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Technologies for Gas Turbine Power Generation with CO_2 Mitigation

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Abstract

A review of the state of the art gas turbine power plants designs with CO_2 capture was performed to set up a list of technologies to be considered in a conceptual process superstructure. It has been found that the efficiency and economics of carbon dioxide capture in gas turbine combined cycle power plants can be remarkably improved by introducing Flue Gas Recirculation (FGR) so as to increase the CO_2 concentration in the flue gas and to reduce the volume of the flue gas treated in a CO_2 capture plant. Thus, this process was chosen as the main focus of the thermo-economic modeling and the combustion system related experimental testing.
Combustion studies were performed to quantify the impact of reduced oxygen content (caused by flue gas recirculation) on combustion stability and emission characteristics (NO_x, CO). Tests were performed with methane, methane/ethane (simulated natural gas), methane/hydrogen and natural gas (as distributed in Switzerland) at different FGR ratios. For all conditions the addition of ethane or hydrogen shows beneficial effects (restoration of flame reactivity) on flame stability and CO emission. Using PSI's high pressure test rig, it has been shown, that by redirecting up to 30% of exhaust gas volume back to the combustor, the CO_2 concentration in the exhaust can be increased to 8% vol. while keeping the flame temperature constant (T_{ad} = 1750 K) and meeting the emission requirements (CO, NO_x < 25ppm @ 15% O_2).
Benchmark tests of catalytic partial oxidation reactors were performed to determine whether sufficient H_2 could be produced in situ by reaction of a slip stream of natural gas with extracted compressor oxidant.
The work confirmed that FGR has the potential to significantly reduce the energy penalty connected with post-combustion carbon capture techniques and still meet the requirements on NOx and CO emissions.

Keywords: fluegas recirculation, gas turbine, power generation, thermo-economic modeling, emission (NO_x, CO)

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1. Introduction & Approach

The focus of the project activities is concerned with technologies for large (400 MW) combined cycle plants with CO_2 capture. In terms of the overall process the target is to achieve a CO_2 avoidance cost of less than 25 € per ton CO_2 for gas turbines.

Although the literature is filled with many creative gas turbine cycle options for CO_2 removal, many of these cycle variations require significant modifications to the key turbomachinery components in order to handle the modified fluid compositions. By simply applying flue gas recirculation (FGR) in order to facilitate CO_2 removal via increased CO_2 concentrations in the exhaust gas, most of these complications for the turbomachinery components are avoided or minimized. The gas turbine process evaluation in this paper thus focused on studies on the effect of exhaust gas recycle upon cycle performance.

The main effort was directed towards process design, using thermo-economic modeling and optimization. The goal is to develop a process superstructure including different options for a gas turbine power plant with CO_2 capture capability. By applying a consistent methodology that is based on thermo-economic modeling and energy integration techniques using multi-objective algorithms, different options have been analyzed, optimized and compared systematically in order to reveal which are most promising. Based on the developed models, the impact of CO_2 recirculation on compressors, turbines, combustion, CO_2 capture and the steam network has been assessed.

With flue gas recirculation major modifications though are required for the combustion section as the combustion properties of highly diluted fuel mixtures can change significantly. Due to the importance of the recirculation rate on the overall performance of the CO_2 removal process combustion studies are required to define the maximum achievable recirculation rate. Combustion stability concerns dictate hereby the minimum amount of oxygen excess concentration allowable. The emissions of other combustion pollutants must remain at current levels (NO_x < 25 ppm, CO < 10 ppm).

The questions addressed in the experimental studies have been related to issues such as the impact of a low O_2 excess and high level of inert gas on combustion stability and emissions, as well as if and how combustion stability can be improved by adding highly reactive species (H_2-rich fuel gases) into the fuel mixture (preferably based on an integrated production of syngas or hydrogen).

High pressure combustion studies have been performed to determine the impact of flue gas recirculation on the lean blow out limit and emission of CO, NO_x for methane and simulated natural gas mixtures. For a given fuel injection geometry, inlet temperature and pressure, combustion stability limits have been determined for conditions corresponding to up to 50% flue gas recirculation. The target has been to have stable combustion at less than 2 %vol. of excess oxygen concentration.

