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# Carbon Clean Combined Heat and Power Production from micro Gas Turbines: Thermodynamic Analysis of Different Scenarios

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## Abstract

With the current shift towards more decentralized power production, micro Gas Turbines (mGTs) appear as a promising technology for small-scale Combined Heat and Power (CHP) production. Nevertheless, if we want to move towards a carbon-clean power production, the $CO_2$ in the exhaust gas must be captured. In this context, mGTs coupled with a Carbon Capture (CC) plant might be a good candidate, however there is still an energy penalty. Especially when there is no demand for heat and the mGT is only producing electrical power, this penalty becomes a major drawback. In this case, a possible solution is waste heat recovery in the system to increase the efficiency or to reduce the energy penalty, but few analyses are available to assess the optimal solution. In this paper, we aim at identifying the optimal strategy for carbon clean mGT operation in CHP applications for different operation scenarios: full CHP mode and operation with no thermal load. The effect of different technological measures such as humidification and internal heat recoveries has been investigated. The goal of these simulations was to evaluate the most efficient strategy for each thermal scenario of the mGT by testing different combinations of the previous measures. Results show that full CHP operation of the mGT with carbon capture has still the highest performance. Nonetheless, if the thermal demand is zero, conversion into mHAT and heat recovery for the stripping process result in a sensible reduction of the CC plant energy penalty, moving closer to the efficiency of traditional mGTs. Future work would include a more detailed analysis concerning mixed operation (part-load heat demand) of the mGT and an exergy analysis to identify where more waste heat can be recovered.

*Keywords:* micro Gas Turbine (mGT), micro Humid Air Turbine (mHAT), Carbon Capture (CC), Aspen Plus® simulations

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Nomenclature

| | |
|---|---|
| CC | Carbon Capture |
| CCUS | Carbon Capture Use and Storage |
| CHP | Combined Heat and Power |
| EGR | Exhaust Gas Recirculation |
| mGT | micro Gas Turbine |
| mHAT | micro Humid Air Turbine |

## 1. Introduction

The target of carbon neutrality set by the IEA would require a broader utilisation of low carbon technologies by 2100. Despite an increasing fraction of renewable energy sources in power generation, its growth is not large enough to replace our consumption of fossil fuel by the end of this century [1]. The expansion of small-scale Combined Heat and Power (CHP) systems, in a more decentralized energy system, may help to attain sensible gains in energy efficiency by simultaneously generating electricity and heat [2]. Micro Gas Turbines (mGTs) (with electrical power outputs of up to 200kWe) running in CHP mode can offer total energy efficiencies of around 80%. However, if we want to move towards a carbon-clean production, the $CO_2$ in the exhaust gas must be captured: Carbon Capture Use and Storage (CCUS) provides a global solution in the transition period towards this fully renewable energy supply.

The concept presented in this paper is in the context of the energy transition where a closed loop would be needed for the $CO_2$ building block when integrated with storage of renewable energy. Since energy production is gradually shifting from centralized to more distributed levels, the development of a simple and efficient way to capture $CO_2$ also at smaller units appears necessary [3]. In this framework, mGT cycles coupled with a Carbon Capture (CC) unit are good candidates to achieve small-scale and load-flexible carbon clean power production, but only a few numerical and experimental analyses are available which assess their real potential [3]. Additionally, it is important to note that the high efficiency of CHP-mGTs is only true when the heat in the exhaust gases is used for external heating purposes. Whenever there is no or low heat demand, the heat must be discarded and the CHP efficiency is therefore reduced to the electrical efficiency, having a severe impact on the economic feasibility of the mGT in CHP [2]. In addition, the constraint of a carbon-clean production further reduces the energy efficiency and the economic feasibility of the plant [4], due to the energy penalty of the CC unit.

