Heat integration of an oxy-combustion power plant: minimization of the CO_2 capture process energy penalty

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Abstract

Oxy-combustion is one of the most promising technologies to reduce CO_2 emissions from coal-fired power plants. The combustion with oxygen diminishes the total volume of flue gases and it concentrates CO_2 at the outlet of the boiler. Nevertheless, important energy penalty is related to the CO_2 capture and compression process. Air separation unit (ASU) and compression and purification unit (CPU) are process with a high energy consumption that include high cooling demands. On the other hand, the oxidant flow, which is a mixture of O_2 and recirculated flue gases (RFG), requires a high heating demand in order to preheat it before the boiler inlet. Additionally, residual heat can be integrated in the steam cycle feedwater preheating, reducing steam turbine bleeding and increasing electric power production. In this sense, heat integration results mandatory in order to improve the overall power plant efficiency by reducing the energy penalty.

For developing accurate heat integration between systems, Pinch analyses has been applied to evaluate the heat recovery options and to design an optimized heat exchanger network (HEN). Finally, a methodology that involves pinch analyses an Aspen Plus simulation models has been proposed. Final power plant configuration includes ASU and CPU optimized designs with reduced auxiliary energy consumption and the heat from the coolers integrated with the steam cycle. Boiler performance with a high O_2 concentration in oxidant (up to 40% by volume) has been considered. Results show an important increase in power plant net efficiency (36.42%, LHV basis) regarding oxy-fuel reference power plant (32.91%). As consequence, energy penalty can be reduced from original 10.6 points to finally 7.0 points. In addition, final heating and cooling demands have been significantly reduced.

Keywords: oxy-combustion, CO_2 capture, heat integration, pinch analyses

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1. Introduction

Currently, it is a big challenge to find ways to increase the efficiency of the processes involved in carbon capture and storage (CCS) and thereby reducing the energy penalty. While the efficiency of supercritical air-fired thermal power plants can reach 45% [1], the efficiency significantly reduces by 12% when the oxy-fuel CCS components are added to capture the CO_2 [2]. This is a significant reduction in the efficiency and will drastically increase the fuel consumption for unit power produced resulting in increased cost of electricity and further CO_2 emissions. Therefore significant improvement in the efficiencies of the additional CCS units and the oxy-fuel boiler are necessary to make the process economically viable.

The O2GEN project (Optimization of oxygen-based CFBC technology with CO_2 capture [3]) focuses on one of the most important recommendations of the Zero Emission Platform´s (ZEP) report for the deployment of CCS in the European Union (EU): the use of higher O_2 concentrations in oxy-fuel combustion reducing the flue gas recirculation and energy penalty. The project researches and demonstrates different options in state-of-the-art facilities with the view of drawing conclusions that will be included in future large scale power plants. O2GEN includes relevant participation of key industrial partners, technology suppliers and facilities that also assure improvements in operational flexibility.

One of the main activities in the O2GEN project consists of the integration and optimization of the entire process. The main components of the oxy-fuel power plant have been optimized individually. New ASU and CPU concepts that involve optimized configurations and new materials installation have been defined. CFB boiler has been designed to burn with a high oxygen concentration (40% by volume). All these improvements produce large residual heat flows. At this point, an accurate heat integration methodology is required in order to optimize the whole concept, leading to the development of a 2^{nd} generation oxy-fuel power plants with minimum CO_2 energy penalty.

2. Heat integration methodology

One of the main drawbacks to CO_2 capture development refers to the high energy penalty of the process. In an oxy-fuel power plant facility, the complexity of the process along with the cooling and heating requirement at different temperature levels makes mandatory the design of a complete heat integration methodology with the aim to reduce this CO_2 capture energy penalty. Pinch analysis can tackle this problem by defining an optimized heat exchanger network.

In order to address the problem, pinch analysis has been applied to evaluate the heat recovery options and to design the optimized heat exchanger network. In addition, an Aspen Plus simulation model has been proposed to simulate the whole power plant, including all the subsystems and the new HEN. Figure 1 shows heat integration methodology scheme.

