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Towards Second Generation Oxy-Pulverized Coal Power Plants: Energy Penalty Reduction Potential of Pressurized Oxy-Combustion Systems

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Abstract

During the last decade, CO_2 capture on coal power plants has been the subject of sustained attention as one of the most credible way to drastically reduce anthropogenic greenhouse gas emissions. Significant reduction in the energy penalty related to the oxy-combustion routes has been achieved but uncertainties remain in the operation of such a process inducing major modifications of the power island. In this context, for oxy-combustion, and more generally carbon capture to become a reality, its energy penalty shall be drastically reduced. In that perspective, cutting edge strategies allowing taking full advantage of oxy-fired operation have to be investigated. Among them, boiler pressurization has been identified as one of the most promising solution. Two major pressurized oxy-combustion concepts have emerged in literature: the flameless combustion technology (ISOTHERM®) and the staged-pressurized oxy-combustion (SPOC) concept. According to the authors describing those two processes, whilst very different in the combustion temperature control strategy, they both succeed in allowing pressurized operation.
In this work, those two concepts have been compared to an air-fired, a conservative and optimized atmospheric oxy-fired power plants in terms of energy performances. The reason underlying below the observed differences, have been determined using exergy analysis. The SPOC process leads to significantly lower energy penalty, as low as 3.8 %-pts compared to the ISOTHERM® concepts which lead to performance in the same order of magnitude than the optimized atmospheric design. It has been highlighted that this difference is essentially due to the large flue gas recycling requirement for the latter concept to control combustion temperature.

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Keywords: Carbon capture; Exergy analysis; Oxy-combustion; Pressurized-Combustion; Process integration

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1. Introduction

During the last decade, the energy penalty related to CO_2 capture on oxy-fired coal power plants has been significantly reduced thanks to the development of advanced cryogenic air separation units (ASU) and to the gains brought by process integration. Indeed, modern ASU can achieve specific consumptions as low as 170 kWh/t_{O2}, which represents a 15 % reduction compared to the conventional double-column process, and process integrations such as the valorization of the adiabatic compression and the flue gas heat into the steam cycle could lead to energy penalties around 7 %-pts with already demonstrated technologies [1].

However, despite the significant fundamental and experimental researches that have been carried on, uncertainties remain about the operation in oxy-mode since considerable structural modifications are brought to the power island which leads the plant operators to give their preference to post-combustion capture by chemical absorption. Thus, for oxy-combustion to become a credible contender as best technology available for carbon capture, its energy penalty shall be significantly reduced. For that purpose, cutting edge strategies have to be investigated in order to assess their capability to fully take advantage of operating in oxy-firing, and pressurized boilers have been identified as one of the most promising pathways to drastically reduce the energy penalty induced by CO_2 capture [2]. Indeed, the increased flue gas pressure induces a higher flue gas dew point, allowing an improved latent heat recovery. The absence of air infiltration leads to higher CO_2 concentration at the inlet of the compression and purification unit (CPU) not to mention the size reduction related to the reduced flue gas volume, the increased gas side heat transfer coefficient and the possible associated cost reductions. Several authors have studied such a system [3, 4, 5] and significant efficiency improvements have been reported when compared to atmospheric operation. However, to the best of our knowledge, studies available in literature focus on one specific pressurized boiler technology - the ISOTHERM® flameless boiler technology patented by ITEA [6] – the issues related to the effect of oxygen purity on the global system performance as well as the integration of the ASU compression heat have not been treated yet.

In this study, on the one hand, the ISOTHERM® concept has been compared on a consistent basis to a recently published alternative pressurized oxy-combustion process based on staged combustion to moderate flame temperature [7] using exergy analysis.

2. Methodology

In this work, the two pressurized oxy-combustion power plants are assessed using the commercial sequential modular process simulation software Aspen Plus® 7.2. Base-load steady-state operation is assumed. In order to accurately represent the system, three different thermodynamic models have been used: 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). Despite not being represented in the figures nor extensively described within this work, the ASU and CPU have been thoroughly modeled, as in [1]. Concerning the adopted 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 [8]. The energy performance of the investigated pressurized oxy-combustion processes have been compared to an optimized atmospheric oxy-combustion power plant and state-of-the art air-fired power plant, both modeled using the same set of hypotheses for sake of consistency.