For this reason, the aim of this paper is to investigate state-of-the-art technological measures to be applied to the mGT to improve the load flexibility of the system and to limit the energy penalty of the CC unit. First of all, Exhaust Gas Recirculation (EGR) appears as a simple and attractive solution to retrofit existing mGT systems to CC-compatible facilities. Its application may offer three main advantages: higher $CO_2$ concentration and lower flue gas mass flow rate (to reduce both capital and operative costs of the CC unit) and lower $NO_x$ emissions [5]. More specifically, whenever there is no requirement for external heating, the thermal energy can be used for other purposes. This waste heat might be used directly to reduce the reboiler heat demand for the stripping process, reducing the energy penalty or it might be used to heat up water that will be used to humidify the mGT cycle and by doing so improving the electrical efficiency.

This paper is the continuation of previous work about the study of mGTs coupled with a CC unit [4]. While in the previous work, the mGT was directly coupled with a CC unit neglecting any possible energy integration of the two plants, the current paper has made a step forward by optimizing this novel system, based on different heat demands. In this preliminary analysis, two operating scenarios, typical for small-scale CHP units in residential applications, are studied: 1) the facility is operated in full CHP mode and 2) the case in which there is no heat demand and the waste energy of exhaust gas is re-used in the system to increase the electrical efficiency. Different combinations of the previously mentioned technological measures are applied to the mGT unit and their impact on the cycle performance are compared to define the best layout for each scenario.

The paper is organized as follow: the mGT plant coupled with a solvent-based CC unit is firstly presented. Thereafter, a list of technological measures which might be applied to the traditional plant are described in detail. In conclusion, numerical results of the model are discussed comparing different performances of different solutions.

## 2. Methodology

The performance of a mGT coupled with a CC plant, when applying different measures, such as EGR, humidification and heat recovery to increase electrical efficiency and reduce the capture penalty, has been investigated numerically. Numerical models of the mGT coupled with a CC plant have been constructed, with integration of the different technological measures. The dry and wet mGT models have been validated before using experimental results which can be found in [6], [7]. The model of the CC plant is also described and validated with experimental data from [8]. The application of EGR has not yet been validated experimentally, but it is an objective of future studies.

### *2.1 mGT with Carbon Capture unit*

The Turbec T100 is a single-shaft recuperative mGT (Figure 1). The air is first compressed in a variable speed radial compressor (1). The compressed air passes through a recuperator (3) where it is preheated by the exhaust gas coming from the turbine. The compressed air is heated further in the combustion chamber by burning natural gas (4). The combustion gases, which leave the combustor at nominal temperature of 950°C, expand over the turbine (5) to deliver the necessary power to drive the compressor. The remaining power on the shaft is converted into electrical power by a variable speed generator (6).

The flue gas to be treated are directed to the CC unit (Figure 1). The solvent-based CC plant is composed of two columns, one packed tower for gas absorption and one packed tower for gas stripping. The flue gas, after passing through a cooler (15) is fed in the bottom of the absorber (16), while the lean solvent, generally an aqueous solution of amine, enters at the top. As the liquid and the gas phase interact, the concentration gradient at the liquid/gas interface drives $CO_2$ to the liquid phase. Subsequently the rich solvent is pumped (17) first into the rich-lean heat exchanger (18), where it is heated to higher temperature by the lean solvent from the stripper bottom. In the stripping column (19), 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 reboiler (20) is supplied by pressurized hot water. The thermal energy input of the stripper column is provided by a natural gas-fired boiler (21) and the flue gas of the boiler are mixed with the flue gas of the mGT. Part of the heat for the stripping process can be provided by another water heat exchanger (13) which recovers heat from the exhaust gas. The regenerated solvent, after being pumped (22) into the rich-lean heat exchanger, is cooled further down in an air-cooled plate cooler (23).