First stage of the process consists of the definition of the reference state-of-the-art oxy-fuel power plant. The design of the power plant must be based on an exhaustive literature review and boiler, ASU and CPU manufacturers detailed information. Then, within this initial stage, a simulator is developed and it is programmed in suitable software in order to be used as an analytical tool (Aspen Plus). Once reference power plant is set and initial net electric efficiency is established, the involved streams in pinch analysis must be selected and defined (mass flow, CP, source temperature, objective temperature). Minimum temperature difference is then chosen and cooling and heating demands can be calculated by running the pinch analysis. Afterwards, HEN is built and it is included in previous Aspen Plus model. The new configuration is simulated and finally power output and efficiency results are available. Sensitivity analyses can be later implemented in order to complete the whole heat integration process.

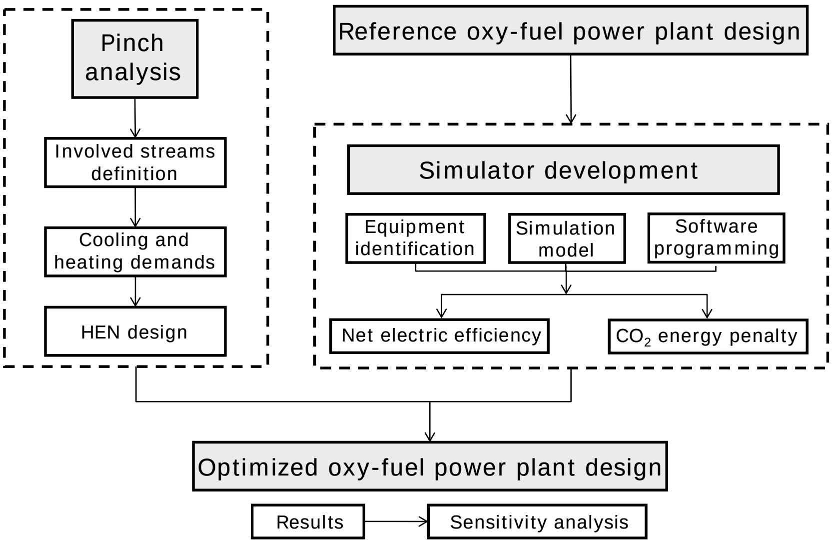


Fig.1. Heat integration methodology

3. Case study

In order to apply the heat integration methodology previously described, a case study has been accomplished. This application case has been carried out within the O2GEN activities and the main parameters for the initial configuration of the oxy-fuel power plant are according to the state-of-the-art of the different systems.

This oxy-fuel power plant includes an air separation unit (ASU) for pure oxygen generation. For the case study, an oxygen mass flow of 128.6 kg/s is produced in the ASU plant with 96.6% purity by volume. In addition, the oxy-fuel power plant includes a CO_2 compressor and purification unit (CPU) that is able to produce up to 145 kg/s of 99% pure CO_2 mass flow. The boiler is a circulating fluidized boiler (CFB) that can operate with an oxygen range between 25-40% (in volume). Depending on the oxygen concentration, the recirculated flue gas (RFG) parameters are modified and new mass flow and temperature levels have to be taken into account in the heat integration process. The power cycle includes a steam turbine with a single reheat, four high-pressure heaters, a deaerator and three low-pressure heaters. Steam is expanded up to a condenser pressure of 0.05 bar. The predesign of the steam cycle has been carried out according to the state-of-the-art for supercritical power plants. Figure 2 shows the complete scheme for the reference power plant.

