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Assessment of the Flue Gas Recycle Strategies on Oxy-Coal Power Plants using an Exergy-based Methodology

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While oxy-combustion CO₂ capture was foreseen to have higher improvement potential than post-combustion a decade ago, research has not been carried out at the same pace since then and today, the latter exhibits higher technological maturity along with low energy penalty thanks to advanced process integration and solvents formulation. Thus, significant efficiency improvement is needed for the oxy-combustion route to be competitive with post-combustion for carbon capture on coal-fired power plants. In order to achieve such improvements, process integration at system level is required to assess the true energy savings potential of oxy-combustion.

In this study, an exergy-based methodology is performed to compare various flue gas recirculation strategies on a state-of-the-art 1100 MWe gross oxy-fired power plant. Exergy analysis at unit operation level allows the identification of the location and the magnitude of the thermodynamic irreversibilities occurring in the process, leading to an enhanced understanding of the studied system. In addition to the reference case in which the secondary recycle is fully depolluted and dehydrated; three alternative flue gas recirculation options have been investigated.

Among the studied strategies, recirculation of the secondary flow prior the regenerative heat exchanger with a high temperature particle removal device leads to the highest net plant efficiency. This option not only allows the minimal exergy losses in the boiler but also minimizes the flowrate going through the downstream depollution devices. The net plant efficiency obtained for this architecture is 38.0%_{LHV}, which represents a 3% increase compared to the reference oxy-combustion plant. Comparing this figure to an air-fired power plant modeled with the same set of hypotheses, the energy penalty is 8.1%-pts.

1. Introduction

The greenhouse gas and particularly carbon dioxide (CO₂) mitigation is a central focus of the scientific community for more than a decade. In 2010, electricity and heat production was responsible of 41% of the world CO₂ emissions (IEA, 2012a). In addition of that, since 41% of the electricity is produced from coal (IEA 2012b), the development of CO₂ capture technology on coal-fired power plants is of a crucial importance in order to meet future emissions reduction targets.

A decade ago, post-combustion and oxy-combustion CO₂ capture technologies exhibited equivalent energy penalty while higher improvement potentials were expected for the latter. However, research has not been carried out at the same pace since then and post-combustion technologies with advanced process integration and solvents exhibits very low energy penalty along with a high technological maturity. Thus, significant efficiency improvement is needed for oxy-combustion to be competitive with post-combustion. Although studies have been carried out concerning the optimization of air separation units (Fu, 2012, Chang, 2012) or the boiler (Scheffknecht, 2011), only few system level analysis of the oxy-fired coal power plant has been performed (Hu, 2012).

This work focuses on the exergetic-based assessment of various flue gas recirculation options offered by oxy-combustion. In addition to enhancing the understanding of the system by locating the losses at unit operation level, this study allows the assessment of further process integration opportunities.

2. Methodology

A 1100 MWe gross oxy-fired coal power plant operating at base-load and steady-state is modelled and simulated using Aspen Plus v7.2. Oxygen at 95%_{mol} purity is provided by a conventional double column air separation unit (ASU) and an auto-refrigerated compression and purification unit (CPU) produces a 96%_{mol} purity CO₂ flow at 110 bars in dense phase for further pipeline transportation. For the sake of consistency with other European studies on carbon capture technologies, the modelling hypotheses adopted in this

study are based on the recommendations of the European Benchmarking Task Force (EBTF, 2011), unless otherwise stated. Low sulphur, international grade, Bituminous Douglas Premium coal with lower heating value (LHV) of 25.2 MJ/kg is considered and ISO standards for inland plant construction are adopted regarding the ambient conditions. Concerning the thermodynamic models, STEAM-NBS model is used for the steam cycle, RK-SOAVE for the boiler and flue gas depollution train and PR-BM for the cryogenic processes.