Without any other additional modification, the concentration of $CO_2$ in the exhaust gas of both mGT and mHAT is around 1.5%vol, which is too low for an efficient capture in the CC unit. However, this value can be increased by performing EGR. The EGR stream is simulated by splitting part of the exhaust gas, cooling it down (8) to maintain a high compression efficiency, separating the condensed water (9), installing a blower (10) to provide the necessary pressure increase to drive the EGR loop and, finally, adding a filter (11) before the compressor inlet to remove possible impurities from the stream. This measure is represented by block A (in red).

As mentioned in the introduction, in this study we focussed on two different operating scenarios: the first one is mGT coupled with CC plant running in CHP mode. The second one evaluates the same plant with no thermal demand. These two cases are the upper and lower limits of a whole span of heat loads. The intermediate operation of the plant, at partial heat load, is not investigated in this paper. For both scenarios, several combinations of technological measures have been performed and compared calculating the total efficiency, defined as:

$$\eta_{tot} = \eta_{el} + \eta_{th} = \frac{P_{el} + Q_{th}}{\sum_i \dot{m}_i \cdot LHV} \tag{1}$$

where $P_{el}$ is the electrical power output of the turbine plant, $Q_{th}$ is the thermal power output of the turbine plant, is the low heating value of the natural gas and $\Sigma_i m_i$ is the sum of natural gas mass flow rates burnt in the mGT and in the external boiler.

In the first scenario, thermal power output is provided with a gas-water heat exchanger (7), which recovers the remaining heat in the exhaust gas after the recuperator. This option has been represented as block B (in blue).

If there is no thermal load, the global efficiency is therefore reduced to the electrical efficiency. The utilisation of the waste heat in moments of low external heat demand could allow boosting the global efficiency of the plant. Two different heat recoveries are proposed: using the thermal energy of the exhaust gas to humidify the mGT to increase its efficiency or using the waste heat directly to reduce the heat demand of the stripper reboiler and thus reducing the energy penalty.

The traditional mGT can be easily converted into a mHAT by adding a saturation tower (2). In this configuration, the air, after being compressed in the variable speed radial compressor, is subsequently humidified in the saturation tower. The hot water, which is injected in the saturation tower, is heated in a heat exchanger (14). The components involved in this modification have been grouped in block C (in orange).

As an alternative, the waste thermal energy of the exhaust gas can be recovered (13) to decrease the natural gas consumption in the external boiler for the stripping process. This heat recovery is defined as block D (in green).

In the model, each block can be included or by-passed depending on the scenario that has been considered. For instance, if the mGT is running in full CHP mode, the block B is included in the calculation process, whereas blocks