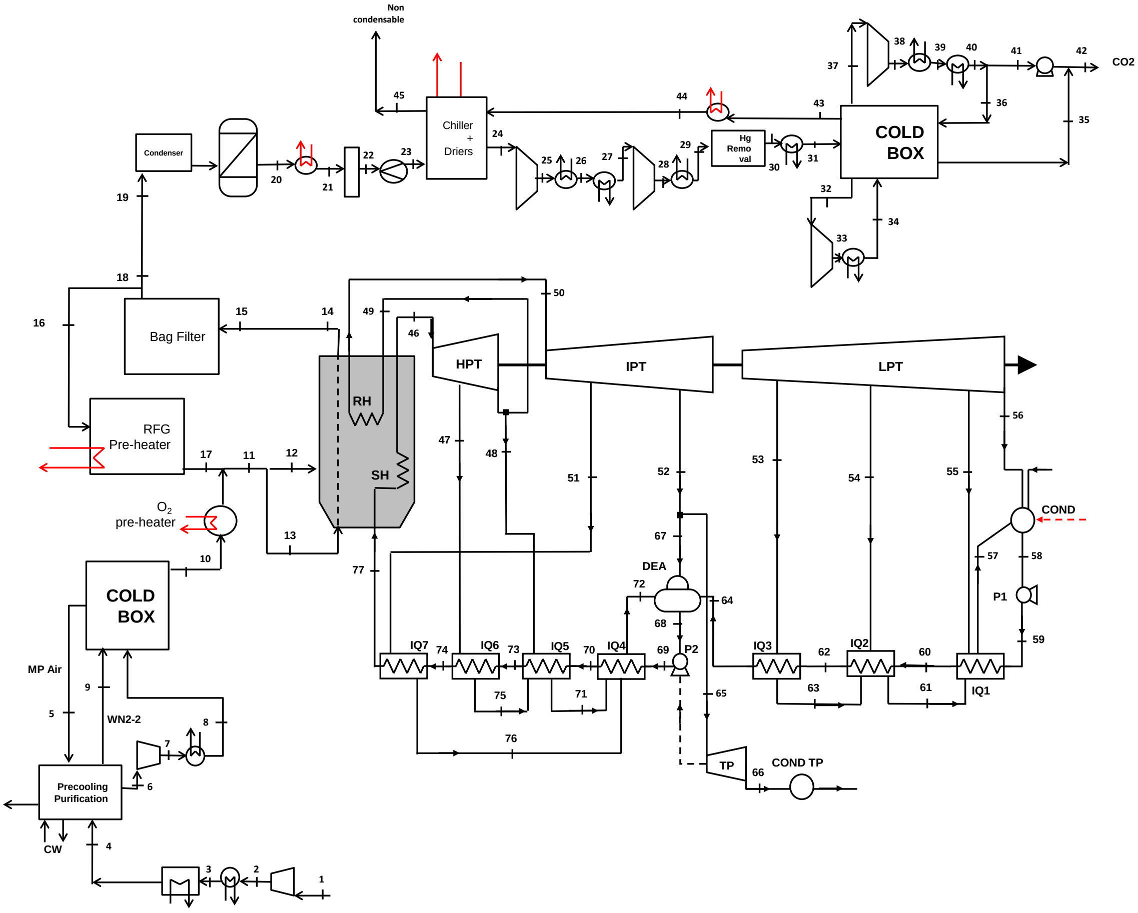


Fig.2. Reference oxy-fuel power plant configuration

To obtain overall plant efficiency and stream variables, a simulator was developed. One of main characteristics of this simulator must be an easy integration of processes and equipment in order to prove different cycle configurations. Therefore, the code Aspen Plus [4] has been used for power cycle modelling. Table 1 includes main reference power plant parameters.

PARAMETER	VALUE	UNITS
Fuel consumption	66.7	kg/s
LHV	23.39	MJ/kg
Boiler input (LHV basis)	1561	MW
Boiler efficiency (LHV basis)	90.0	%
Main steam temperature	600	°C
Main steam pressure	250	bar
Main steam mass flow	512.8	kg/s
Reheat steam temperature	610	°C
Condenser pressure	0.05	bar
Gross electric power	690.4	MW
Gross electric efficiency	44.23	%
Auxiliary consumption	20.0	MW
ASU power consumption	82.2	MW
CPU power consumption	74.4	MW
Net electric power	513.8	MW
Net electric efficiency	32.91	%

Table 1. Reference oxy-fuel power plant main parameters

According to the methodology introduced in section 2, the first stage of the process implies the definition of the streams involved in the pinch analyses. In this sense, some assumptions have been taken into account. No heat exchangers have been considered in order to set an initial scenario without any integration. Thus, CPU, ASU and even steam cycle heaters have been removed. Figure 3 and Table 2 refer to the flows considered in the pinch analyses first stage. The table also includes the source temperature and the target temperature for every stream.