While allowing the comparison between different processes, net plant efficiency does not help in obtaining insights about the cause of the performance difference and identifying possible improvement pathways. Hence, exergy analysis is performed, for both pressurized oxy-fired concepts, on the preliminary process layout considered in this study in which minimal thermal integration is performed, in order to identify the location and the magnitude of the thermodynamic losses occurring within each system. This allows a better understanding of the differences between the two concepts. The exergy related calculations procedure adopted within this study is similar to the one described in [1]. The material flow exergy calculation needed for the establishment of exergy balances at unit operation level is realized using the commercial software ExerCom. Coal exergy content is assessed based on its lower heating value (LHV) and composition, giving a figure of 26.7 MJ/kg for the international grade low sulfur bituminous coal (LHV = 25.2 MJ/kg) suggested by the EBTF.

3. Process description

In this study, two different pressurized oxy-combustion systems are modeled: the ISOTHERM® process and the Staged Pressurized Oxy-Combustion (SPOC) process. Beside the boiler section, which is the core of those two concepts, the rest of the power plant as well as the adopted modeling hypotheses are identical for the sake of consistency in the energetic and exergetic comparison. The following section presents the common features of the two concepts. Provided by an up-to-date cryogenic ASU [9], the oxygen flow is compressed up to the boiler operating pressure by a two-step compressor with an intermediate cooling placed downstream the ASU. For both concepts, an oxygen purity of 95 $\%_{mol}$ is considered and staged-compressors with inter-cooling are considered for air compressors to minimize standalone power consumption. The specific consumption associated to this ASU is 173 kWh/t_{O2}. The CPU is a conventional double-column process producing a CO_2 stream at 110 bar with purity above 96 $\%_{mol}$ [10]. Again, staged-compression is considered for the CO_2 compressor of the CPU. The power production is ensured by a state-of-the-art ultra-supercritical steam cycle with steam parameters of 300 bar/600 °C/620 °C with a topping desuperheater and 8 feedwater preheaters including a deaerator preheating the boiler feedwater (BFW) up to 315 °C. For both cases, the oxygen flowrate is adjusted so that the boiler outlet oxygen concentration is 3 $\%_{mol}$ to ensure satisfying coal conversion rates and at the boiler cold-end, an indirect-contact heat exchanger, so called 'flue gas condenser', is placed to recover the flue gas condensation heat down to 40 °C prior depollution to preheat low temperature BFW from condenser outlet temperature up to the deaerator temperature. This allows the reduction of the medium and low-pressure steam bleedings flowrates dedicated to BFW preheating, which in turn leads to an increased electric production.

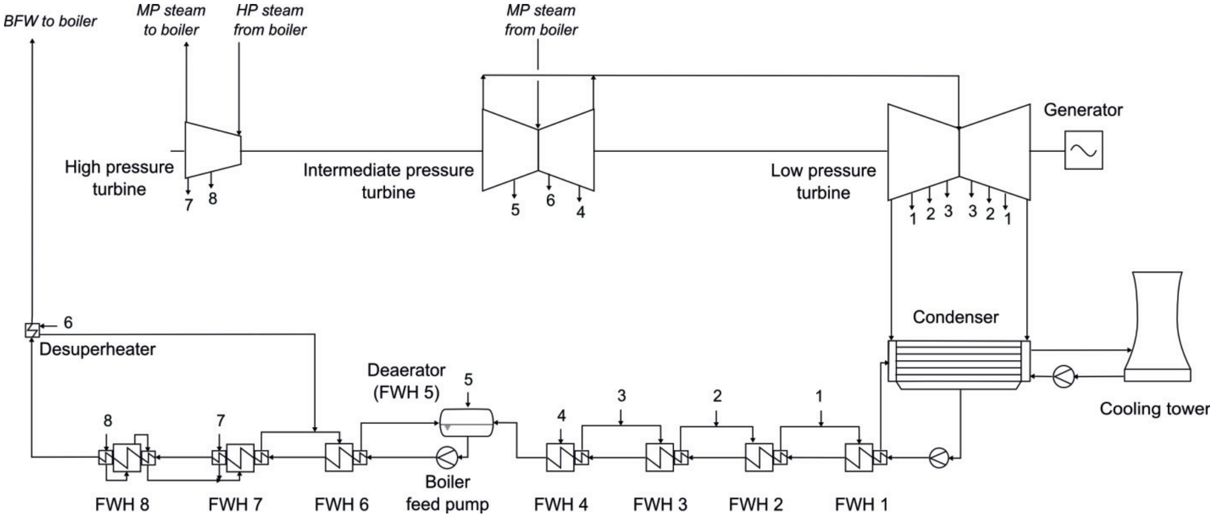

Figure 1 Simplified representation of the state-of-the-art ultra-supercritical steam cycle considered in this study