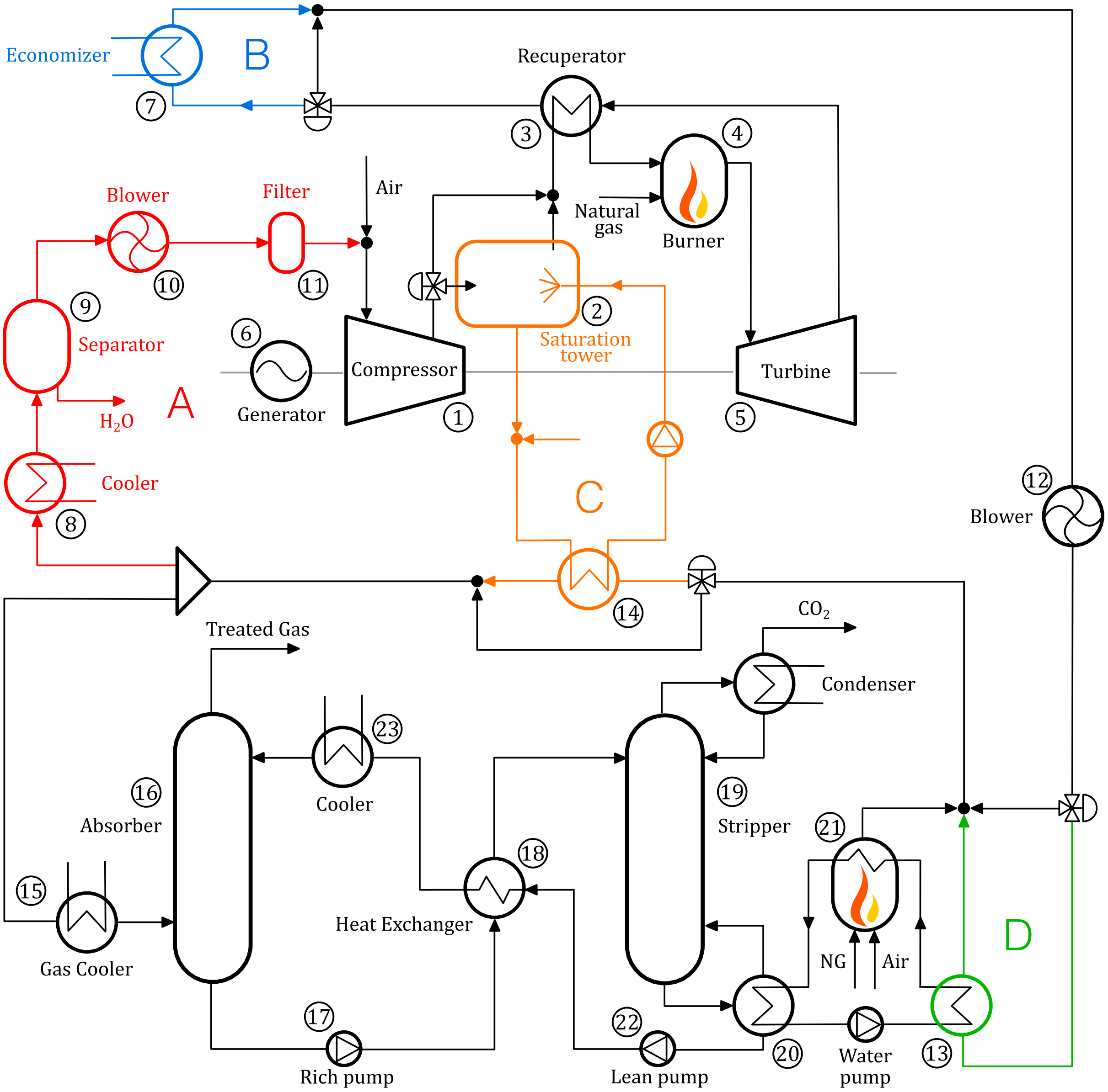

Figure 1: Different layout of the plant can be analysed by including or by-passing components of the plant. Block A (EGR) has been included in all the calculations in which the mGT has been coupled with a CC unit; When the mGT is running in CHP mode, Block B (economiser) is included in the calculation; When there is no heat demand, Block B is by-passed and Block C (saturation tower) and Block D (heat recovery for the stripping process) are activated.

C and D are by-passed. Vice versa, if the heat demand is zero, block B is by-passed but different combination of C and D can be investigated. Block A (EGR) has been always included (except from the traditional mGT and mHAT cases): in fact, the application of EGR is fundamental to have an efficient and low energy cost CC.

### *2.2 Modelling*

Dry and wet operations of the mGT with the EGR channel have been modelled in Aspen Plus v8.8®. The model was validated with experimental data obtained from the Turbec T100 mGT test rig installed at the Vrije Universiteit Brussel (VUB). The ratio of EGR has been adjusted to obtain a concentration of oxygen in the combustor inlet of 16% (wet basis). 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% [9]. Under these conditions, the resulting EGR ratio is around 0.61 for dry nominal operation (100kW$_{el}$ electrical power output under ISO inlet conditions) and 0.46 for wet nominal operation. 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 and PC-SAFT equation of state for vapour phase have been used. Further discussion on the mGT and CC models can be found in [4].

