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# FLUE GAS RECIRCULATION IN A GAS TURBINE: IMPACT ON PERFORMANCE AND OPERATIONAL BEHAVIOR

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## ABSTRACT

The rigorous reduction of greenhouse gas emissions in the upcoming decades is only achievable with contribution from the following strategies: production efficiency, demand reduction of energy and carbon dioxide ($CO_2$) capture from fossil fueled power plants. Since fossil fueled power plants contribute largely to the overall global greenhouse gas emissions (> 25 % [1]), it is worthwhile to capture and store the produced $CO_2$ from those power generation processes.

For natural-gas-fired power plants, post-combustion $CO_2$ capture is the most mature technology for low emissions power plants. The capture of $CO_2$ is achieved by chemical absorption of $CO_2$ from the exhaust gas of the power plant. Compared to coal fired power plants, an advantage of applying $CO_2$ capture to a natural-gas-fired combined cycle power plant (CCPP) is that the reference cycle (without $CO_2$ capture) achieves a high net efficiency. This far outweighs the drawback of the lower $CO_2$ concentration in the exhaust. Flue Gas Recirculation (FGR) means that flue gas after the HRSG is partially cooled down and then fed back to the GT intake. In this context FGR is beneficial because the concentration of $CO_2$ can be significantly increased, the volumetric flow to the $CO_2$ capture unit will be reduced, and the overall performance of the CCPP with $CO_2$ capture is increased.

In this work the impact of FGR on both the Gas Turbine (GT) and the Combined Cycle Power Plant (CCPP) is investigated and analyzed. In addition, the impact of FGR for a CCPP with and without $CO_2$ capture is investigated. The fraction of flue gas that is recirculated back to the GT, need further to be cooled, before it is mixed with ambient air. Sensitivity studies on flue gas recirculation ratio and temperature are conducted. Both parameters affect the GT with respect to change in composition of working fluid, the relative humidity at the compressor inlet, and the impact on overall performance on both GT and CCPP. The conditions at the inlet of the compressor also determine how the GT and water/steam cycle are impacted separately due to FGR. For the combustion system the air/fuel-ratio (AFR) is an important parameter to show the impact of FGR on the combustion process. The AFR indicates how close the combustion process operates to stoichiometric (or technical) limit for complete combustion. The lower the AFR, the closer operates the combustion process to the stoichiometric limit. Furthermore, the impact on existing operational limitations and the operational behavior in general are investigated and discussed in context of an operation concept for a GT with FGR.

## NOMENCLATURE

<u>Abbreviations</u>

| | |
|---|---|
| AAP | Advanced Amine Process |
| AFR | Air to Fuel Ratio |
| CAP | Chilled Ammonia Process |
| CCPP | Combined Cycle Power Plant |
| CCS | Carbon (dioxide) Capture and Storage |
| CoE | Cost of Electricity |
| DCC | Direct Contact Cooler |
| EV | EnVironmental (combustor/burner) |
| FGR | Flue Gas Recirculation |
| GHG | GreenHouse Gases |
| GT | Gas Turbine |
| HP | High Pressure |
| HRSG | Heat Recovery Steam Generator |
| IEA | Internal Energy Agency |
| IGCC | Integrated Gasification Combined Cycle |
| IP | Intermediate Pressure |
| KA | Kombianlage |
| LBO | Lean Blow Out |
| LP | Low Pressure |
| MEA | Monoethanolamine |
| NGCC | Natural Gas Combined Cycle |
| OPC | OPeration Concept |

| | |
|---|---|
| SEV | Sequential EnVironmental (combustor/burner) |
| SSPT | Single Shaft Power Train |
| UHC | Unburned HydroCarbon |
| VIGV | Variable Inlet Guide Vanes |
| TAT | Temperature After Turbine |

## INTRODUCTION

The IEA (International Energy Agency) predicts that the greenhouse gas (GHG) emissions will rise by 130 % above 2005 levels by 2050 in the absence of new legislation or supply constraints [2]. The IEA assesses in a scenario so-called the "ETP Blue Map" [2] where the overall emissions are diminished by 50 % compared to 2005 levels. Although in this scenario many different approaches to mitigate GHG emissions are considered, the potential of carbon capture and storage (CCS) still accounts for 20 % of the overall reduction. Besides CCS, the other contributors to the reduction are: increased fuel and electricity efficiency of end-use, continuous increase of renewable energies, a constant utilization of nuclear energy and higher efficiency in power generation processes. It shows that CCS is not the 'only' option to reduce GHG emissions but rather that CCS plays an important role to fulfill reasonable scenarios.

Regarding fossil fuelled power plants different technologies have been investigated for more than a decade to either separate the carbon from the fuel (pre-combustion $CO_2$ capture), firing under the presence of pure oxygen instead of air (oxyfuel cycles) or to capture the $CO_2$ from the exhaust gases (post-combustion $CO_2$ capture). An early comparison of different $CO_2$ capture technologies was compiled by *Bolland and Mathieu* [3]. A subsequent detailed benchmarking of different $CO_2$ capture technologies was conducted by *Damen et al.* [4] in 2006.

For the various types of fossil fuel, natural gas or coal, different $CO_2$ capture seem to be most appropriate. For coal fired power plants the following configurations with $CO_2$ capture are proposed: (i) Integrated Gasification Combined Cycle (IGCC) where the $CO_2$ capture is sequestrated from syngas, which is produced by gasification of coal, before the syngas is used as fuel for a combined cycle; (ii) oxyfuel boiler where coal is combusted in a conventional boiler but using pure oxygen as oxidizer instead of air; (iii) post-combustion $CO_2$ capture where the $CO_2$ is scrubbed from the exhaust gases by means of chemical absorption. Pre-combustion $CO_2$ capture is currently not perceived to be feasible for natural gas fired combined cycle power plants because of the excessive energy penalty associated with fuel reforming. For natural gas fired power plants the most promising capture technology is post-combustion $CO_2$ capture. An important aspect for implementing CCS is the opportunity to retrofit existing power plants.