The impact of hydrogen doping and hydrogen injection into flame stabilization zones of a combustor has been measured. The target was to achieve similar combustion stability (quantified by the residence time necessary for complete combustion) for various degrees of flue gas recirculation. The impact of hydrogen injection on minimum required level of excess oxygen has been identified.

The performance of pilot scale catalytic partial oxidation reactors has been determined as a function of methane/oxygen ratio, pressure, temperature, and residence time. These reactors are designed for integration into a fuel injector of a gas turbine combustor.

2. CO emission characteristics for CH_4/air mixtures with dilution simulating FGR

The goal of this experimental effort was to determine whether NO_x and CO emissions could be maintained within allowable limits when FGR is applied and whether the operation range is still compatible with requirements (mainly firing temperatures) imposed by the gas turbine system. A series of measurements was taken for every FGR rate, covering a wide range of fuel/air ratios limited only by the maximum allowable exhaust gas temperature (1400°C; as measured) and by excessively high CO emissions near the lean flame blowoff limit (high excess air ratio). The limits for the emission values of CO and NO_x were chosen to be 25 ppm (normalized to 15% O_2), which is still the widely accepted limit for large stationary power plants.

Figure 1 shows a typical example for the CO emission trends observed for varying air excess ratios (i.e. flame temperatures) when simulated flue gas recirculation is applied. A pronounced minimum in the CO emission can be observed for most of the chosen pressure conditions (indicated by the dashed black line at $\lambda = 1.85$). Towards even leaner fuel/air ratios ($\lambda > 1.85$) the steep rise in the CO emission is a result of increased dilution and decreased flame temperature which causes the flame to approach its lean blow out limit. The decreasing flame temperature slows down the chemical kinetic reaction rates required for the complete conversion of the fuel components including CO (as the most important product of partial oxidation of hydrocarbon species). For less lean conditions ($\lambda < 1.85$) a steep increase of the CO emissions is likewise observed, but, in this case, it is coupled with a certain pressure dependence (most significantly seen for the highest pressure data, p = 20bar). For these fuel/ratios and the related (high) flame temperatures high CO chemical equilibrium values (due to dissociation of carbon dioxide) are the determining factor for the CO emissions. High pressure conditions are thus confirmed to be favorable for low CO emissions, especially for high FGR.

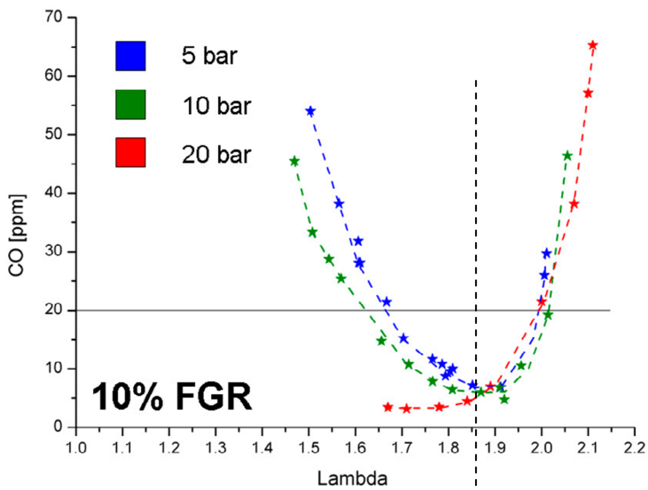

Figure 1: CO emission in dependence of the fuel/air ratio for three different pressure levels (FGR = 10%)

In Figure 2 the results for CO emission for three different FGR rates at constant pressure (20 bar) are shown. This was the highest pressure at which data could be acquired so far (limitation given by the air supply infrastructure), and matches typical pressure conditions of modern gas turbine engines. At this high operating pressure the introduction of even high amounts (30%) of

FGR did not change the CO emission level significantly, as long as the decreased reactivity due to high FGR could be counteracted by running the flame less lean (keeping the flame temperature up at levels of around 1750 K). This compensation measure does not work however for an FGR rate of 40%. For these conditions it is not possible to achieve CO emission levels below 30 ppm CO for the given combustor geometry and flow rates.