## 3. Results

### *3.1 Full CHP operation*

In terms of global efficiency, the full mGT-CHP mode is the most efficient solution amongst all. At nominal power output conditions, the Turbec T100 has an electrical efficiency equal to 29.4% (producing 100 kW$_{el}$) and it can provide a thermal power output of 166 kW$_{th}$, which corresponds to a 49.5% thermal efficiency. Therefore, the total efficiency of the plant in full CHP mode is around 79% (80% total efficiency reported by the manufacturer [10]). The application of EGR adds a slight energy penalty to the turbine plant, decreasing the electrical efficiency by 1.3 absolute percentage points, whereas the thermal output is unvaried. When the mGT with EGR is coupled with a CC plant, the reboiler duty is provided by burning natural gas in an external boiler. The mass flow rate of natural gas which is burnt to satisfy the stripping process is about 30% of the mass flow rate of natural gas used in the mGT plant. Therefore, although the electrical power output and the thermal power output are the same as the ones of the previous case without CC unit, the higher energy requirement for a “clean” production penalizes both electrical and thermal efficiency. In these conditions, the global efficiency is equal to 59.2%. All these results are summarized in Table 1.

Table 1. Comparison of the electrical efficiencies for different plant layouts operating in full CHP mode.

| | **Plant layouts** | **Blocks** | $\eta_{el}$ | $\eta_{th}$ | $\eta_{tot}$ | $\Delta\eta_{el}$ (compared to reference case) |
|---|---|---|---|---|---|---|
| **Reference case** | mGT | B | 29.4% | 49.5% | 78.9% | - |
| | mGT + EGR | A+B | 28.1% | 49.5% | 77.6% | -1.3% |
| | mGT + EGR + CC | A+B | 21.4% | 37.8% | 59.2% | -19.7% |

### *3.2 No thermal load operation*

Compared to the efficiency of the traditional mGT cycle, humidification would lead to an increment of the electrical efficiency by around 3 absolute points. The application of EGR on the mHAT entails an energy penalty that is lower compared to the one of the dry mGT since the EGR steam has a lower mass flow rate. A detailed description about the influence of EGR on the turbine cycle can be found in [11]. The application of the carbon capture unit has also, in this case, a remarkable effect on the final electrical efficiency, decreasing it by 8.3 absolute percentage points compared to the mHAT efficiency and 5.3% compared to the dry mGT base case. The energy penalty of the CC unit is more severe in wet operation since the maximum ratio of EGR which can be applied to the plant is lower compared to the dry operation (therefore also the $CO_2$ concentration is lower). Instead of humidifying the cycle, the waste heat

Table 2. Comparison of the electrical efficiencies for different plant layouts where there is no heat demand.

| | **Plant layouts** | **Blocks** | $\eta_{el}$ | $\Delta\eta_{el}$ (compared to reference case) |
|---|---|---|---|---|
| **Reference case** | mGT | - | 29.4% | - |
| | mGT + EGR + CC | A | 21.4% | -8% |
| | mHAT | C | 32.4% | +3% |
| | mHAT + EGR | A+C | 31.5% | +2.1% |
| | mHAT + EGR+ CC | A+C | 24.1% | -5.3% |
| | mGT + EGR + CC+ Heat Recovery | A+D | 25.9% | -3.6% |
| | mHAT + EGR + CC + Heat Recovery | A+C+D | 26.8% | -2.6% |

of exhaust gas can be used to reduce the heat demand of the reboiler. Compared to the previous case, heat recovery, which does not involve thermodynamic transformations like evaporation, but direct heat transfer between two fluids, has, generally, a higher efficiency. Therefore, heat recovery for the stripping process is a solution which leads to a smaller energy penalty of the CC unit compared to the option with mHAT and CC unit. At this point, an attractive option that is worth to investigate is the combination of both humidification and heat recovery. If humidification is applied in the first place, the temperature of the exhaust gas after the water heat exchanger is around 100˚C and it is not sufficiently high to allow the heat recovery for the stripping process (the boiling temperature of the solvent in the reboiler is 105˚C). On the contrary, humidification can be applied after the heat recovery (solution with blocks B+C+D) as the temperature of the water before entering the economiser is around 75˚C. The combination of these two solution leads to a more efficient heat extraction and the final energy penalty is the lowest amongst the system with CC with no heat load (2.6 absolute percentage points compared to the dry mGT efficiency). As for the case of full CHP mode, the electrical efficiencies of each plant layout have been computed and compared, as shown in Table 2.