Post-combustion $CO_2$ capture is currently under investigation for applications of various size [5]. Alstom accumulated experience with two different capture technologies, namely Advanced Amine Process (AAP) and Chilled Ammonia Process (CAP). AAP and CAP both employ chemical absorption to separate the $CO_2$ from the exhaust gases but they differ in both, their operating conditions and the required expenditure of energy which is required for the regeneration of the solvent. For both technologies the thermal energy for the regeneration process is best provided by low pressure (LP) steam extracted from the water/steam cycle.

Future $CO_2$ targets most probably can only be attained by implementing CCS in CCPP [6]. In line with this expected requirement, Alstom has initiated the development of combined cycle power plants with post-combustion $CO_2$ capture. Various power train configurations based on an Alstom's reheat GT were investigated, extracting regeneration steam (for the $CO_2$ capture unit) from different locations within the water-steam cycle. The additional power and cooling water requirements - and the equipment necessary to meet these - were considered. Furthermore, all the main components necessary for implementing flue gas recirculation were included. The results presented in this section encompass some of the principal findings of the thermoeconomic assessment, which highlights the performance and CoE benefits of FGR.

In this paper a combined cycle power plant with $CO_2$ capture is presented which is based on a Alstom's reheat GT24/GT26 in single shaft arrangement. This configuration is investigated with and without flue gas recirculation. The impact of FGR on the major components of the combined cycle and the $CO_2$ capture unit are presented. Furthermore, the consequences in terms of power and efficiency on the overall power plant are shown. For a better understanding of the impact due to FGR, parameter variation on the mass flow and the temperature of the recirculated flue gas is conducted. Some aspects on the operational flexibility and the partload performance are highlighted.

## A COMBINED CYCLE POWER PLANT (CCPP) WITH POST-COMBUSTION CO2 CAPTURE – REFRENCE CYCLE

The CCPP with post-combustion $CO_2$ capture is based on Alstom's reheat GT engine GT24/GT26. Gas and steam turbines are arranged in a single shaft power train (SSPT) configuration. The HRSG comprises three pressure levels, with a condenser pressure of 45 mbar corresponding to reference conditions.

In the case of a CCPP with $CO_2$ capture (without flue gas recirculation), the flue gas leaving the HRSG is further cooled before entering the $CO_2$ capture unit. Cooling is carried out by means of a direct contact cooler (DCC) in which water is sprayed into the gas stream. Due to the water produced in the combustion process, some condensate forms and is drained in the DCC. The flue gases are cooled down to around 40 °C. A blower compensates the additional pressure drop and then propels the flue gases into the $CO_2$ capture unit. A schematic layout of the CCPP with $CO_2$ capture is illustrated in figure 1.

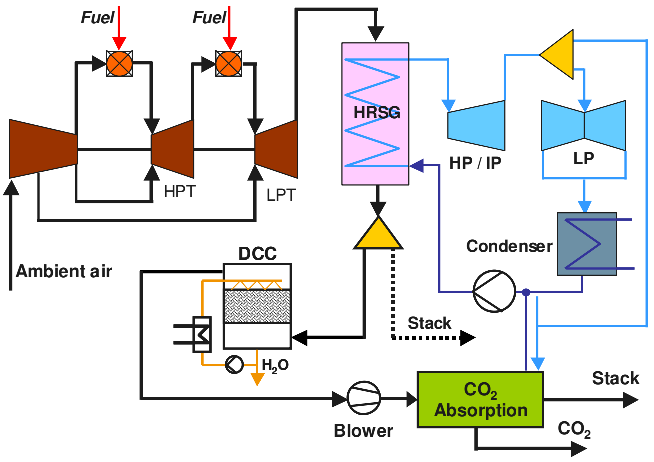


*Figure 1* *Schematic layout of a combined cycle power plant with $CO_2$ capture – reference cycle.*

In this work AAP is used as $CO_2$ capture technology. Steam extracted from the IP/LP cross-over provides the necessary regeneration energy to the stripper in the AAP unit. The hot condensate is subsequently returned to the water/steam cycle.

This configuration is used as reference cycle in this work. The impact of flue gas recirculation on the overall performance (power output and efficiency) is compared to this reference cycle.

## MODELING THE REFERENCE CYCLE WITH AND WITHOUT FLUE GAS RECIRCULATON

Alstom-internal evaluation tools are used for modeling the reference cycle. The reference cycle can be divided into the gas turbine, the water/steam cycle and the $CO_2$ capture process. These sub-processes are modeled separately using consistent boundary conditions in different Alstom-in-house software tools.

In the framework of the development of combined cycle power plants with post-combustion $CO_2$ capture a comprehensive feasibility study of various power cycles with $CO_2$ capture (and flue gas recirculation) was performed. Different configurations based on an Alstom's reheat GT have been analyzed. Variations on the location for extracting the regeneration steam (for the $CO_2$ capture unit) have been carried out. The additional auxiliary power, including the expenditure of energy for compression of the $CO_2$ (to 100 bar), was considered. A variation of the mass flow rate and the temperature of the recirculated flue gas was done. Out of the feasibility study, a promising configuration was chosen as configuration for the reference cycle.

The aim of the present work is neither to investigate specific components of the combined cycle power plant nor to quantify the impact of $CO_2$ capture and flue gas recirculation separately from each other. The approach of this paper is to show the impact if flue gas recirculation is applied to a reference cycle, comprising a combined cycle power plant with $CO_2$ capture. The impact of flue gas recirculation on both the overall reference cycle and on the gas turbine itself as well as on the combined cycle is expressed relatively. Therefore a quantification of the reference cycle is not required to describe the impact of flue gas recirculation.