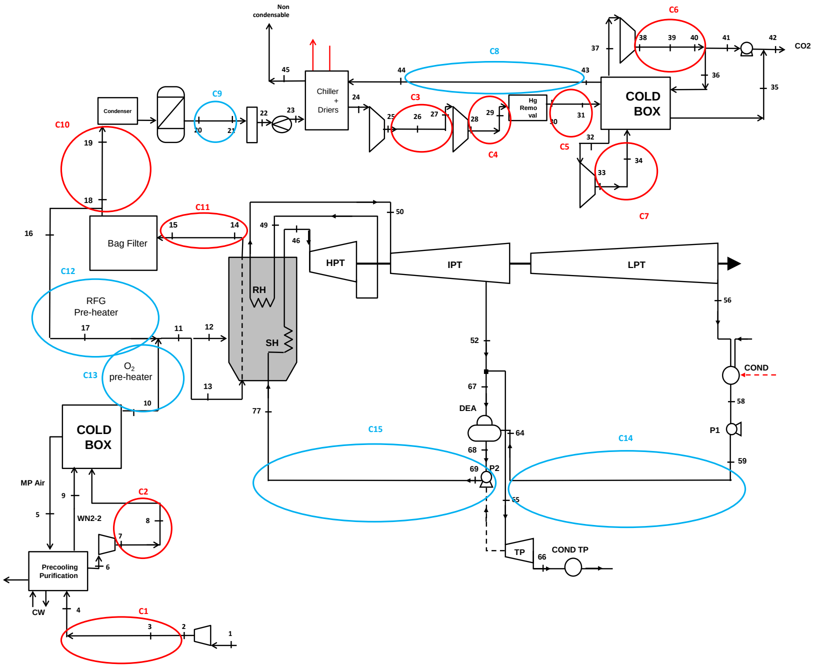


Fig.3. Hot and cold streams considered for pinch analyses

STREAM	Type	Source T. (°C)	Target T. (°C)	CP (kW/K)	ΔH (kW)
C1	HOT	143.4	25.0	546.5	64705.6
C2	HOT	71.3	25.0	157.9	7310.8
C3	HOT	160.0	25.0	155.3	20965.5
C4	HOT	158.5	43.0	165.9	19161.4
C5	HOT	47.7	25.0	170.8	3877.2
C6	HOT	208.4	25.0	199.8	36643.3
C7	HOT	73.3	25.0	11.9	574.3
C8	COLD	22.7	70.0	21.0	-993.3
C9	COLD	24.9	34.1	154.6	-1422.3
C10	HOT	145.9	24.9	226.9	27457.2
C11	HOT	331.0	140.0	457.8	90877.8
C12	COLD	154.2	260.0	246.1	-26037.4
C13	COLD	19.5	260.0	119.2	-28667.6
C14	COLD	33.0	139.6	2059.0	-219633.5
C15	COLD	195.7	298.6	2380.0	-244878.2

Table 2. Hot and cold streams considered for pinch analyses

Then, pinch analysis is applied considering a minimum temperature difference of 10°C. After solving the problem, the heat cascade is built and the maximum heat recovery and heating and cooling demands are obtained. Figure 4 shows the shifted hot and cold composite curves for the first stage pinch analyses. As result, high external heating demands are required in this configuration, which actually means that steam extractions from turbine will be needed in every case. Nevertheless, this initial case is the basis for subsequent modifications of the heat exchanger network design. Therefore, after starting case analyses, no modifications in the high pressure feedwater zone are going to be introduced and extractions from steam turbine will be kept in the steam cycle.