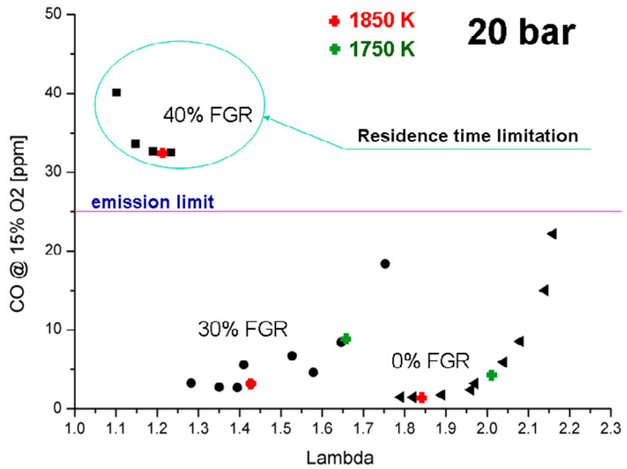

Figure 2: CO emission characteristics in dependence of the fuel/air ratio for three different FGR rates (p = 20bar). Green/red markers indicate flame temperatures of 1750K/1850K, respectively.

To restore the original flame reactivity (judged by the flame location and the CO emission without FGR) hydrogen was added to the fuel mixture either as pure hydrogen or as part of a syngas mixture (containing 60 % H_2 and 40 % CO by volume)in order to move the flame back to its original location.

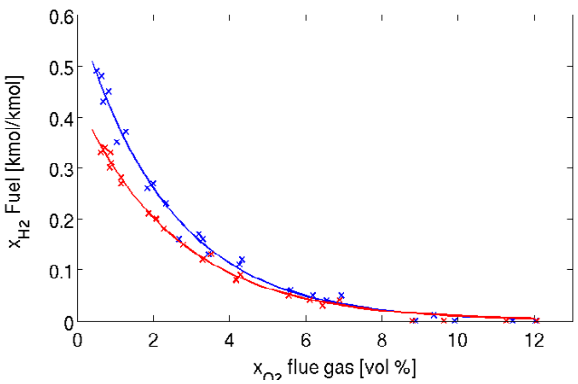

Figure 3: Required level of H_2 to restore reactivity as a function of O_2 vol % in the exhaust gas. Tests performed at 8 bar and 1750 K adiabatic flame temperature. Hydrogen added to the fuel via pure hydrogen (blue line) or syngas 60% H2 and 40% CO (red line).

The overall amount of hydrogen necessary to compensate for the reduction in reactivity due to the depletion of oxygen was measured for a variety of conditions for Swiss natural gas, Figure 3. It was shown that the inlet temperature played a minor role, but also that less hydrogen was required if syngas was added, indicating that CO also plays a stabilizing role.

The concept of adding hydrogen to restore the reactivity of flames in case of FGR has been followed also in the conceptual studies for process modeling. It has been evaluated to what extent an in-situ generation of hydrogen-rich syngas (via steam reforming or catalytic partial oxidation) influences the performance of a combined cycle plant with CO_2 capture.

3. Thermo-economic modeling of novel gas turbine cycles

The conceptual superstructure for future gas turbine power plants designs represented in Figure 4 includes pre-combustion, oxy-combustion and post-combustion options for CO_2 capture, as for example a natural gas gas-turbine combined cycle plant (NGCC) with exhaust gas recirculation, an advanced zero emission gas turbine power plant (AZEP) and a catalytic partial oxidation (CPO) power plant.

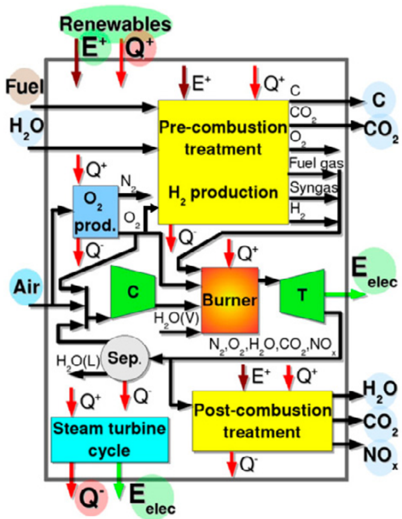

Figure 4: Conceptual superstructure of gas turbine power plants with CO_2 capture

This project is focused on power plants with post-combustion CO_2 capture, consisting of a gas turbine with flue gas recirculation, a CO_2 capture unit (chemical absorption with amines) and a steam network. This system can be represented in a more classical scheme in Fig. 5.