## OPERATIONAL ASPECTS OF A GAS TURBINE (GT) WITH REHEAT COMBUSTOR

The main technology differentiator of Alstom's GT24/GT26 gas turbines is the sequential combustion principle, which was already introduced in 1948 by predecessor of Alstom into the market as a way of increasing efficiency at low turbine inlet temperature levels [7]. The GT24/GT26 combustion system is based on a well-proven Alstom combustion concept using the EV (EV = EnVironmental) burner in an annular combustor followed by the SEV (Sequential EnVironmental) burner in the second combustion stage, see figure 2.

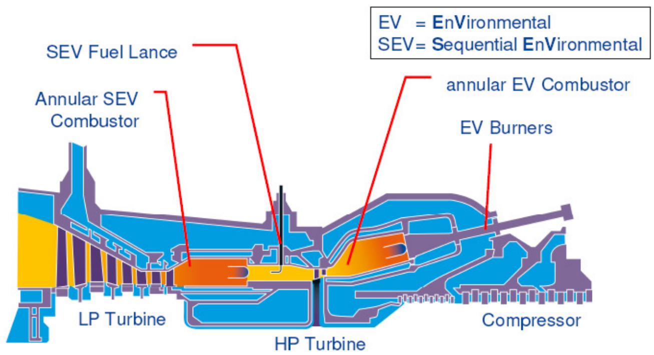


*Figure 2* *GT24/GT26 sequential combustion system [7].*

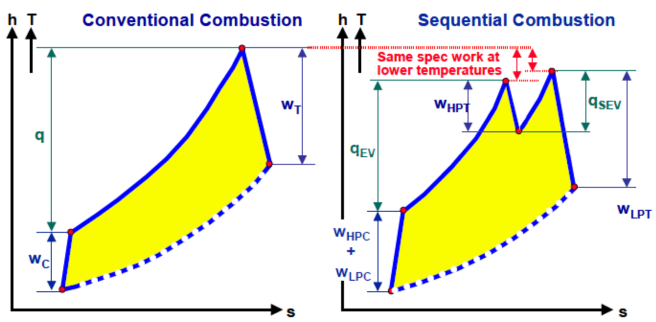


*Figure 3* *Comparison of a conventional non-reheat and a reheat concept in a h,s-diagram [7].*

Thermodynamically, the effect of the reheat concept is that the pressure ratio is increased (> 30) while the GT exhaust temperature remains on a comparable level to that of a non-reheat machine – for the similar level of hot gas temperature(s). A comparison between a conventional non-reheat and a reheat cycle is illustrates in a h,s-diagram in figure 3. GT24/GT26 gas turbines result in a machine with a high power density and a smaller footprint compared to non-reheat GT's. Low emission level can be achieved because a reheat combustor makes more efficient use of the oxygen by burning twice in lean premix mode [7].

## ASPECTS ON FLUE GAS RECIRCULATION (FGR)

In a conventional combined cycle power plant the energy of the flue gases leaving the gas turbine are utilized in a heat recovery steam generator (HRSG). If flue gas recirculation is applied to such a conventional CCPP, part of the flue gas is recirculated back to the inlet of the GT. After the HRSG the recirculated flue gas is further cooled down, close to ambient temperature, before being mixed with fresh ambient air. An additional blower is located between cooler and mixer to overcome the additional pressure drop in the FGR-path, see figure 4.

The intention of the DCC (direct contact cooler) in the flue gas path is not only to reduce the temperature of the flue gases by approx. 50 K, but also to clean the flue gases. The flue gases from the GT will contain some impurities produced by the combustion process such as NOx and SOx. In a FGR system, these species will accumulate and be returned to the GT, which should be avoided to reduce the risk of various corrosion mechanisms.

The desired effect of FGR is the so-called "$CO_2$ enrichment" because the concentration of $CO_2$ increases significantly due to FGR. The fraction of flue gases which are recirculated back to the GT range from 30 to 50 % of the GT exhaust mass flow. For these FGR-ratios the $CO_2$ concentration would be between 6.0 and 8.7 mol-%. Depending on the FGR-ratio, the $CO_2$ concentration can be doubled at the exit of the GT (4.0 mol-% without FGR). The implications due to FGR for the different components of the CCPP with and without CCS are described in the following chapters. Furthermore, more details on the FGR path are given and how they impact the overall cycle performance.

## A CCPP WITH POST-COMBUSTION CO2 CAPTURE AND FLUE GAS RECIRCULATION

The schematic layout of a combined cycle power plant (CCPP) with post-combustion $CO_2$ capture and flue gas recirculation is shown in figure 4, whereby the flue gas is split into two streams after the DCC. The exhaust gas is fed to a mixer where it is mixed with fresh ambient air before entering the compressor of the GT. The remaining proportion the exhaust gas is treated by the $CO_2$ capture unit.

The major consequence of flue gas recirculation is that the $CO_2$ concentration increases, whereas the $O_2$ concentration decreases. The change in composition is determined by the amount of recirculated flue gases. This is expressed by the FGR-ratio, which is defined as the mass flow entering the mixer in relation to the GT exhaust mass flow. As previously mentioned, a typical range of FGR-ratio is 30 to 50 %.