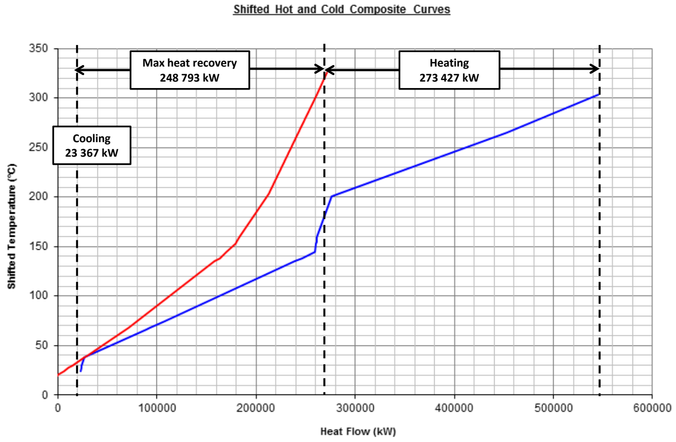


Fig.4. Hot and cold composite curves

Next analyses are performed for the two main operation conditions in boiler (O_2 25%-v and O_2 40%-v) taking into account the variation in boiler efficiency and oxidant and flue gas mass flows conditions. In these cases, all the streams are involved in the analyses except the high pressure feedwater stream, C15. This stream C15 comprises the four high pressure (HP) feedwater heaters in the steam cycle. Therefore, no modifications have been considered and energy requirements are covered by the steam turbine bleeds in this stream.
However, after a previous study, results indicate that the inclusion in the problem of a cold stream with no necessarily too low temperature could decrease the external demand of the process. This is the reason why a fraction of the C15 stream (HP feedwater flow) has been finally considered. Additionally, heating of part of the feedwater mass flow by integration reduces high exergy steam extractions from the turbine and as consequence, increases the steam turbine power output. A preliminary analyses with HP feedwater heaters modification in steam cycle has been carried out. Stream C15 has been divided into four different zones corresponding to the temperature levels of every heater in the original scheme. In order to reduce the high steam turbine extractions mass flow, it has been established that the first point of integration is the stream C15b, with a temperature increase from 265 to 294.8ºC. Figure 5 shows this approach schematically.

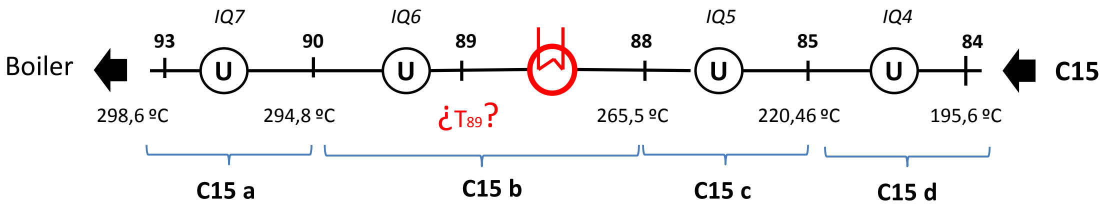
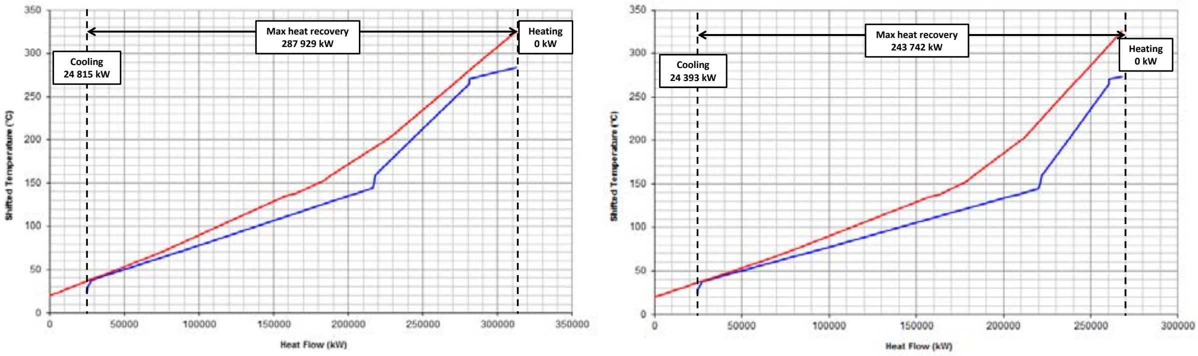