Using the material flow exergy content determination methodology described by Hinderink et al. (1996) and implemented by Jacobs Consultancy (2009), exergy analysis is carried out at unit operation level. The reference environment described by Szargut (1988) is adopted and the reference state is 25°C and 1.01325 bars. The coal exergy content has been assessed from its LHV using the method described by Szargut and Strylska (1964). The bituminous coal considered in this study has an exergy content of 26.7 MJ/kg.

3. Process Description

3.1 General description

Figure 1 presents a schematic representation of the reference oxy-fired power plant. A state-of-the-art supercritical power cycle with steam conditions of 300 bars / 600°C / 620°C is considered. The boiler feedwater (FW) is heated up to 315°C by steam extractions in seven feedwater heaters (FWH) and a deaerator. Regarding heat rejection, natural draft cooling tower is used, leading to a condenser pressure of 48 mbars considering a cooling water temperature of 18°C.

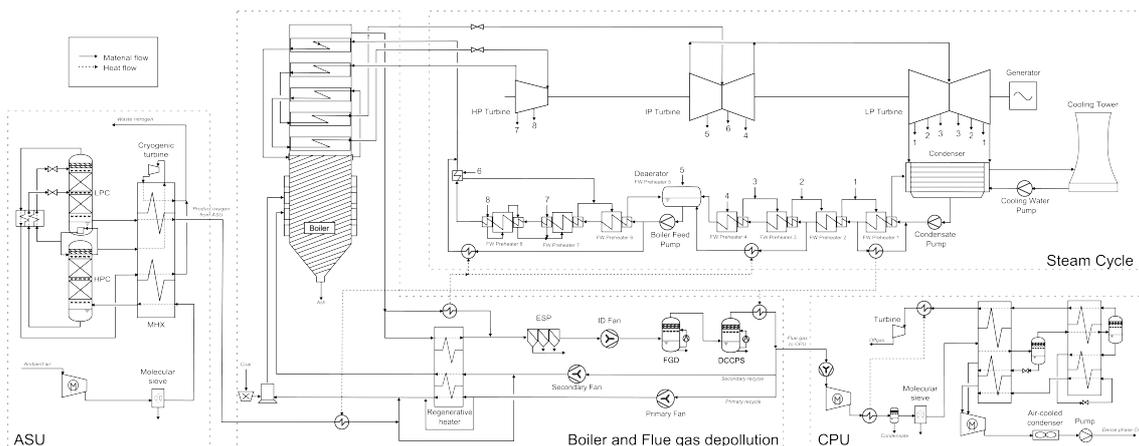


Figure 1. Simplified PFD of the reference oxy-combustion power plant

The boiler is modelled as a reactor calculating the chemical and phase equilibriums by minimization of the Gibbs free energy of the system at 1250°C and the feedwater flows successively through an economizer, the water wall tubes and two superheaters. The reheat steam flows through two resuperheaters. After denitrification in a selective catalytic reduction (SCR) unit operating at high temperature, the flue gas heads to a Ljungstrom-type regenerative heater (RH). A flue gas bypass allows the integration of the surplus heat into the steam cycle. A portion of the primary recycle is also bypassed and remixed straight after the RH in order to cool down to 110°C the flow heading to the coal handling system. Then, the flue gas passes successively through an electrostatic precipitator (ESP) for particles removal, a wet flue gas desulfurization unit (FGD) and a direct contact polishing scrubber (DCCPS) for further depollution and dehumidification. The flue gas, saturated at 18°C, is then reheated up to 40°C to ensure that no downstream condensation occurs. Air infiltration of 3%_{wt}, located in the boiler (30%) and at the ESP (70%) is assumed (Kather, 2011).