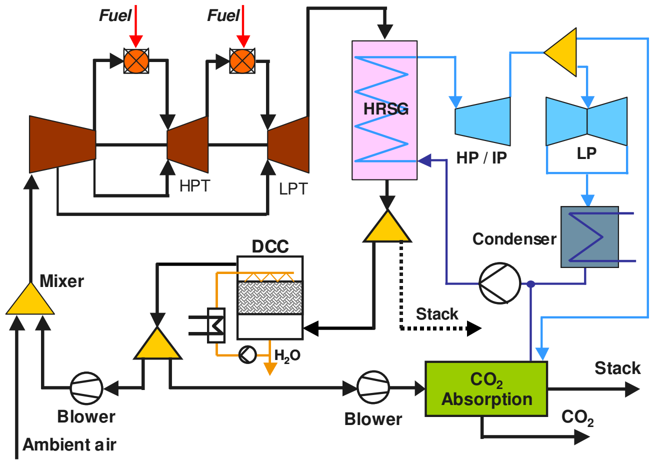


***Figure 4*** *Schematic layout of a combined cycle power plant with $CO_2$ capture and flue gas recirculation.*

## IMPACT OF FGR ON THE COMBINED CYCLE POWER PLANT WITH CO2 CCAPTURE

In this section the impact of FGR is discussed regarding operation at the design-point (i. e. baseload). The CCPP with $CO_2$ capture and with or without flue gas recirculation is presented in table 1. It can be seen that the net power output increases by 3.6 % if flue gas recirculation is applied. The two drivers for this increase are, firstly, the significantly lower steam extraction from the steam turbine and, secondly, the auxiliary power decreases slightly. The first aspect, the lower steam extraction, leads to the increase of the gross power, whereas a reduction of the auxiliary power reduces the difference between gross and net power output. The lost power diminishes by about 30 % and the auxiliary power is lowered by 6.2 %.

In general, for a CCPP with post-combustion $CO_2$ capture the increased auxiliaries are mainly due to the $CO_2$ compressor, the blower (between HRSG and $CO_2$ capture unit) and the internal auxiliaries of the capture unit itself. For a conventional CCPP the auxiliary power ranges from 2.0 to 2.5 % of the gross power output.

The major impact of flue gas recirculation on the overall CCPP with $CO_2$ capture is that the lost power due to steam extraction is reduced by 30 %. The reason for the saving on LP steam is less energy consumption of the $CO_2$ capture unit. The specific expenditure of energy for the $CO_2$ capture unit is lowered due to flue gas recirculation because the treated mass flow of $CO_2$ (only a certain fraction of the exhaust mass flow is send to the $CO_2$ capture unit) is smaller and, at the same time, the concentration of $CO_2$ is increased. These two effects describe the positive impact on the CCPP with $CO_2$ capture. It is

***Table 1*** *Breakdown of the overall performance parameter of a CCPP with $CO_2$ capture (=reference cycle) with flue gas recirculation.*

| | **Reference cycle with FGR** |
|---|---|
| Normalized gross power output / % | 102.7 % of the reference cycle |
| Lost power due to steam extraction (in comparison to the reference cycle) | 69.9 % of the reference cycle |
| Auxiliary power (in comparison to the reference cycle) | 93.8 % of the reference cycle |
| Normalized net power output / % | 103.6 % of the reference cycle |
| Normalized net power efficiency / % | 102.1 % of the reference cycle |

expected that in future the energy requirements will reduce further to provide some potential for lowering the penalty on power and efficiency of the CCPP with $CO_2$ capture.

The benefit of flue gas recirculation can also be expressed in terms of cost of electricity (CoE), which again can be transferred to a minimum price to justify $CO_2$ capture from a CCPP. The higher power and efficiency due to flue gas recirculation leads to a reduction of the CoE. This is illustrated in figure 5. Assuming a certain price of the emitted $CO_2$, the CoE is given in figure 5 for a CCPP without $CO_2$ capture (dashed line), a CCPP with $CO_2$ capture (solid line with squares) and for a CCPP with $CO_2$ capture and flue gas recirculation (solid line with diamonds). Since flue gas recirculation reduces the CoE by 5 %, the minimum price where $CO_2$ capture is more attractive than paying the $CO_2$ taxes is lowered by 11 %. Even if there is a high uncertainty regarding the level of future $CO_2$ prices, this shows another benefit of flue gas recirculation for a combined cycle power plant with $CO_2$ capture.

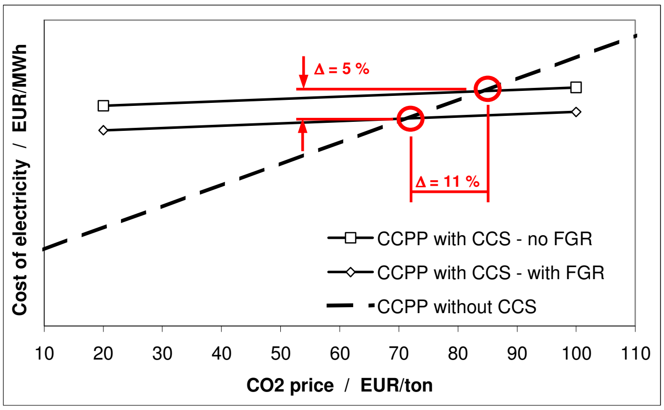


***Figure 5*** *Cost of electricity versus the price of emitted $CO_2$ for varies configurations.*

## IMPACT OF FLUE GAS RECIRCULATION ON CCPP AND GT

This section analyzes in more detail the effect of flue gas recirculation on a combined cycle power plant without $CO_2$ capture, in particular on the GT (as one of the main component of the power plant).

The impact of flue gas recirculation on the GT and on the CCPP is illustrated in figure 6. Ambient conditions are chosen according ISO 3977-2 [8] (15°C, 1.013 bar and 60 %) and a constant flue gas temperature after the DCC is assumed for the calculations supporting figure 6. The impacts upon the CCPP and the GT are different. GT power output continuously decreases with higher FGR-ratios while the power output of the CCPP initially falls and then increases slightly at FGR-ratios above 35 %. For a FGR-ratio of 50 % the GT gross power reduces by approximately 2.5 %, whereas the net power of the CCPP decreases by less than 0.5 %. The reason for this different behavior can be seen in figure 7. Due to the fact that the recirculated flue gases will have a higher temperature than the ambient temperature, the compressor inlet temperature keeps increasing with higher FGR-ratios. The increase of the compressor inlet temperature is linear because a constant ambient temperature and therefore also a constant flue gas temperature after the DCC have been assumed for the different FGR-ratios.