Fig.5. HP feedwater heaters arrangement

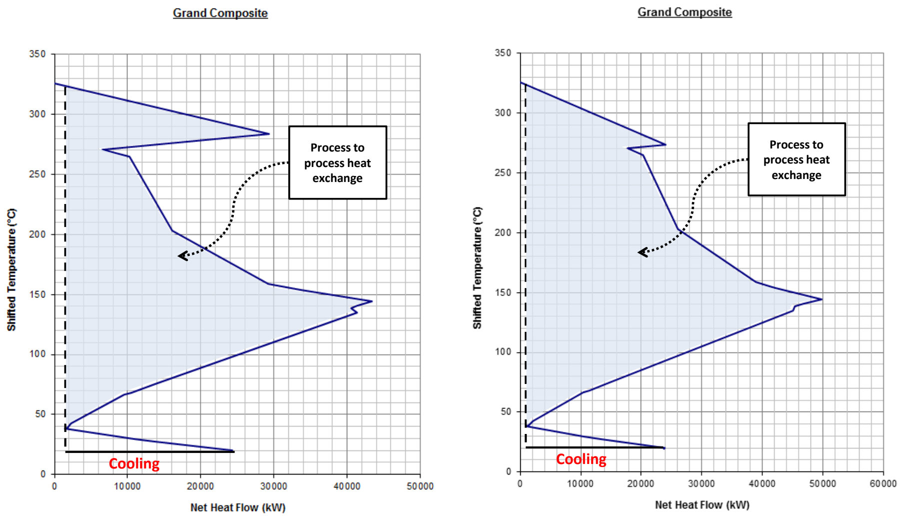
In this figure the utilities (U) represent energy provided by the high pressure turbine bleedings. The stream fraction, in which the heat exchanger is located, is included in the pinch analyses. The objective temperature of this stage (T_{89}) must be as high as possible. The higher this temperature is the lower steam extraction is required from the high pressure turbine. In order to select this temperature, a sensitivity analyses has been carried out. By means of an iterative process that includes a parametric study of the objective temperature for stream C15b (T_{89}), steam cycle parameters and power plant efficiency can be obtained. Optimization stop criterion is based on three main considerations: no heating demands are needed, minimum cooling demands are achieved and maximum power plant net efficiency is obtained. The variation of this objective temperature and the boiler efficiency generates different heat exchanger networks. For every case, energy needs have been recalculated. Finally, the heating and cooling demands are calculated for each resulted configuration. Figure 6 shows composite curves for 90% and 93% boiler efficiency.



(a) (b)

Fig.6. Composite curves: (a) 90% boiler efficiency, (b) 93% boiler efficiency

Grand Composite Curves (GCC) have been plotted in Figure 7. GCC is the graphical way to show the heat cascade. With GCC, is possible to make a graphical representation of the energy utilities and the required temperature level of these utilities. These curves result useful to make an efficient selection of the energy supply. While composite curves provide overall energy targets, they do not clearly indicate how much energy must be supplied by various utility levels. GCC plots process energy deficit (above the pinch) and energy surplus (below the pinch) as a function of temperature.



(a) (b)

Fig.7. Grand composite curves: (a) 90% boiler efficiency, (b) 93% boiler efficiency

The whole curve is below the pinch point and in both cases, it represents an energy surplus. The amount of energy requirements which could be covered by the process itself are represented by the shaded areas (pockets). Most of the demand can be covered with the process itself, but there is still a cooling need (as it has been checked with the composite curves). In these cases, only very low temperatures streams could be used to cover these cooling deficits.

By building the optimized HEN, a net electric efficiency of (36.42%) can be achieved. Nevertheless, the large number of heaters makes unfeasible this solution. In both cases, 90 and 93% boiler efficiency, the optimized heat exchanger network counts with more than 25 new heaters (mathematical process was stopped at this point). In this sense, a different solution was proposed and a trade-off between efficiency and complexity was achieved. Final configuration is shown in Figure 8. In order to build the HEN, next criterion was followed: ASU, CPU and RFG/O_2 heating needs are covered in first place, then steam cycle feedwater preheating is accomplished. In this last stage of the process, the heating demands are covered from high temperature to low temperature. The target of such a procedure is to use the lowest exergy steam extraction for heating up low temperature condensate in the cycle (33-50°C, temperature change). Finally, the number of heaters is reduced to 11 and a steam extraction mass flow of 12-15 kg/s is needed to cover last heating demand for condensate preheating.