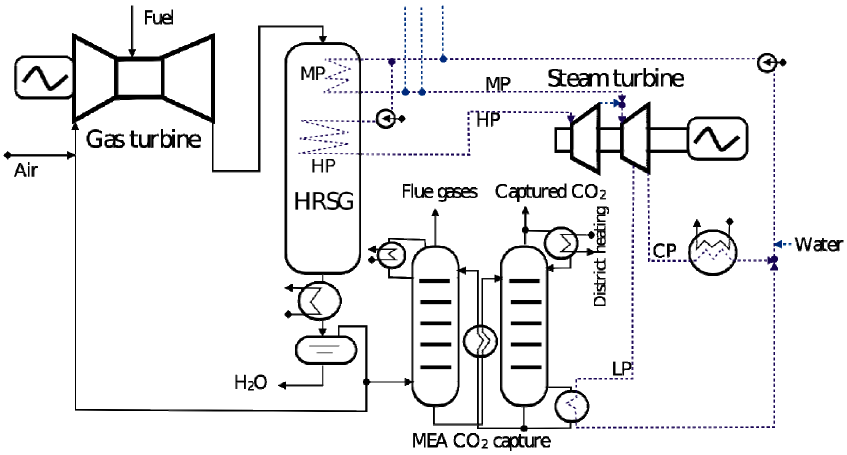

Figure 5: Process scheme

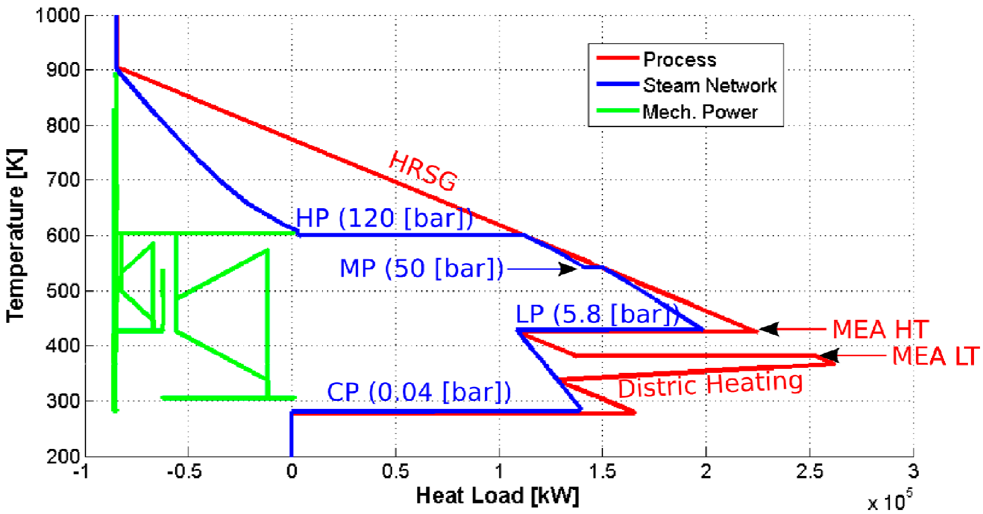

Figure 6: Composite curve: Steam network integration with the gas turbine and the CO_2 capture unit without FGR and including district heating potential.

Compared to the base case without FGR and without CO_2 mitigation, capture of around 90% of the CO_2 emissions induces a thermodynamic process efficiency penalty in the range of 10 points if one considers a preliminary simple, non-optimized steam network as illustrated in Figure 6. This representation is widely used in energy integration. One of its main advantages is that the surface between the process (in red) and the steam network (in blue) is an indicator of the losses.

Figure 7 shows the net electricity produced demonstrating that the increase of power consumption due to syngas production can be more than compensated by the increase of power produced by turbines (with the assumption of constant turbine isentropic efficiency).