The described increase of the compressor inlet temperature leads to a lower mass flow through the GT and, thus, the GT gross power decreases with higher FGR-ratios, see figure 6. This effect is reduced somewhat above FGR-ratios of 30 % because the humidity also rises with higher FGR-ratios and a higher humidity generally promotes power output and efficiency.

Two effects lead to the increase of the GT exhaust temperature when FGR is applied. On the one hand the smaller compressor inlet mass flow induces a lower pressure ratio in the compressor and consequently the GT exhaust temperature will rise (assuming a constant turbine inlet temperature). On the other hand the change in composition of the working fluid is enhanced at higher FGR-ratios due to increased $CO_2$ and $H_2O$ concentration. The impact of the different thermophysical properties is explained in the section “Parametric studies”. The combinations of these two effects results in the increase of the GT exhaust temperature, see figure 7. The steep slope in GT exhaust temperature from 30 to 50 % FGR-ratio is the reason for the increase of the of the CC net power; compare figure 6 and figure 7.

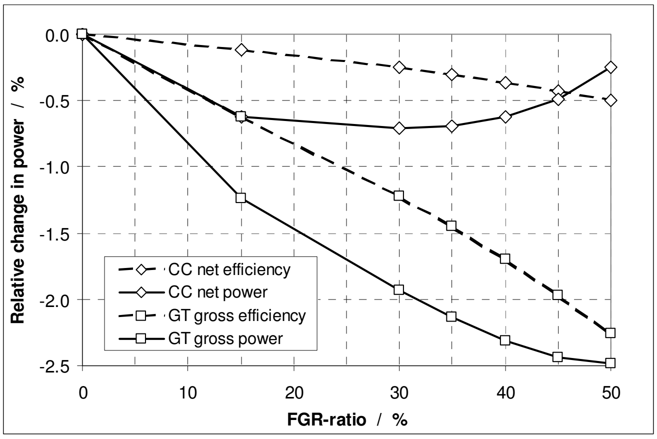


***Figure 6*** *Normalized change in power output and efficiency for GT gross and CC net vs. FGR-ratio at 100 % load.*

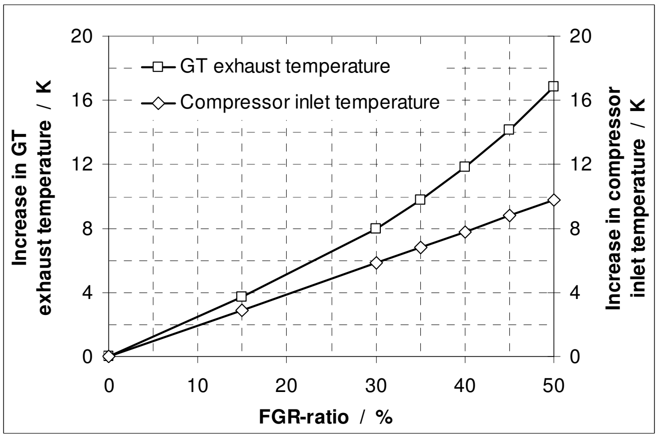


***Figure 7*** *Change of GT exhaust temperature (ordinate on the left hand side) and change of compressor inlet temperature (ordinate on the right hand side) versus FGR-ratio at 100 % load.*

Two effects lead to the increase of the GT exhaust temperature when FGR is applied. On the one hand the smaller compressor inlet mass flow induces a lower pressure ratio in the compressor and consequently the GT exhaust temperature will rise (assuming a constant turbine inlet temperature). On the other hand the change in composition of the working fluid is enhanced at higher FGR-ratios due to increased $CO_2$ and $H_2O$ concentration. The impact of the different thermophysical properties is explained in the section “Parametric studies”. The combinations of these two effects results in the increase of the GT exhaust temperature, see figure 7. The steep slope in GT exhaust temperature from 30 to 50 % FGR-ratio is the reason for the increase of the of the CC net power; compare figure 6 and figure 7.

The effect on GT gross efficiency and CC net efficiency can be explained by the change in GT and CC power output, respectively, see figure 6. The GT gross efficiency is linearly decreasing with FGR-ratios, in the same order of magnitude as the GT power output. At an FGR-ratio of 50 %, the GT gross efficiency is reduced by about 2.2 %. Due to the fact that the CC power increases to some extend above FGR-ratios of 35 %, the effect on the CC net efficiency is weakened. The CC net efficiency is also linearly decreasing with higher FGR-ratios but the reduction remains smaller than 0.5 %.

The effect on the net power output of a CCPP (without CCS) is smaller than 1 % and depends not only the FGR-ratio but also on the temperature of the recirculated flue gas. As a reminder it is mentioned again that the variation of the FGR-ratio is done for a constant ambient temperature (15 °C) and therefore for a constant temperature of the recirculated flue gases. The impact of the flue gas temperature will be discussed later in this article.

## IMPACT OF FGR ON THE COMBUSTION PROCESS

$CO_2$ enrichment by application of FGR leads inherently to the effect that the concentration of available oxygen for the combustion process diminishes. This circumstance results consequently in a physical limit for the amount of the recirculated flue gases. Theoretically the FGR-ratio could be increased until only the amount of oxygen required for stoichiometric combustion is left over. Obviously the technical limit has to some extent be lower than the theoretical limit to account for:

- Inhomogeneity of the oxygen distribution from burner to burner
- Inhomogeneity inside each burner for local zones close to a reducing atmosphere
- Combustion stability and emission limits
- Adjustment of the FGR-ratio in transient operation

The oxygen concentration along the flow path throughout the GT is qualitatively illustrated in figure 8. The level of oxygen concentration is vertically shifted for a change in the FGR-ratio. Figure 8 shows that if the FGR-ratio reaches a certain limit the SEV combustor would receive too less oxygen. In this case incomplete burnout would occur and consequently CO-emissions would rise dramatically and even unburned hydrocarbons (UHC) may enter the LP turbine.

