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Energy Procedia 63 (2014) 7359 – 7366

Energy Procedia

GHGT-12

Optimal Integration of the Flue Gas Heat for the Minimization of the Energy Penalty of Oxy-fired Power Plants

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Abstract

Oxy-fired coal power plants require the recycling of flue gas to dilute the oxygen in order to moderate the combustion in the boiler. This induces a significant structural modification of the boiler and flue gas train compared to air-fired power plants, offering the opportunity for new thermal integrations opportunities.

In this study, a methodology allowing the assessment of the net plant efficiency increase brought by finely integrating heat sources into the steam cycle with minimal simulation runs is used for the comparison of several flue gas heat valorization layouts. Three configurations described in literature have been compared to an alternative option aiming for the minimization of exergy losses. For each of those configurations, the net plant efficiency after integration has been assessed and compared to an air-fired power plant in order to determine the energy penalty induced by carbon capture. Results show that the proposed alternative leads to promising energy performances: a net plant efficiency increase of 0.5 $\%_{LHV}$ can still be obtained compared to the already integrated base-case, reducing the energy penalty from 7.1 %-pts down to 6.5 %-pts.

Keywords: Carbon capture; Heat valorization; Oxy-combustion; Process integration

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doi:10.1016/j.egypro.2014.11.772

1. Introduction

Carbon capture and storage has been identified as one of the most promising solution to comply with the greenhouse gas emissions mitigation targets fixed as a first step toward a more decarbonised energy mix. Among the routes foreseen by the scientific community, oxy-combustion is the most credible alternative to post-combustion by chemical absorption for pulverized-coal applications. However, despite fundamental and experimental demonstration of the technology during the last decade, uncertainties remain about oxy-fired operation and the structural changes of the boiler island lead the plant operators to have a leaning toward post-combustion capture, especially for retrofit applications.

Thus, for oxy-combustion to become a credible contender, significant energy penalty reductions are mandatory and an optimal heat integration pattern taking full advantage of operating in oxy-combustion has to be identified in addition to the reduction of the energy demand of the air separation unit (ASU) and compression and purification unit (CPU). In that perspective, many studies have highlighted the benefits of the integration of the flue gas heat but authors have not reached a consensus in its most efficient valorization pathway [1, 2, 3, 4]. In this study, different flue gas heat valorization options have been compared on a consistent basis in order to identify the most efficient solution.

