [9] as described in [10] and the model was validated with experimental data obtained from the Turbec T100 mGT test rig installed at the Vrije Universiteit Brussel (VUB) [10]. The relative amount of recirculating exhaust gas is expressed as:

$$EGR_{ratio} = \frac{\dot{V}_{EGR\ stream}}{\dot{V}_{Exhaust\ gas}} \tag{1}$$

where $\dot{V}$ is the volumetric flow rate.
The EGR_{ratio} has been adjusted to obtain a concentration of oxygen in the combustor inlet of 16%. In fact, although a premixed flame can be sustained at O_2 concentration as low as 14 mol%, the levels of Unburned Hydrocarbons (UHC) and CO become excessively high when the O_2 concentration goes below 16 mol% [11]. In these conditions, the resulting EGR_{ratio} is around 0.61. As for the CC plant, it has been modelled based upon the model of the Pilot-scale Advanced Capture Technology (PACT) facilities at the UK Carbon Capture and Storage Research Centre (UKCCSRC) described by Agbonghae et al. [8]. The Electrolyte Non-Random Two Liquid (Electrolyte NRTL) thermodynamic model for liquid phase electrolyte properties and PC-SAFT equation of state for vapour phase are used. In open literature, these thermodynamic model

for CO_2 absorption in aqueous MEA solution are extensively validated against sets of experimental data [12,13]. The Aspen Plus® RadFrac model was used to simulate the absorption and stripping columns and the Rate-Based MEA model is adopted to provide a rate-based rigorous simulation of the two processes. Although the model has been designed to reproduce the Agbonghae model, some important modifications have been made in order to maintain the same fluid dynamics behaviour inside the columns. The mass flow of the flue gas exiting the mGT is bigger than the mass flow rate studied in Agbonghae's paper and for this reason the diameter of the absorber and the stripper have been changed to maintain the same F-factor, which is defined as:

$$F_{factor} = v_{fg} \cdot \rho_{fg}^{0.5} \quad (2)$$

where v_{fg} is the velocity of the flue gas and ρ_{fg} is the density of the flue gas.

Furthermore, the mass transfer coefficient method and the interfacial area method adopted in this current model are Hanley IMTP (2010) [14], considered more adequate for unstructured packing. In Agbonghae's paper two different experimental campaigns were discussed. We use the first campaign as reference point for our model validation where the concentration of CO_2 is 4.48%. The comparison between experimental results and simulation results from Agbonghae's paper and the current model results for the CO_2 capture plant is given in Table 2. As may be seen, the current model results are in good agreement with the Agbonghae's model results.

3. Results

Under the condition of 90% CO_2 removal rate, an optimum Liquid/Gas (L/G) ratio of about 1.2 was found (Fig.2). This value corresponds to a regeneration energy of about 4.38 MJ/kgCO_2. The L/G ratio has a

Table 2. Comparisons between Agbonghae experimental data, Agbonghae numerical model and the current numerical model

Model Inputs	Units	Agbonghae experimental data	Agbonghae model / Current model	
Flue gas mass flow	[Nm3/h]	207.3±1.8	207.3	
Flue gas temperature	[°C]	41.3±0.5	41.3	
Flue gas pressure	[barg]	0.17±0.02	0.17	
%CO2 in flue gas	[vol%]	4.48±0.11	4.48	
CO2 in flue gas	[kg/h]	18.23±0.1	18.23	
Solvent mass flow	[kg/h]	515.6±5.4	515.6	
Lean solvent concentration	[wt.%]	28.2±0.1	28.2	
Lean solvent temperature	[°C]	39.9±0.9	39.9	
Lean Loading	[molCO2/molMEA]	0.246±0.001	0.246	
Stripper condenser pressure	[barg]	0.2±0.02	0.2	
Results				
Rich loading	[molCO2/molMEA]	0.409±0.001	0.416	0.416 (0%)*
CO2 captured	[kg/hr]	16.47±0.4	16.98	16.75 (-1.3%)*
CO2 capture efficiency	%	90.35±3	93.14	93.14 (0%)*
Specific Reboiler Duty	[MJ/kgCO2]	5.92±0.8	5.47	5.64 (+3%)*