As far as flue gas depollution is concerned, conventional equipments, which are selective catalytic reduction for nitrogen oxides (NOx) removal and wet flue gas desulfurization for sulfur oxides (SOx) removal, are substituted by an integrated NOx and SOx removal from the flue gas at elevated pressure similar to the “sour compression” process demonstrated by Air Products at the Schwarze Pumpe pilot plant [11]. For both cases, it is assumed that a unique direct contact column operating around 15 bar is sufficient to fully remove NOx and SOx from the flue gas. In the following paragraphs, a description of the ISOTHERM® and SPOC concepts are briefly described.

3.1. ISOTHERM® process

The considered flowsheet for the ISOTHERM® concept is presented in Figure 2. The adopted layout is very similar to the one described in detail by Zebian et al. [4]. Coal is introduced in a refractorized pressurized oxy-combustor, in which it is burnt by a flameless combustion. Then, the flue gas is sent toward a convective heat recovery steam generator (HRSG). No radiative heat transfer takes place in the combustor for this concept.

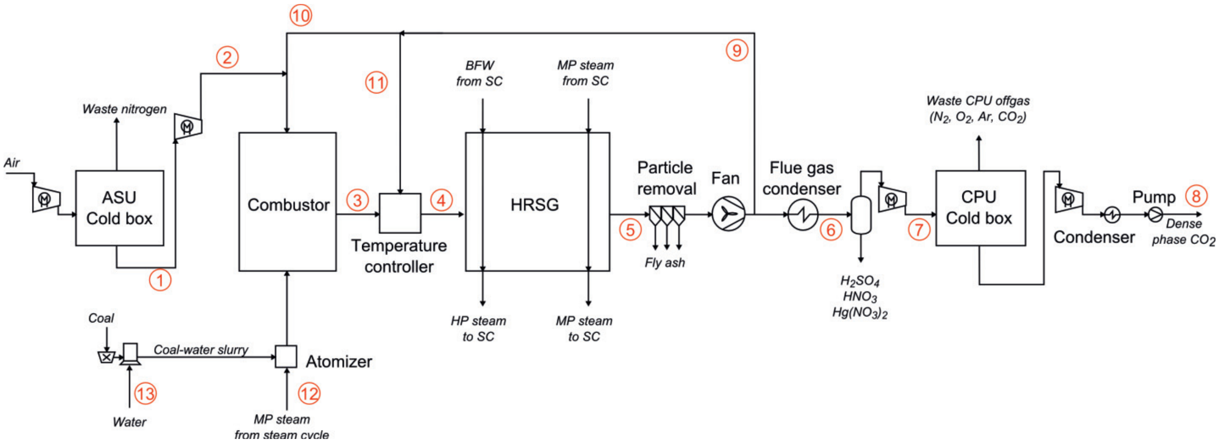

Figure 2 Simplified flow scheme of the ISOTHERM® pressurized oxy-combustion concept

The issue of operating pressure dependency of this system has been tackled by Hong et al. [13] and 10 bar has initially been identified as the optimum. Despite Zebian et al. [4] have subsequently suggested that a better accounting of pressure drops occurring in the HRSG and in flue gas paths shifts the optimal operating pressure towards lower values (in the range of 3.75 and 6.25 bar), the most conventional value of 10 bar has been kept in this preliminary study. In order to control both combustor temperature around 1550 °C and HRSG flue gas inlet temperature at 800 °C, a large portion of the flue gas at the HRSG outlet is recycled. This outlet temperature is fixed at 330 °C, driven by the BFW preheating temperature and the considered HRSG temperature approach of 15 K. This figure, despite being lower than in atmospheric operation (25 K), has been considered viable in a techno-economic point of view since the higher flue gas pressure increases the gas-side heat transfer coefficient. The delivery of coal to the pressurized combustor is realized by mixing the pulverized coal to pressurized water in order to obtain a coal-water slurry, which is atomized into the combustor thanks to a small flow of medium-pressure steam provided by a turbine drawn-off. The addition of water also contributes to controlling the combustion temperature. Finally, the flue gas compression at the CPU inlet is realized in a two-stage compressor (pressure ratio=1.7) with intermediate cooling. Concerning the flue gas condenser, the heat duty available is 340 MW_{th}, which exactly corresponds to duty required to heat the entire BFW at the condenser outlet up to the deaerator temperature (172 °C).