2. Process description

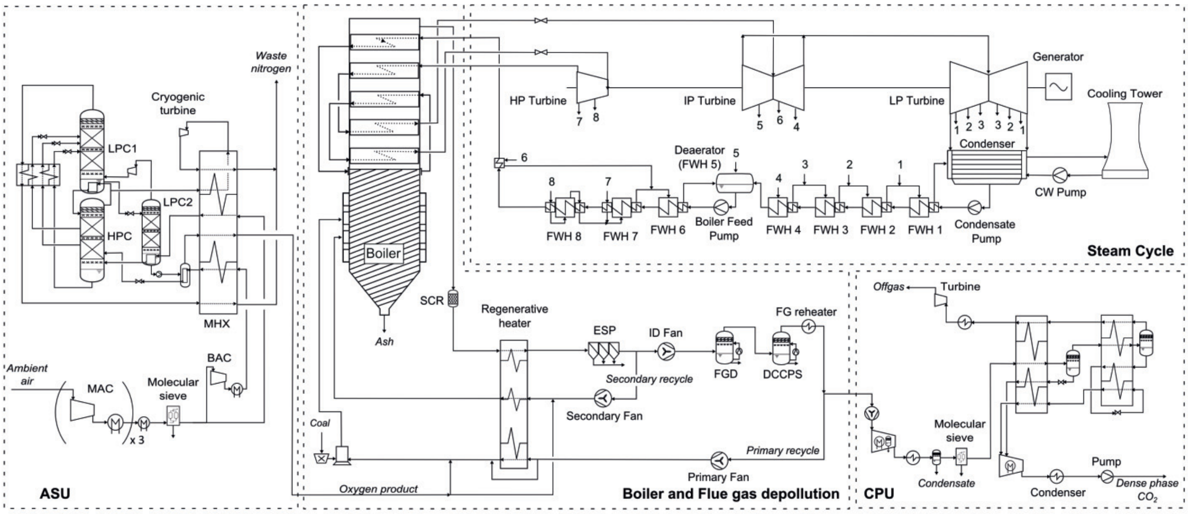

Figure 1 Simplified flowscheme of the considered oxy-fired plant

Figure 1 shows the simplified flowscheme of the state-of-the-art 1100 MW_e gross ultra-supercritical warm-recycle oxy-fired power plant considered in this study. A single reheat Hirn cycle with steam conditions of 300 bar/600 °C/620 °C is used for power production and the boiler feedwater is preheated up to 315°C in seven indirect heat exchanger and a direct contact exchanger also playing the role of deaerator. Oxygen is provided by an up-to-date cryogenic air separation unit (ASU), similar to the one described by [5], featuring a booster air compressor, multiple condenser-reboilers and three distillation columns for minimal energy consumption. The specific consumption of the ASU, producing a 95 $\%_{mol}$ purity oxygen flow, is around 170 kWh/t_{O2}, which is in accordance with the announcements of technology providers [6]. A conventional depollution train is employed: a selective catalytic reduction (SCR) unit for denitrification, an electrostatic precipitator (ESP) for particulate removal and a wet flue gas desulfurization unit (FGD) for the removal of sulfur oxides. A direct contact polishing scrubber (DCCPS) is placed downstream the wet FGD for further depollution and saturation of the flue gas at low temperature, and after slight reheat to avoid any risks of acid condensation, the flue gas is sent to a double-flash CPU to obtain a 96 $\%_{mol}$ purity CO_2 at 110 bar. The recovery rate of the capture unit is 90 %.

3. Methodology

The commercial sequential modular simulation software Aspen Plus is used for the modeling of the base-load steady-state operation of the oxy-fired plant described above. Three different thermodynamic models are used in order to accurately represent the power plant: Redlich Kwong-Soave cubic equation of state for the boiler and the flue gas depollution train, Steam-NBS for the steam cycle and Peng-Robinson cubic equation of state with Boston-Mathias alpha function for the cryogenic processes (ASU and CPU). Concerning the modeling hypotheses, according to the recommendations of the European Benchmarking Task Force, an international grade bituminous coal is used and ISO conditions are adopted for ambient conditions [7]. More detailed information about the power plant model and adopted hypotheses can be found in [8].

In this study, a heat integration methodology, allowing the assessment of the power plant performance gains brought by thermal integration with a minimal number of simulations, has been used in order to assess and compare different flue gas heat integration configurations. This approach relies on the systematic use of boiler feedwater (BFW) for performing rational thermal integrations. Available in large quantity and in a broad range of temperature (from 32 °C to 315 °C), the BFW can conveniently act alternatively as heat source and heat sink, and minimal exergy losses can be achieved for each thermal integration by adjusting the involved BFW flowrates.