The reheat combustion concept separates the limits of the combustion process to the different burners. The lowered oxygen concentration is limiting a stable combustion in the EV-combustor. The high operating pressure of the reheat GT has a positive effect on the stabilization. The CO-emissions generated in the EV-combustor are not relevant because the overall GT CO-emissions are exclusively determined by the SEV-combustor. Due to its high inlet temperature the SEV-combustor operates in auto ignition mode and is not affected by the lean blow out limit (LBO limit). Because of the high inlet temperature the SEV-combustor can be operated at lower oxygen levels than a combustor of the non-reheat GT. For more information see [9] and [10]. The conditions for the combustion process under FGR conditions were investigated intensively [11], [12], [13].

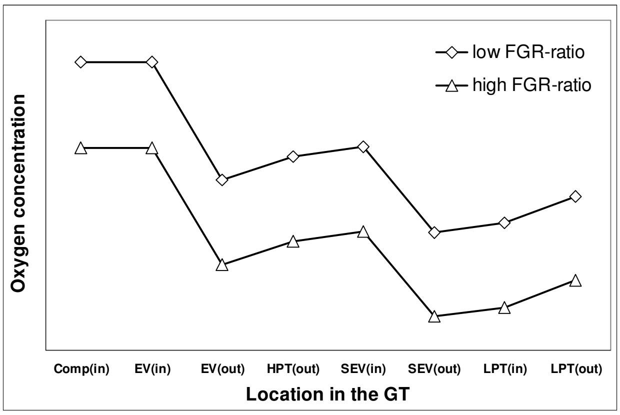


***Figure 8*** *Oxygen concentration along the flow path throughout the GT.*

## PARAMETRIC STUDIES ON THE FLUE GAS TEMPERATURE AND MASS FLOW

In this section the impact of FGR on the mass flow and temperature in the GT is discussed and the impact on performance on the CCPP are presented. As stated previously, the two FGR-related parameters determining the GT performance are the mass flow (recirculation ratio) and the temperature of the recirculated flue gases. Whilst the effect of the mass flow (different FGR-ratios) has been discussed in the previous chapter, the combination of both parameters is now presented. The minimum achievable temperature after the direct contact cooler (DCC) depends on the kind of cooling technology but also on the quality of the cooler. A cooler of a high quality (high investment costs) will obviously achieve a lower temperature than a cooler with a lower quality (lower investment costs). To investigate the impact on the outlet temperature of the DCC, the temperature of the gas after the cooler is varied by ±10 K. In figure 9 the curves with the lower flue gas temperature are designated with 'T(DCC, low)', whereas the curves with the upper temperature are labeled as 'T(DCC, high)'. For charts (i), (ii) and (iii) in figure 9 the ambient conditions are assumed to be constant with 15 °C, 1.013 bar and 60 %.

The root cause underpinning the results of this parametric investigation is the change in composition of the working fluid due to FGR. The strongest impact on the change in composition is the different amounts of water and carbon dioxide. The variation of these species is shown in the upper left chart of figure 9. It is observed that the amount of $CO_2$ is determined by the FGR-ratio. The impact of the flue gas temperature has only a minor impact on the $CO_2$ concentration. Between an FGR-ratio of 40 and 50 % the $CO_2$ concentration ranges between 3 and nearly 5 mol-%. In contrast the amount of water is strongly influenced by both the temperature and the mass flow rate of the recirculated flue gases. The high level of water in the GT exhaust gas stems from the combustion process. The GT exhaust gas contains 11-12 mol-% water resulting in condensation when the recirculated flue gases are cooled down approaching ambient temperature. The flue gases leaving the DCC are thus fully saturated. Due to the distribution of the vapor pressure curve of water, the absolute humidity increases exponentially with the outlet temperature of the DCC. For the colder flue gas temperature the mole fraction of water at the compressor inlet remains below 2 %, whereas for the warmer flue gas temperature the water concentration rises to more than 4 mol-% at high FGR-ratios. Of course, at high ambient temperatures this effect plays an even more important role.

The combination of increased water and carbon dioxide concentrations leads to a change in specific isobaric heat capacity and specific gas constant, which in turn result in a smaller isentropic exponent. A smaller isentropic exponent results in a smaller temperature difference (for compression or expansion) for a given pressure ratio. Due to this change in compressor and turbine, the temperature differences are reduced. For a constant pressure ratio, the compressor discharge temperature would decrease and for a constant hot gas temperature, the temperature after turbine (TAT) would increase.

In the lower left chart in figure 9 the increase of the compressor inlet temperature is graphically illustrated. It shows that for a cold flue gas temperature, the increase of the compressor inlet temperature across the entire FGR-ratio range can be limited to around 4 K, but for the high flue gas temperatures the increase rises to more than 12 K. The change in the compressor inlet temperature is the reason for the variation of the CC gross power, which is presented in the third chart of figure 9. The upper chart on the right hand side shows how the CC gross power is influenced for different FGR-ratios in both cases, assuming a cold and warm flue gas temperature. In case of the cold flue gas temperature, flue gas recirculation has a positive effect on CC gross power. At an FGR-ratio of 50 %, the CC net power output increases by about 1.0 %. For the higher flue gas temperature the CC net power decreases significantly. For high FGR-ratios (> 40 %) the CC net power reduces by nearly 3.0 %.

This demonstrates the importance of the DCC outlet temperature because it determines the temperature of the recirculated flue gases and, thus, the impact on the power out of the GT and consequently of the CCPP. The impact on the CCPP is partly compensated by a higher GT exhaust temperature, but nevertheless the overall impact of FGR (at a given ratio) is

mainly determined by the temperature of the recirculated flue gas.
In contrast the impact on the CC net efficiency is negligible, see also upper chart on the right hand side. As already shown in figure 6, the CC net efficiency decreases linearly with higher FGR-ratios. Due to the fact that a DCC outlet temperature is a reduction of mass flow through the GT (because of higher compressor inlet temperature), the impact on CC net efficiency is that small.