3.2. SPOC process

The SPOC concept, depicted in Figure 3 aims at carrying out the pressurized combustion with reduced flue gas recycle flowrate in order to further minimize equipments sizes and parasitic load. To do so, this concept exploits the oxygen-to-coal stoichiometric ratio dependency of the combustion temperature by staging the coal into several boilers. In the first boiler, the very high stoichiometric ratio allows the control of the temperature while on downstream boilers; the high stoichiometric ratio effect is assisted by the cooling down of the flue gas coming from the upstream boiler from its operating temperature down to 700 °C. By this means, the combustion heat duty is transferred to the steam cycle at each boiler. According to authors [12], a four step staged-combustion allows obtaining boiler temperatures which are acceptable combustion temperatures. The combustion temperatures of the four boilers, taken from [12], are respectively 1891 °C, 1950 °C, 1755 °C and 1618 °C. An economizer is placed downstream the last boiler in order to recover heat down to 330 °C to heat the BFW from the steam cycle.

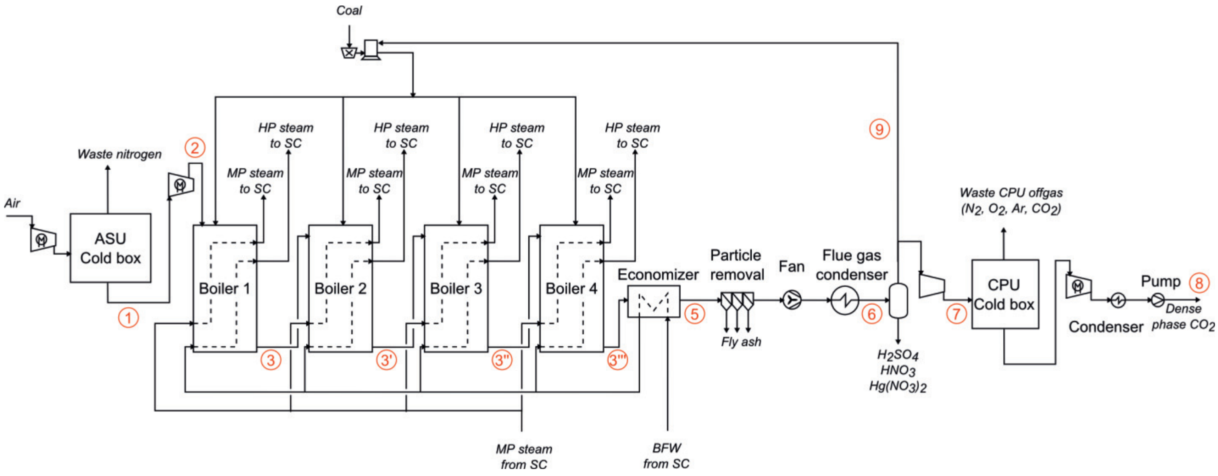

Figure 3 Simplified flow scheme of the SPOC pressurized oxy-combustion concept

Compared to the ISOTHERM® concept, where the heat exchange is exclusively convective, the flue gas flow-path in the SPOC concept induces significantly less pressure drop since the heat exchange is mainly radiative. Finally, dry feeding similar to the systems used for IGCC applications is considered for pressurization up to the boilers operating pressure (16 bar) in the SPOC concept, as opposed to the previously described coal-water slurry solution. Here, the compression of the flue gas at the CPU inlet is realized in one-step since the higher boiler operating pressure leads to a pressure ratio of 1.9 which can be handled without intercooling. In this configuration, the heat duty available for integration at the flue gas condenser is significantly lower than in the previous case (175 MW_{th}), only allowing the preheating of 48 % of the total BFW flowrate up to 172 °C.