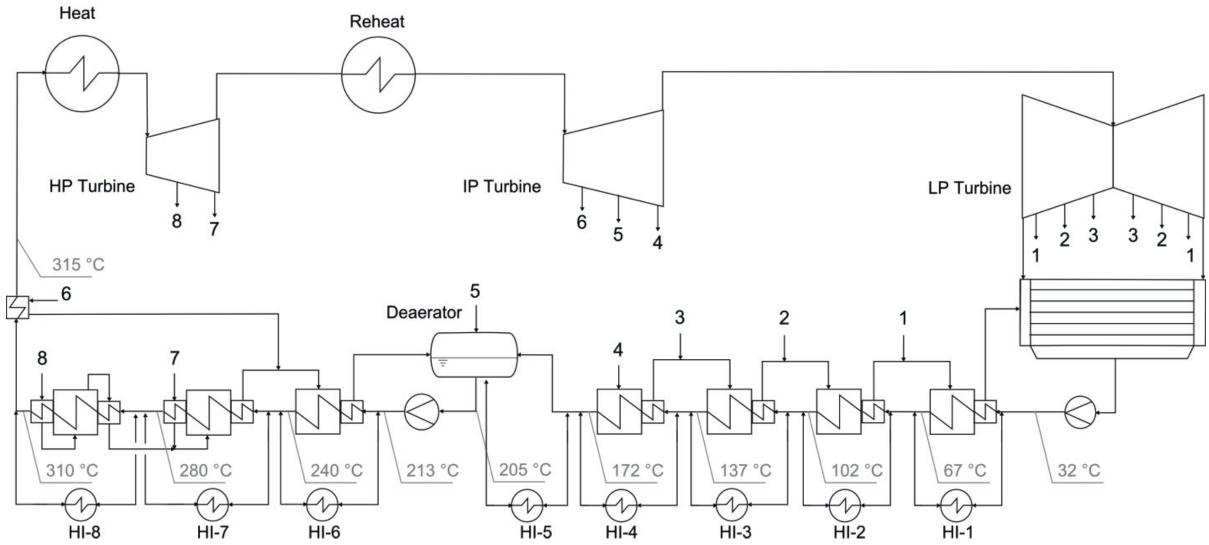

Figure 2 Simplified representation of the steam cycle with virtual parallel heat exchangers devoted to the evaluation of thermal integration

Figure 2 illustrates the adopted heat integration methodology. Integrating thermal energy into the BFW preheating train allows the reduction of the steam bleeding flowrates from the steam turbines, leading to an increased electric production. To each heat exchanger preheating the BFW is associated a virtual heat exchanger called HI-i disposed in parallel. The bypassed BFW flowrate is regulated in order to achieve a constant temperature difference along the heat exchanger so that exergy losses are minimized. This approach allows the assessment of the energetic gains brought by the valorization of a heat source available elsewhere in the oxy-fired power plant and the production drop associated to the use of heat at a given temperature by associating to each of the HI-i a marginal efficiency (η_{HI-i}). Marginal efficiency is defined as the electric power to thermal duty conversion ratio, corresponding either to an energy conversion efficiency when an available heat source is integrated into the steam cycle and a coefficient of performance when thermal energy is provided to a heat sink. The marginal efficiencies of each of the eight HI-i have been determined by Aspen Plus simulation (see Table 1). Those, which are specific to the considered steam cycle, have been proven to be independent to the amount of integrated heat duty.

Table 1 Marginal efficiencies, inlet and outlet temperatures relative to the parallel heat exchangers

		HI-1	HI-2	HI-3	HI-4	HI-5	HI-6	HI-7	HI-8
$\eta_{HI\text{-}i}$	MW_e/MW_{th}	0.09	0.16	0.23	0.28	0.33	0.36	0.40	0.44
$T_{cold\ in,\ HI\text{-}i}$	°C	32	67	102	137	172	213	240	280
$T_{cold\ out,\ HI\text{-}i}$	°C	67	102	137	172	213	240	280	310

Thanks to the marginal efficiencies, the additional work or production drop (ΔW) relative to the thermal integration of a heat duty Q_{Total} available or needed between two temperatures $T_{hot\ in}$ and $T_{hot\ out}$ can be immediately assessed by the following relation:

$$\Delta W[MW_e] = \sum_{i=1}^{8} \eta_{HI-i} Q_{HI-i} [MW_{th}] \tag{1}$$

With $Q_{HI\text{-}i}$ the fraction of the total heat duty Q_{Total} that can be integrated in the heat exchanger i, which is negative for a heat demand and positive when heat is integrated.