*Relative difference between the current model results and Agbonghae's results

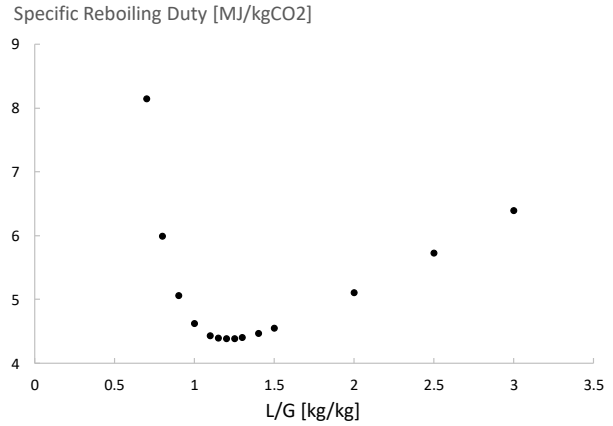
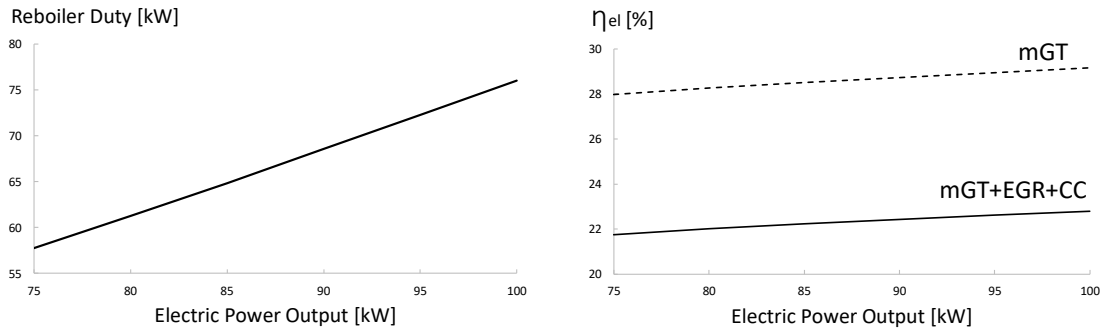


Fig. 2: The specific reboiler duty is very sensitive to the variation of the L/G ratio

significant impact on the performance of the CO_2 capture plant. For the same conditions (CO_2 concentration, removal rate, lean loading), similar results were obtained by Agbonghae et al [8]. significant impact on the performance of the CO_2 capture plant. For the same conditions (CO_2 concentration, removal rate, lean loading), similar results were obtained by Agbonghae et al [8]. The increase in the specific reboiler duty at lower L/G ratios than the optimal ones is related to the high amount of energy demand to regenerate the solvent, due to the high concentration of CO_2. The increase in duty when increasing the L/G ratios above the optimum is due to the energy requirement to heat up the higher solvent flows [15]. Maintaining the optimal L/G ratio of 1.2, simulations have been carried out varying the power output of the new mGT. The thermal energy requirement to regenerate the solvent shows a quasi-linear relation with the electric power output of the mGT (Fig.3a). For part load, the reboiler duty decreases since the mass flow rate of flue gas decreases considerably (around -19% for a power output of 75 kW). Comparing the thermal inputs of these two plants, the reboiler duty is around 22% of the thermal energy input of the mGT for the whole span of electrical power. Although the reboiler duty has a wide variation range, the specific reboiler duty (MJ per kg of CO_2 captured) remains quite constant, between 4.38 MJ/kgCO_2 for the nominal power conditions to 4.25 MJ/kgCO_2 for a power output of 75 kW. In fact, for part load, the mass flow rate of flue gas is lower than the nominal one, so the CC plant is oversized for these conditions and the capture efficiency increases. Finally, the electric efficiency of the whole plant has been computed and compared to the traditional mGT efficiency (Fig.3b).



(a) (b)

Fig. 3: (a) The reboiler duty has a quasi-linear dependence with the power output, although the specific reboiler duty is quite constant; (b) The electric efficiency of the entire plant is around 6.2 percentage points lower than the traditional mGT efficiency

The new efficiency includes the electric power output of the mGT, the electrical power requirement of all the auxiliaries (pumps and blowers) and all the thermal inputs of the two plants (thermal input of mGT and the reboiler duty). Comparing the current electric efficiency to the efficiency of the traditional mGT, the efficiency loss is rather constant varying the power output, with a value of 6.2 absolute percentage points.

4. Conclusions

In this study, the impact of the CC plant on the performance of the mGT cycle has been investigated by means of Aspen Plus®. The energy impact of the CC plant applied to the micro Gas Turbine (mGT) still remains unclear because few quantitative analyses are available. For this reason, these simulations provide detailed information on the optimization of the CO_2 capture plant and on the mGT performance along with the impact of varying the electric power output. Simulation results show that the specific reboiler duty is rather constant (around 4.3 MJ/kgCO_2) varying the electric power output of the mGT and the thermal energy requirement for the solvent regeneration significantly alters the cycle performance, decreasing the global electric efficiency around 6.2 percentage points. Therefore, a more efficient energy integration between the mGT and the MEA-absorption capture plant should be considered, for instance using the heat in the exhaust gas to partially compensate the reboiler duty.

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Biography

Simone Giorgetti is a joint PhD student between the Université Libre de Bruxelles and the Université de Mons since October 2015. He is also a member of the BURN joint research group.