Exemplarily, another variation is shown in fourth chart of figure 9. In the lower chart on the right hand side the impact of the flue gas temperature and ambient temperature, on CC net power and CC net efficiency is depicted, at a constant FGR-ratio. A certain correlation for the temperature of the recirculated flue gases is assumed which connects it to the ambient temperature. Same as for the other charts, this nominal temperature is then varied by ±10 K, so that the difference between the lower glue gas temperature 'T(DCC, low)' and the higher flue gas temperature 'T(DDC, high)' corresponds to a temperature difference of 20 K. The variation shows that for an ambient temperature above 0 °C the CC gross power may be even higher with FGR compared to standard operation (without FGR). Furthermore, the impact of the flue gas temperature increases continuously with higher ambient temperatures. At low ambient temperatures (< 0 °C) the CC power decreases in any case with FGR because the recirculated flue gas is limited to a certain temperature, so that the difference between flue gas and ambient air is relatively large. The inducement of the flue gas temperature on the CC net efficiency, also given in the fourth chart of figure 9, increases for high ambient temperatures. For a low flue gas temperature the CC net efficiency does not decrease more than 0.8 % over the whole range in ambient temperature, whereas in the case of warm flue gas the CC net efficiency decreases by more than 1.5 % (for high ambient temperatures).

## IMPACT OF FGR ON PARTLOAD PERFORMANCE AND OPERATIONAL FLEXIBILITY

Given that operational flexibility is a key feature of current combined cycle power plants, the implications of operating a

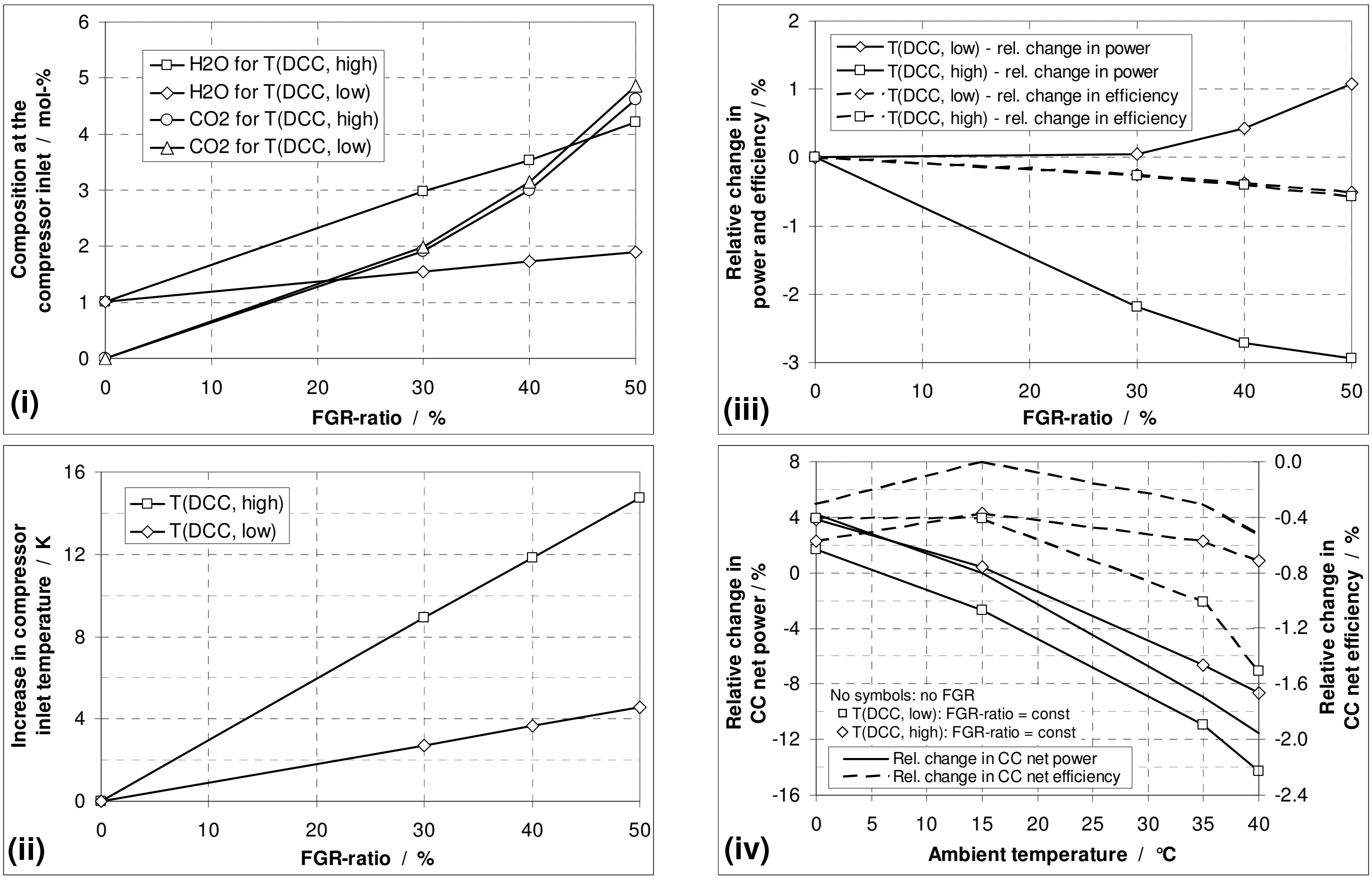


***Figure 9*** *Parameter variation versus the FGR-ratios for different flue gas temperature after the direct contact cooler: (i) amount of* $H_2O$ *and* $CO_2$ *at the compressor inlet, (ii) increase of compressor inlet temperature, and (iii) change in CC net power and CC net efficiency. Parameter variation versus ambient temperature: (iv) change in CC net power and CC net efficiency for different flue gas temperatures after the direct contact cooler. The temperature difference between the 'T(DDC, high)' and the 'T(DDC, low)' flue gases is 20 K in all charts.*

plant with flue gas recirculation at part load should be considered. The combustor is the component of the gas turbine, which is mainly affected by flue gas recirculation. The impact on the compressor and turbine is compared to the combustor small. Therefore the focus in this section is on the operational aspects of the combustion system.