The main operating parameters (temperature, pressure, flowrate) relative to the most important process streams for both concepts have been provided in Table 1.

Table 1 Operating parameters of selected streams

	ISOTHERM® (Figure 1)			SPOC (Figure 2)		
	Temperature (°C)	Pressure (bar)	Flowrate (t/hr)	Temperature (°C)	Pressure (bar)	Flowrate (t/hr)
1	24	1.2	677	24	1.2	670
2	149	10.7	677	181	16.1	670
3	1550	10.0	3787	700	16.1	745
3’	n/a	n/a	n/a	700	16.1	821
3’’	n/a	n/a	n/a	700	16.1	896
3’’’	n/a	n/a	n/a	700	16.1	981
4	800	10	10717	n/a	n/a	n/a
5	330	9.5	10717	330	16.0	981
6	42	10.1	1125	42	16.1	971
7	76	30.0	809	83	30.0	803
8	37	110.0	718	37	110.0	722
9	339	10.1	9558	28	16.1	42
10	339	10.1	2617	n/a	n/a	n/a
11	339	10.1	6941	n/a	n/a	n/a
12	545	38.9	25	n/a	n/a	n/a
13	15	10.0	166	n/a	n/a	n/a

4. Results

Table 2 presents the energetic figures relative to the ISOTHERM® and SPOC processes described above. Those have been compared to performances of the base-case (conservative) and optimized atmospheric oxy-fired plant described in [1] and a state-of-the-art ultra-supercritical air-fired power plant. A common set of modeling hypotheses and boundary conditions have been adopted for sake of consistency, except for the CO_2 recovery targets for pressurized cases. Indeed, the absence of air infiltrations in those cases leads to significantly higher CO_2 concentration at the CPU inlet (respectively 87.7 $\%_{mol}$ and 89.4 $\%_{mol}$ on dry basis for the ISOTHERM® and SPOC process) compared to the atmospheric counterpart (around 78 $\%_{mol}$), which makes the fulfillment of the usual CPU specifications (96 $\%_{mol}$ purity, 90 $\%_{wt}$ recovery) very easy. Although not directly impacting positively on the net plant efficiency, a higher recovery rate allows significant reduction of the plant specific CO_2 emission as well as the energy penalty when the latter is expressed in kilowatt-hour per metric ton of captured CO_2. Thus, instead of forcing a 90 $\%_{wt}$ CO_2 recovery rate for pressurized cases, an arbitrary value of 95 $\%_{wt}$ achievable without significant increase of energy consumption of the CPU has been chosen.

Table 2 Comparison of the energy performances of the two studied pressurized oxy-combustion processes with the reference air-fired, a conservative and an optimized atmospheric oxy-combustion process

		Air-fired plant	Atmospheric-oxy (conservative)	Atmospheric-oxy (optimized)	Pressurized-oxy (ISOTHERM®)	Pressurized-oxy (SPOC)
Plant heat input (LHV)	MW_{th}	2112.7	2112.7	2112.7	2112.7	2112.7
Gross electric output	MW_e	1077.4	1073.4	1138.5	1099.2	1148.3
ASU consumption	MW_e	n/a	121.5	117.2	110.6	109.4
Oxygen compression	MW_e	n/a	n/a	n/a	42.1	52.7
CPU consumption	MW_e	n/a	78.6	88.5	29.7	22.0
Auxiliary consumption	MW_e	102.5	109.7	107.2	105.7	69.9
Net electric output	MW_e	974.8	763.3	825.6	811.2	894.3
CO_2 purity	$\%_{mol}$	n/a	96	96	96	96
CO_2 recovery rate	$\%_{wt}$	0	90	90	95	95
CO_2 emissions	t/h	730	73	73	34	34
Specific CO_2 emissions	g/kWh	749.4	95.6	88.5	42.4	37.6
Net plant efficiency	$\%_{LHV}$	46.1	36.1	39.1	38.4	42.3
Energy penalty	%-pts	n/a	10.0	7.0	7.7	3.8
Energy penalty	kWh/t_{CO2}	n/a	321.9	227.1	235.4	114.6