To determine the value of each $Q_{HI\text{-}i}$, a minimal acceptable temperature approach has to be supposed. In this study, a value of 10 K is chosen which corresponds to a typical value given by chemical engineering heuristics for gas-liquid heat exchanges. For example, when the valorization of a heat source Q_{Total} available between T_{hot_in}=130 °C and $T_{hot\ out}$=30 °C is considered:

- $Q_{HI\text{-}1}$ is the share of Q_{Total} available between 77 °C ($T_{cold\ out,\ HI\text{-}1}$+10) and 42 °C ($T_{cold\ in,\ HI\text{-}1}$+10). The low exergy content duty beyond 42 °C cannot be valorized in the steam cycle thus cooling water is used when the cooling of the heat source below 30 °C is required.
- $Q_{HI\text{-}2}$ the share available between 112 °C and 77 °C plus the one between 130 °C and 112 °C since $T_{hot\ in}$ is lower than ($T_{cold\ out,\ HI\text{-}3}$+10), hence not allowing the valorization of the duty in HI-3.

Consequently, by discretizing the heat sources and the heat sink along the temperature, the determination of the production increase (or drop) brought by each thermal integration can be assessed. Consequently the total net work differential ΔW_{Total} induced by thermal integration is determined. In turn, the net plant efficiency (NPE) of the plant after thermal integration can be calculated:

$$NPE[\%_{LHV}] = \frac{W_{witout\_HI} + \Delta W_{Total}}{Q_{LHV}} \times 100 \tag{2}$$

Where $W_{without\_HI}$ is the net plant output of the oxy-fired plant prior heat integration and Q_{LHV} is the plant heat input based on the lower heating value.

4. Description of the considered cases

The objective of this study is to compare different flue gas heat valorization patterns. The impact of the preheating of the oxygen flow provided by the ASU has been assessed for each case. The considered flue gas heat valorization options, illustrated in Figure 3, are described below:

- Base-case: the flue gas is cooled down to 130 °C in an indirect contact heat exchanger so called ‘flue gas cooler’, placed right after the regenerative heater. It corresponds to a configuration similar to the one described in [1,2] ;

- Case A: In addition to the ‘flue gas cooler’, a ‘flue gas condenser’ is placed upstream the wet FGD to recover the heat down to 90 °C [3];
- Case B: The flue gas is cooled down to 90 °C upstream the ESP [4];
- Case C: In the alternative flue gas heat valorization layout proposed in this study, a portion of the hot flue gas upstream the regenerative heater is derivated and a recuperative heat exchanger is introduced to recover the flue gas heat. This heat exchanger is called ‘bypass heat exchanger’. This configuration allows the increase of the temperature at which the heat source is valorized, hence increasing its exergy content. In the meantime, the reduction of the temperature difference in the regenerative heater allows the reduction the exergy losses occurring within this heat exchanger. As in Case A, a ‘flue gas condenser’ is placed upstream the wet FGD.