## 4. Concluding remarks and perspective

This paper presents a thermodynamic analysis of the Turbec T100 coupled with a solvent-based CC unit by using the software Aspen Plus®. The analysis has been performed for two main scenarios: full CHP operation of the mGT and "no heat demand" consumer. While, for the full CHP mode, the global efficiency is still quite high despite the energy penalty of a "carbon-clean" production, in the latter scenario the performance of the mGT is severely penalized. Nevertheless, there is still a significant scope of improvements by applying different technological measures, such as EGR, humidification and heat recovery to reduce the reboiler duty for the stripping process. Simulation results show that the application and combination of these measures resulted in a remarkable electrical efficiency increase of the global system: compared to the dry mGT electrical efficiency, the mHAT with EGR, heat recovery and CC unit achieved an electrical efficiency equal to 26.8%.

Future work would include a more detailed numerical analysis concerning mixed mHAT mode – operation with partial humidification/heat recovery and partial heat production. Furthermore, an exergy analysis will be performed to identify where more waste heat can be recovered to reduce the energy requirement of the plant further.

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## References

[1] International Energy Agency (IEA); *"Tracking clean energy progress 2014"*; Tech. rep., International Energy Agency (2014).
[2] Montero Carrero M., De Paepe W., Parente A., Contino F.; *"T100 mGT converted into mHAT for domestic applications: Economic analysis*

*based on hourly demand"*; Applied Energy, (2016), **164**, 1019-1027.

[3] Majoumerd M.M., Somehsaraei H.N., Assadi M.; "Micro gas turbine configurations with carbon capture – Performance assessment using a validated thermodynamic model"; Applied Thermal Engineering, (2014), **73**, 172-184.

[4] Giorgetti S., Bricteux L., Parente A., Blondeau J., Contino F., De Paepe W.; *"Carbon capture on micro gas turbine cycles: assessment of the performance on dry and wet operations"* Applied Energy, (2017).

[5] Gonzàlez-Salazar M.A.; "*Recent developments in carbon dioxide capture technologies for gas turbine power generation";* Greenhouse Gas Control, (2015), **34,** 106-116.

[6] Delattin F., Bram S., Knoops S., De Ruyck J.; *"Effects of steam injection on microturbine efficiency and performance"*; Energy, (2008), **33**(2), 241-247.

[7] Montero Carrero M., De Paepe W., Magnusson J., Parente A., Bram S. and Contino F.; *"Experimental characterisation of a micro humid air turbine: assessment of the thermodynamic performance"*; Applied Thermal Engineering, (2017), **118**, 796-806.

[8] Agbonghae E.O., Best T., Finney K., Palma C.F., Hughes K.J., Pourkashanian M.; "*Experimental and Process Modelling Study of Integration of a Micro-turbine with an Amine Plant"*; Energy Procedia (2014), **63**, 1064-1073.

[9] Ditaranto M., Hals J., Bjørge T., "*Investigation on the in-flame NO reburning in turbine exhaust gas*"; Proceedings of the Combustion Institute, (2009), **32**(2), 2659–2666.

[10] Turbec AB, 2000-2001. "*T100 microturbine CHP system: Technical description ver. 4.0"*.

[11] De Paepe W., Montero Carrero M., Contino F., Bram S., Giorgetti S., Parente A. "*Exhaust gas recirculation on humidified flexible micro gas turbines for carbon capture applications";* ASME Conference Proceedings, no. ASME paper GT2016-57265 (2016).