The 95%_{mol} purity oxygen is provided at 1.2 bars by a conventional double column air separation unit (ASU). This value is regarded as the best energy trade off considering the consumptions of both the ASU and the compression and purification unit (CPU) (Wilkinson, 2001). Ambient air is compressed up to 4.9 bars in a three-stage compressor with inter-cooling and flows through a molecular sieve for water and CO₂ removal before entering the main heat exchanger (MHX). The air flow is cooled down near its dew point and sent to the high pressure column (HPC) operating at 4.4 bars. This column is thermally coupled by a

condenser-reboiler system with the low pressure column (LPC) operating at 1.2 bars. Assuming pinch temperatures of the condenser-reboiler and the MHX of, respectively, 0.5°C and 1.5°C, the specific consumption of the ASU is 199 kWh/t_{O₂}.

The depolluted flue gas is sent to the compression and purification unit (CPU) for final purification and compression. After compression up to 26.5 bars in a three-stage compressor with inter-cooling, the flue gas is sent to a molecular sieve for water removal to avoid ice formation in the cryogenic section. The dry flue gas is then cooled down and the incondensable gases (oxygen/nitrogen/argon) are separated in a double flash system, the bottom flows being partially expanded in valves for cold production. The vapour stream of the second flash is warmed against the inlet flue gas, heated by the compression heat and expanded in a turbine for power recovery. The two CO₂ rich liquid flows are mixed and compressed up to 65 bars in a three-stage compressor with inter-cooling, condensed with ambient air, and pumped to 110 bars for further pipeline transportation. The purity of the product CO₂ is 96%_{mol} and the specific consumption of the CPU is 117 kWh/t_{CO₂}.

In order to control the flame temperature in the boiler, dilution of the oxygen flow provided by the ASU is required. The oxygen content needed to achieve the same adiabatic flame temperature as in air-fired combustion is around 28%_{mol} (Wall, 2009). A 3.5%_{mol} oxygen excess at the economizer outlet is supposed. For all the investigated configurations, the primary recycle, heading to the coal handling system, is fully depolluted and dehydrated. The primary oxidant to coal mass flowrates ratio at the inlet of the coal handling system is fixed at 2.4. The secondary recycle, on the other side, can be realized at different locations as long as the sulphur level in the boiler remains low enough to avoid excessive fireside corrosion issues.

3.2 Recirculation schemes

Figure 2 is a schematic representation of the flue gas recirculation options considered in this study. It is assumed that the low-sulphur content of the considered coal (0.5%) allows the recirculation of the secondary flow without undergoing desulfurization. It has to be noted that, since recirculation without sulphur removal increases the SO_x concentration in the flue gas, the recirculation options investigated in this study might not be suited for coals with higher sulphur content.

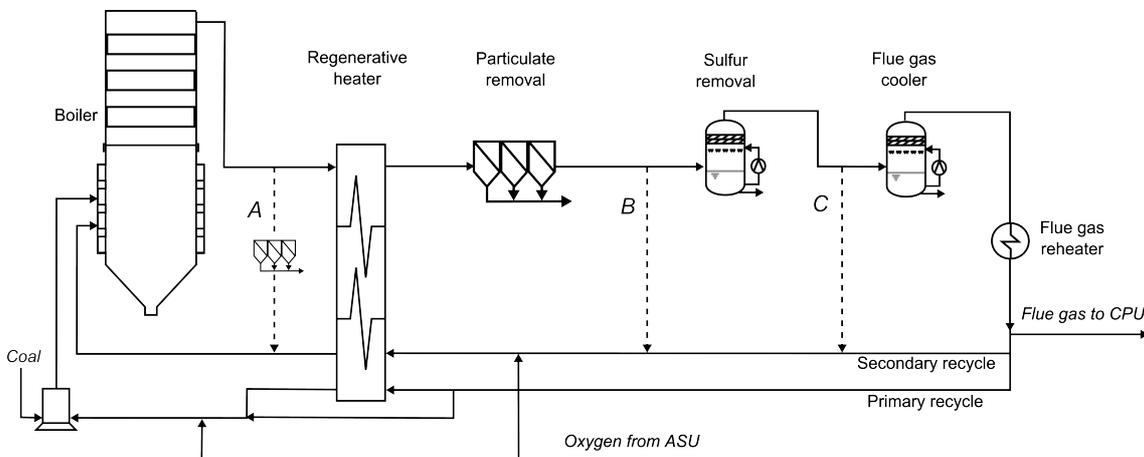


Figure 2. Schematic representation of the investigated flue gas recirculation options