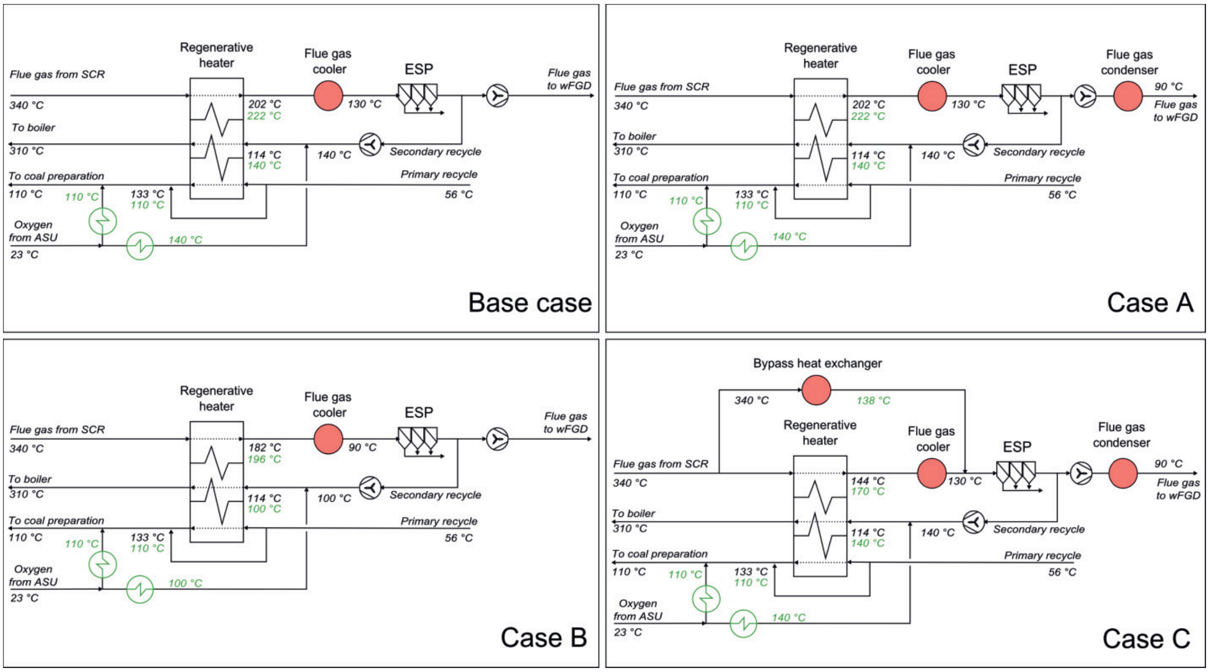

Figure 3 Illustration of the different flue gas heat recovery options

5. Results and discussions

For each of the four flue gas heat valorization cases, the NPE of the oxy-fired power plant has been assessed using equation 2. These efficiencies take into account the integration of the adiabatic compression heats of the ASU (main air compressor) and CPU compressors (flue gas compressor and CO_2 compressor), which have been identified as beneficial in terms of global system efficiency in previous works [8] despite the additional compression power requirement compared to staged-compression with inter-cooling. Additionally, since the flue gas compression heat is valorized into the steam cycle, the duty necessary for the preheating of the CPU offgas prior expansion in a turbine for power recovery is realized using warm BFW. Finally, the slight reheating of the saturated flue gas downstream the direct contact polishing scrubber (DCCPS, see Figure 1) from 19 to 40 °C, is also ensured by BFW for minimal exergy destruction. The information used for the different cases have been displayed in Table 2 for reference.

Table 2 Information used for the heat integration

		Q_i ($\mathrm{MW_{th}}$)	$T_{in,\,i}$ (°C)	$T_{out,\,i}$ (°C)	ΔW_i ($\mathrm{MW_e}$)
Flue gas heat without oxygen preheating					
Base-case					
	Flue gas cooler	65	202	130	
Case A					
	Flue gas cooler	65	202	130	
	Flue gas condenser	21	136	90	
Case B					
	Flue gas cooler	81	182	90	
Case C					
	Bypass heat exchanger	56	340	138	
	Flue gas cooler	9	144	130	
	Flue gas condenser	21	136	90	
Flue gas heat with oxygen preheating					
Base-case					
	Flue gas cooler	83	222	130	
	Oxygen preheating	-18	23	140	
Case A					
	Flue gas cooler	83	222	130	
	Flue gas condenser	21	136	90	
	Oxygen preheating	-18	23	140	
Case B					
	Flue gas cooler	95	196	90	
	Oxygen preheating	-13	23	110	
Case C					
	Bypass heat exchanger	58	340	138	
	Flue gas cooler	25	170	130	
	Flue gas condenser	20	136	90	
	Oxygen preheating	-18	23	140	
Common features to all cases					
ASU main air compressor		91	157	42	-10.2
CPU flue gas compressor		81	206	42	-9.8
CPU CO_2 compressor		31	156	42	-3.3
CPU pressurized offgas reheating		-9	11	110	
Flue gas reheater (after DCCPS)		-8	19	40	+8

These figures have been compared to the NPE of a state-of-the-art ultra-supercritical air-fired pulverized coal power plant modelled with the same set of hypotheses to determine the energy penalty associated to the capture process (see Table 3).