Results show that even though both pressurized oxy-combustion concepts have higher net plant efficiencies than conservative atmospheric oxy-combustion, only the SPOC concept yields significantly higher energetic performance compared to state-of-the-art atmospheric oxy-fired plant with advanced heat integration. This observation remains true even when the CO_2 recovery rate increase is taken into account since the energy penalty of the ISOTHERM® process, 235 kWh/t_{CO2}, is 4 % higher than the optimized atmospheric case. The SPOC concept, thanks to a significant reduction in auxiliary consumption (-35 % compared to the optimized atmospheric case) and increased gross electric production, allows a drastic increase of the net plant efficiency (+3.2 %-pts), largely breaking the symbolic threshold of 5 %-pts energy penalty (3.8 %-pts) even without considering potential thermal integration, especially the ASU compression heat which is recognized to be profitable for atmospheric oxy-combustion. Since the mitigated performances obtained for the ISOTHERM® concept could be attributed to the large pressure drop induced by the operation at 10 bar, the effect of this parameter on the net plant efficiency has been studied. Considering a pressure drop equivalent to the SPOC process (0.1 bar), which is a strong hypothesis since convective heat transfer is considered in the ISOTHERM® concept, the obtained hypothetic energy penalty is, while lower than the optimized atmospheric case is still higher by a significant margin compared to the SPOC concept (6.4 %-pts).

Exergy analysis on both pressurized concepts (see Figure 4) allows a better understanding the performance gap between those two processes. Aside the auxiliary power consumption difference, largely due to the additional fan consumption to overcome the large pressure drop in the ISOTHERM® concept's HSRG, large exergy losses in the temperature controller occur in the latter process. An interesting observation is that the distribution of the exergy losses in the boiler and flue gas train is very different for the two considered concepts.

The lower temperature of the flue gas flow at the HSRG inlet allows the reduction of the temperature difference in the *Steam generator*, and consequently the exergy losses occurring in this section. However, the large losses caused by the quench of the cold flue gas to control the flue as temperature (*Temperature controller*), the pre-mixing of the flue gas prior the combustor (*Flue gas – oxygen mixing*) and the irreversibilities occurring within the *Combustor*, caused by the large ballast of flue gas and water needed for coal atomization and combustion temperature control, leads to a larger overall exergy losses in this section for the ISOTHERM® concept. When those four irreversibility sources are aggregated, the exergy losses in the ISOTHERM® concept are about 9 % larger than in the SPOC concept (respectively 950 MW and 862 MW). Elsewhere, the larger losses in the *FG condenser* in the ISOTHERM® concept is due to the larger heat duty involved in the heat exchange and when the *Total steam cycle* losses difference is taken into account, the two concepts are on equal footing (respectively 179 MW and 182 MW).