In general, at partload the combustor outlet temperature is reduced and the variable inlet guide vane (VIGV) are closed to lower the mass flow through the GT, see figure 10. A GT with reheat combustor allows a flexible operation of the engine enabling to find an optimized operation range for given conditions and fuel composition. In general, the two combustors can be operated on different temperatures with only a minor impact on overall power output. This increases the flexibility of allowing to combust more or less reactive fuel [7]. The conditions of flue gas recirculation lead to a decreased reactivity due to the lower oxygen concentration. In case of flue gas recirculation, the variation of these two combustor temperatures offers more flexibility than a non-reheat concept. The differences in reactivity due to FGR can be handled in such a way that the operating conditions are optimized with respect to stability and overall GT emissions. For example, increasing the exit temperature of the HP turbine can compensate the lower reactivity. A higher HP turbine exit temperature affects the flame temperature in the EV and the SEV combustor in the same manner. At the same time, also the inlet temperature of the SEV combustor increases, which helps the stabilization of the flame in the SEV combustor. In terms of flame stability the exit temperature of the HP turbine can be used to adapt the conditions for both combustors (EV and SEV). In particular for high FGR-ratios – resulting in low oxygen concentration in the SEV combustor – a high inlet temperature of the SEV combustor is beneficial with respect to flame stabilization.

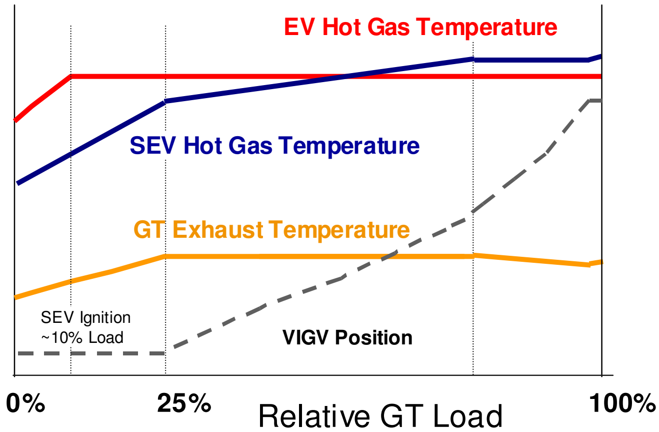


*Figure 10 Distribution of EV and SEV hot gas temperature, GT exhaust temperature and VIGV position versus relative load.*

In figure 10 the operation concept of both hot gas temperatures, the GT exhaust temperature and the VIGV position are qualitatively shown from baseload to idle operation for an Alstom's reheat GT (without FGR). Generally, in partload operation the EV hot gas temperature remains more or less constant, while the SEV hot gas temperature is used to control the desired GT load. For example, in case of FGR one could think to keep the SEV combustor hot gas temperature on a higher level for lower loads while reducing the EV hot gas temperature (this also provides more O2 for the SEV). The two different temperatures can be optimized to meet emissions targets in partload operation.

A method of maintaining FGR at low part loads is based on the Low Load Operation Concept [14], modified such that the EV runs warmer so as to increase the margin to FGR-induced LBO limits; the SEV can be run colder or even turned off completely.

Another aspect of operating a CCPP with $CO_2$ capture in partload operation is the requirement for the $CO_2$ capture unit. The CCPP itself is affected by the steam extraction from the LP steam turbine. Technically it is feasible to extract LP steam even at low relative loads but most likely it will also be a economically driven question down to which relative load the $CO_2$ capture unit will be in operation.

## CONCLUSIONS

This paper describes the impact of FGR upon a combined cycle power plant (based on Alstom's reheat GT24/GT26) with $CO_2$ capture, on both general and technical terms. In the first instance, the following aspects were analyzed in order to illustrate the technical impact of FGR:

- Intrinsic differences between reheat and non-reheat GT.
- Impact of FGR upon combustion process.
- Variation of the FGR parameters most influencing the GT.
- Influence of FGR upon CCPP.

Subsequently, the effects of flue gas recirculation upon a combined cycle power plant with $CO_2$ capture are elucidated, in terms of overall performance and operational flexibility. The main findings of the investigations presented in this report are:

- Reheat GT promotes operational flexibility, both with and without flue gas recirculation.
- The Flue gas temperature after DCC is the most influential FGR-parameter (in the flue gas path) affecting performance.
- The high inlet temperature of the SEV combustor is beneficial in terms of flame stabilization, in particular, for high FGR-ratio resulting in low oxygen concentrations.
- Flue gas recirculation reduces regeneration steam requirements of $CO_2$ capture unit.
- For the reference cycle (CCPP with CCS): FGR increases net power and efficiency by 3.6 % and 2.1 %, respectively.
- For the reference cycle (CCPP with CCS): FGR reduces CoE by 5%. It also reduces minimal $CO_2$ price needed to make $CO_2$ capture viable. Nevertheless, the minimum

feasible $CO_2$ prices are markedly higher than the current market levels.

Furthermore, the effects of flue gas recirculation upon the combined cycle power plant itself (without $CO_2$ capture) results in the main findings presented in this report:

- The temperature of the recirculated flue gas (after the direct contact cooler) determines mostly the impact on the GT and the CCPP.
- FGR leads to both an increased compressor inlet temperature and a higher GT exhaust temperature. These two effects (partly) compensate each other such that the GT is more affected than the CCPP.
- In terms of change in working fluid the $CO_2$ concentration depends on the FGR-ratio, whereas the water content strongly depends on the temperature of the recirculated flue gas (after the direct contact cooler).

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