The comparison of the different studied cases reveals that Case C leads to the higher overall plant energy performance. The integration of the flue gas heat at a higher temperature level than the other cases and an optimized hot flue gas flowrate in the regenerative heater allow maximum exergy recovery along with minimized losses in terms of exergy. The net plant efficiency for this case is 39.6 %$_{\mathrm{LHV}}$, which corresponds to a 0.5 %$_{\mathrm{LHV}}$ increase compared to the integrated base-case. Another observation is that for all the configurations, the preheating of the oxygen flow provided by the ASU by steam cycle feedwater at the adequate temperature level is beneficial in terms of net plant efficiency since it allows the upgrading of lower exergy containing heat into high value flue gas heat.

Table 3 Comparison of the energy performances of the studied flue gas heat integration patterns

		Base-case	Case A	Case B	Case C
Plant heat input (LHV)	MW_{th}	2112.7			
Gross electric output w/o integration	MW_e	1084			
ASU consumption (staged-compression)	MW_e	107			
CPU consumption (staged-compression)	MW_e	76			
Auxiliary consumption	MW_e	111			
Net plant output ($W_{without\_HI}$, equation (2))	MW_e	790			
<u>Without oxygen preheating</u>					
Total net work differential (ΔW_{Total})	MW_e	33	35	37	43
NPE	$\%_{LHV}$	38.9	39.0	39.2	39.4
Energy penalty	%-pts	7.2	7.1	6.9	6.7
<u>With oxygen preheating</u>					
Total net work differential (ΔW_{Total})		36	38	41	43
NPE with oxygen preheating	$\%_{LHV}$	39.1	39.2	39.3	39.6
Energy penalty with oxygen preheating	%-pts	7.0	6.9	6.8	6.5

It has to be stressed that, despite the large flowrate of the BFW, a maximum amount of heat that can be integrated into each parallel heat exchanger HI-I still remain. When several thermal integrations are performed, it is important to carefully consider those cases in order not to overestimate the production gains. Indeed, for the base-case, cases A and B, for both with and without oxygen preheating, this situation happens: due to large amounts of heat sources available between 147 and 182 °C, HI-3 is saturated. Consequently, the exceeding duty is downgraded into HI-2, thus valorized with a lower marginal efficiency. In Case C, this situation does not occur since the flue gas heat is integrated at much higher temperature, reducing the share of the heat duty to be integrated into HI-3. Although the difference in the gain due to the downgrading of heat at lower temperature is not predominant, it also contributes to the better energy performance of Case C compared to the other cases.

Finally, it has to be noted that due to methodology adopted, the energy performance figures presented in this study can be rather higher than it would be in reality. Indeed, no additional gas side pressure drop is considered and each heat source and heat sink is divided into several fictive heat sources for obtaining minimal temperature differences along the heat exchangers involved in the heat integration. Those factors should be taken into account if the assessments of absolute energy performances are desired. However, results related to the comparison of different process layout are reliable. In a similar manner, several additional factors such as capital cost requirement and the impact on the availability on the power plant have to be taken into account in order to be fully conclusive about the best flue gas heat valorization configuration.

5. Conclusion

In this study, a simple thermal integration methodology allowing the assessment of thermal integration benefits has been presented. This methodology has been applied to compare several flue gas heat integration configurations suggested in literature for fine optimization of oxy-fired power plants. Despite the limitations of the methodology, a consistent comparison of different process layouts has been realized and a promising alternative to the solutions proposed in the literature has been suggested. Indeed, it appears that from an energetic point of view, bypassing of a portion of the hot flue gas coming from the boiler before the regenerative heater leads to the best energetic performances among the studied cases.

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