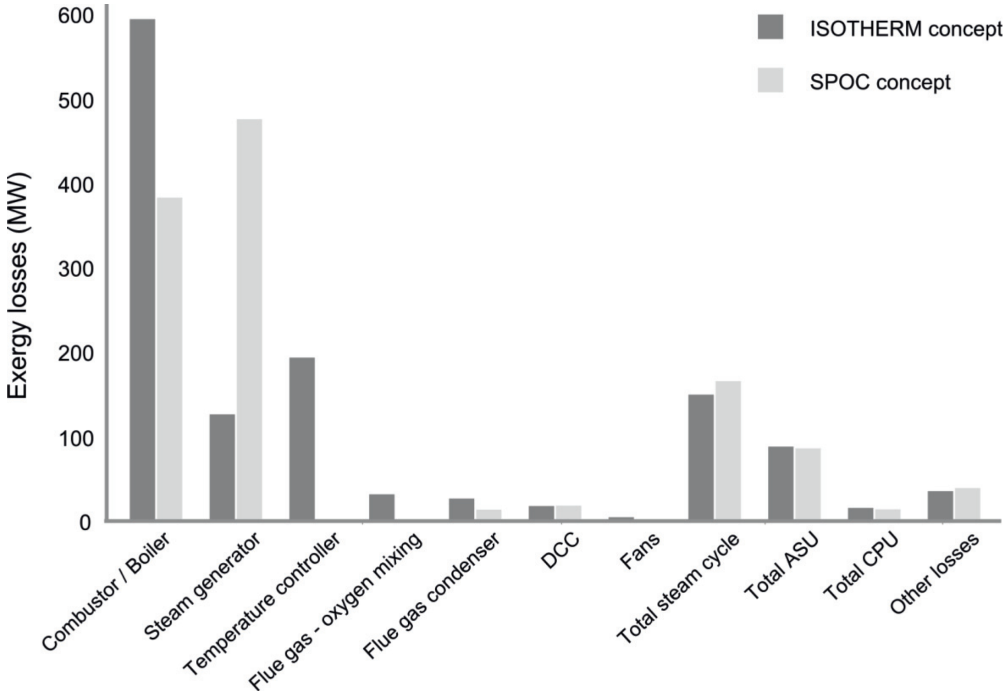

Figure 4 Exergy losses relative to the ISOTHERM® and SPOC concepts

The previously emphasized exergy losses difference in the boiler section corresponds to the difference in the amount of exergy transferred to the steam cycle in the *Steam generator*. Whilst the heat duty available for the preheating of the BFW in the *Flue gas condenser* is significantly larger in the ISOTHERM® case than in the SPOC case (respectively 339.7 MW_{th} and 175 MW_{th}), this difference in terms of exergy is less important (respectively 67 MW and 35 MW). Consequently, the cumulative exergy transferred from the flue gas to steam cycle (*Steam generator + Flue gas condenser*) is larger for the SPOC concept (1283 MW) than for the ISOTHERM concept (1234 MW), which explains the larger electric production of the former.

5. Discussions

The possibility to further increase the energy efficiency of the pressurized concepts has been mentioned earlier. Gopan et al. [7] have suggested that in addition to the flue gas condensation heat, the ASU main and booster air compressors (MAC and BAC) compression heats, as well as the oxygen compressors intercooler heat can be valorized within the steam cycle to entirely substitute the low pressure preheaters train (FWH 1 to 4 in Figure 1). In addition to the importance of the temperature compatibility of the heat sources, one has to careful about the maximal amount of heat duty that can be valorized at a given temperature range and a given process architecture.

Hong et al. [13] identified 10 bar as the optimal operating pressure for a given flue gas condensation heat valorization configuration (heating the entire BFW flow up to deaerator temperature) and without considering the possibility to valorize potential heat sources available elsewhere in the system, for example ASU MAC compression heat. Indeed, for this configuration, the valorization of the compression heat is impossible since the steam cycle boiler feedwater heating demand up to 150°C is entirely fulfilled by the flue gas condensation heat, leaving no room for the integration of heat duties beyond that temperature level. A preliminary study aiming the assessment of the benefits in valorizing ASU MAC compression heat reveals that, the increase of the operating pressure up to 25 bar makes the thermal integration possible. The flue gas dew point increases with the pressure and at 25 bar, its value is around 180 °C. Following the heat integration methodology described in [1], the flue gas condensation heat is valorized at higher temperature levels. This shift towards higher temperatures offers possibilities to valorize heat sources available at lower temperature. Consequently, despite larger fan consumption due to the increased pressure drop, the integration of the ASU MAC heat duty (94 MW_{th}, available at 155 °C) into the steam cycle BFW train allows the recovery of 3 MW_e net, which represent a 0.2 %-pts gain in terms of net plant efficiency. This example stresses the necessity to adopt a holistic approach when trying to improve the energy efficiency of power systems by thermal integration for further studies aiming the assessment of fully integrated pressurized oxy-fired plants.

Finally, the results of the present study have to be weighted by the technological feasibility and economic viability of such pressurized power plants. Indeed, major concerns remain about the capability to handle the radiative heat transfer in the SPOC's, especially when ultra-supercritical steam conditions are considered.

6. Conclusion

The comparison of two pressurized oxy-combustion concepts has been realized on a consistent basis. The obtained energy performances have been compared to a state-of-the-art air-fired power plant, a conservative and optimized design of atmospheric oxy-combustion plants. Results show that, for the considered preliminary process designs, the SPOC concept leads to significantly better performance than the ISOTHERM® concept. Indeed, the significantly lower fan power consumption and exergy losses within the boiler thanks to a near zero flue gas requirement allows both a minimized auxiliary power requirement and increased gross electric output. This leads to a drastic reduction of the energy penalty, breaking the symbolic threshold of the 5 %-pts fairly largely (3.8 %-pts). While particularly promising since subsequent efficiency increase it expected via thermal integration, the technological feasibility of the radiant boiler operation as well as a techno-economic study have to be carried out in order to state on the viability of this concept.

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