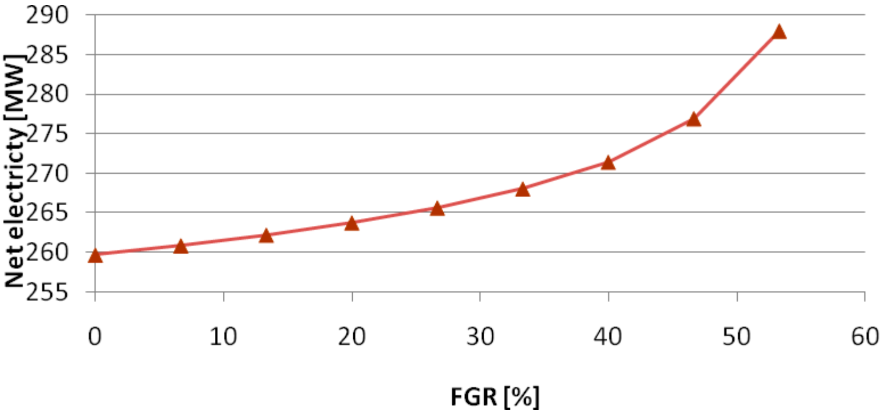

Figure 7: Influence of FGR on the net electricity generation

The efficiency appears to be optimal at 40 % recirculation as shown in Figure 8. However, variation is smaller than 1 %. Two points have to be taken in consideration. First a fix steam network design has been used for every points of the sensitivity analysis, whereas, it must be optimized for each configuration. Moreover, the isentropic efficiency has been assumed to be constant. This underlines the importance of simulation of turbomachinery with different fluids.

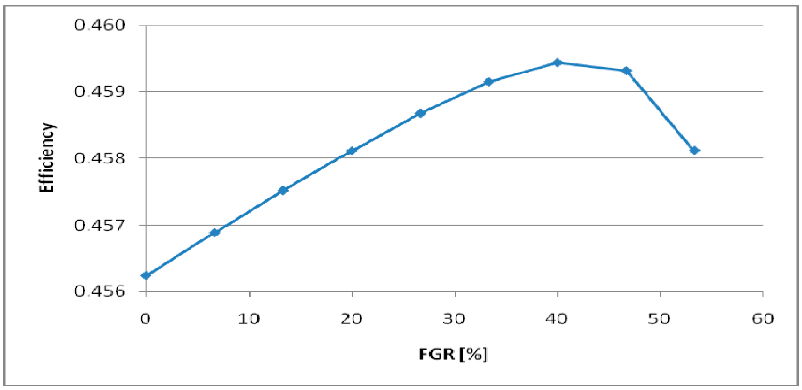

Figure 8: Efficiency variation for different amounts of FGR

Summary & Conclusions

Combustion testing has determined the impact of both oxygen content and fuel composition on combustion stability, for gas turbine processes with flue gas recirculation (FGR). These results have been incorporated into the thermo-economic process calculations.

A pronounced minimum in the CO emission can be observed for most of the chosen pressure conditions with high pressure conditions (20bar) being confirmed to be favourable for low CO emissions, especially for high FGR. This highlights a specifically high risk of elevated CO emission if a gas turbine engine is run at part load condition (i.e. at low/moderate pressure levels).

To restore the original flame reactivity (judged by the flame location and the CO emission without FGR) hydrogen addition (either as pure hydrogen or as part of a syngas mixture (containing 60 % H_2 and 40 % CO by volume) can be very effectively applied.

In summary it can concluded that for adiabatic flame temperatures of around 1750 K - which is a typical operating range for gas turbine combustors - both emission species of concern (NO_x and CO) can be kept safely below 25 ppm @15% O_2 with FGR rates up to 30%.

The efficiency and economics of carbon dioxide capture in gas turbine combined cycle power plants can potentially be improved by introducing Flue Gas Recirculation (FGR) so as to increase the CO_2 concentration in the flue gas and to reduce the volume of the flue gas treated in the CO_2 capture plant. Thus, this process was chosen as the main focus of the thermal-economic modeling performed.

Different process configurations were investigated in order to study the impact of FGR on combustion and CO_2 capture. The impact of hydrogen injection to stabilize the combustion has been studied by considering several ways of integrating the hydrogen or syngas production processes. The results show that the detrimental effect of FGR on the combustion performance (flame stability, CO emissions) can be counteracted with the addition of reactive species (such as hydrogen/syngas) and that this measure does not compromise the efficiency of the power generation process. Economic advantages (reduced CO_2 avoidance cost) thus cannot be expected via a reduced energy penalty in the operation of a post-combustion capture process but only via reduced capital cost due to a more compact component design.

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