In the reference case, the secondary recycle flows through particle removal in the ESP, desulfurization in the wet FGD and water removal in the DCCPS. The alternative secondary recycle options investigated in this study are the followings:

Case A - The secondary recycle is carried out before the regenerative heater in order to maximize the temperature. A high temperature particle removal device is used in order to avoid excessive ash concentration in the boiler and erosion of the secondary fan.

Case B - In this recirculation option, the flue gas undergoes particle removal and is recycled, wet, at a temperature around 130°C and is reheated against the flue gas up to 310°C in the RH.

Case C - In this last option, the secondary flow is sent recycled after sulphur removal but before the DCCPS.

Table 1. Flue gas acid dew point at the regenerative heater outlet calculated using Okkes correlation

	Reference	Case A	Case B	Case C
P_{SO_3} (μbar)	3.4	6.8	6.9	3.2
P_{H_2O} (bar)	0.09	0.17	0.17	0.22
$T_{\text{dew point}}$ ($^{\circ}\text{C}$)	116	127	127	126

In oxy-fuel combustion, the higher water content in the flue gas generally leads to acid dew points 20-40 K compared to air-fired (Kather, 2011). Thus, the flue gas temperature has to be kept above the acid dew point associated to the flue gas sulphur trioxide and water content. The acid dew points assessed using the correlation described by Okkes and Badger (1984) are reported in Table 1. The temperature of the flue gas is kept above 130°C as long as it has not been desulfurized in order to ensure that no acid condensation occurs.

4. Results

Figure 3 shows the exergy losses occurring in the boiler and flue gas depollution sections for the reference oxy-fired plant and the three alternative cases. The oxygen flow is preheated by feedwater according to the temperature of the flue gas recycle flow (Table 2). The temperature approach for these liquid/gas heat exchanges is assumed to be 10°C . It has to be noted that the oxygen preheat temperature in Case A is limited by the feedwater maximum temperature (315°C).

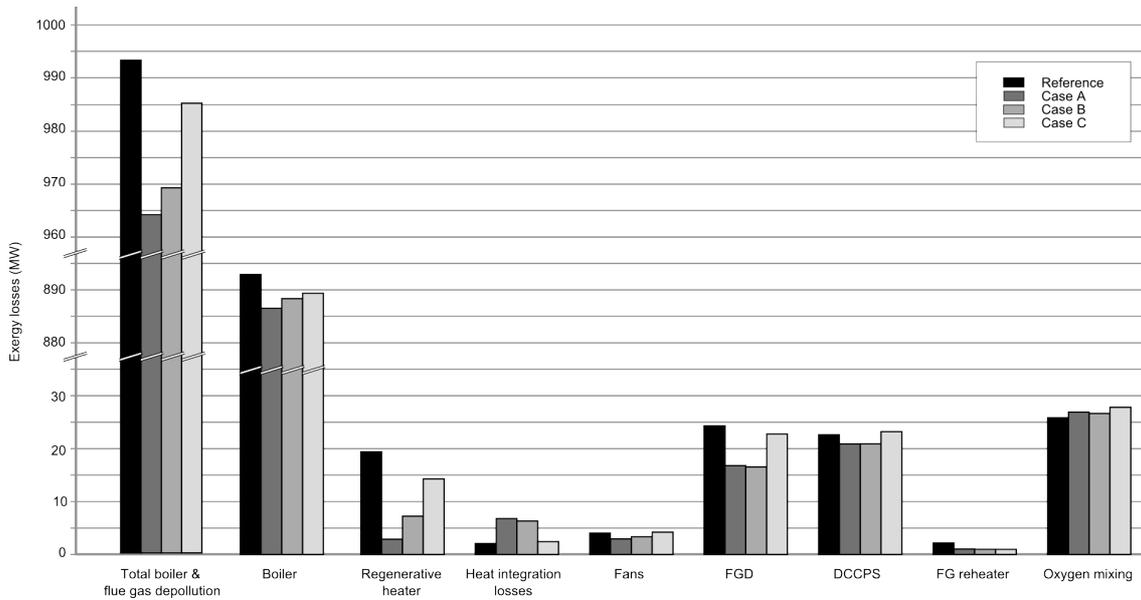


Figure 3. Exergy losses occurring in the boiler and flue gas depollution sections for the different cases

Table 2. Oxygen preheat temperatures and temperatures of the secondary recycle flow

	Reference	Case A	Case B	Case C
$T_{\text{preheat primary oxygen}}$ ($^{\circ}\text{C}$)	110	110	110	110
$T_{\text{secondary recycle}}$ ($^{\circ}\text{C}$)	47	348	140	73
$T_{\text{preheat secondary oxygen}}$ ($^{\circ}\text{C}$)	47	305	140	73

Compared to the reference plant, the alternative cases A, B and C lead respectively to 3.0, 2.5 and 0.9% decrease in terms of total exergy losses in the boiler and flue gas depollution section. These gains are

mainly due to the increased temperature of the secondary recycle flow at the regenerative heater inlet, and the reduced flowrate going through the FGD, the DCCPS and the flue gas reheater. Concerning the boiler, the higher the secondary recycle temperature, the lower the losses. The oxygen mixing induces substantial losses. However, these losses are unavoidable since they are due to the material flow composition change. Finally, when comparing the losses due to heat integration, the amount of recovered exergy has to be taken into account. This value is respectively 11.7, 33.2, 30.0 and 16.7 MW for the reference, Case A, Case B and Case C.

Table 3. Overall energy performances of the different recirculation options

	Reference	Case A	Case B	Case C
Plant net output (MW)	775	797	792	779
Net plant efficiency (% _{LHV})	36.9	38.0	37.8	37.2
Energy penalty (%-pts)	9.2	8.1	8.4	9.0
Energy gain (%)	0	3.0	2.4	0.8

The main energy performances of the different cases are gathered in Table 3. The option leading to the best energy performance is Case A, with a net plant efficiency of 38.1%_{LHV}, which represents a 1.2%-pts increase compared to the reference architecture.

5. Conclusions

In this study, an exergy-based assessment of different flue gas recirculation strategies in oxy-fired pulverized power plant has been performed. Among the options investigated, Case A yields the lowest exergy losses closely followed by Case B. Recirculation of the secondary recycle at high temperature not only allows minimal exergy losses in the boiler section but also minimizes the flue gas flowrate passing through the FGD, the DCCPS and the flue gas reheater, decreasing the associated exergy losses. It also enables the downsizing of these units, leading to lower capital costs compared to the reference case.

The trend given by the exergy analysis is in accordance with the calculated overall plant performance. Case A is the most efficient architecture leading to a net plant efficiency of 38.0%_{LHV}, followed by Case B with 37.8%_{LHV}, which represent respectively a 1.1 and 0.8%-pts increase compared to the reference plant. Concerning Case C, the performance associated to the recirculation after desulfurization could be increased by using a high temperature desulfurization device such as spray dry absorber.

Finally, economic considerations still remain to be taken into account to determine if the 0.2%-pts gain observed for Case A compared to Case B worth the investment of a costly additional particle removal device. Further work will include substitution of the Ljungstrom type regenerative heater by a finned tube or a plated heat exchanger in order to minimize the temperature approach and avoid the leaks and the introduction of a condensing heat exchanger for flue gas latent heat recovery.

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