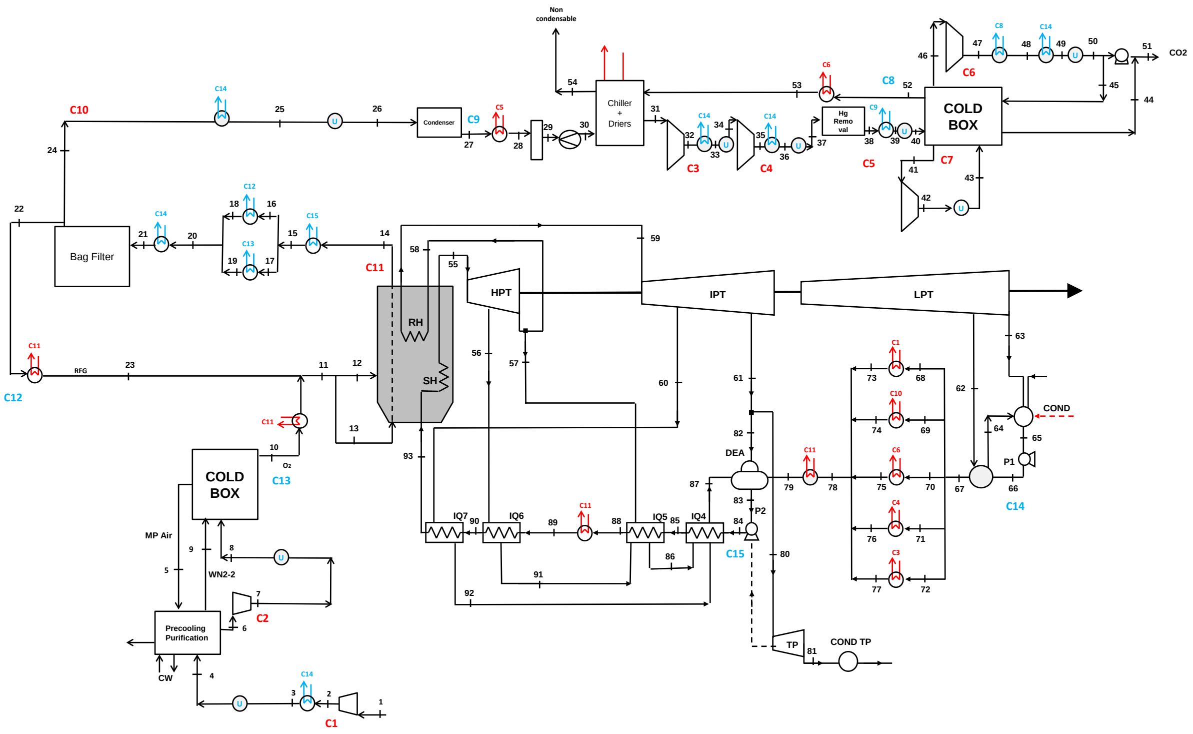


Fig.8. HEN and final oxy-fuel power plant configuration

The high temperature flow corresponds with the RFG stream and it exchanges with the high pressure feedwater and the low pressure condensate before deaerator inlet. Finally, ASU and CPU hot streams are integrated with the rest of the low pressure condensate flow. Main results of the heat cascade and power plant outputs are showed in the Table 3.

PARAMETER	Optimized HEN		Final feasible HEN	
Boiler efficiency (%, LHV basis)	90.0	93.3	90.0	93.3
Hot/Cold pinch temperature (°C)	331/321	331/321	331/321	331/321
Heating demand (MW)	0.0	0.0	0.0	0.0
Cooling demand (MW)	24.8	24.4	60.9	52.9
Gross electric power (MW)	722.7	745.1	718.1	741.2
Gross electric efficiency (%)	46.30	47.73	46.00	47.48
Net electric power (MW)	546.2	568.5	541.5	564.6
Net electric efficiency (%)	35.00	36.42	34.69	36.17

Table 3. HEN and final oxy-fuel power plant results

Final heating demands are eliminated in both situations. The cooling demands are higher in the final HEN because heat integration has not been completed, but the plant efficiency is just slightly lower (36.17%) although the number of heaters has been significantly reduced.

4. Conclusions

A heat integration methodology based on pinch analyses together with Aspen Plus modelling has been developed and applied to a representative case study. As a consequence, overall oxy-fuel power plant net efficiency has been increased more than three efficiency points and in addition, cooling demands have been significantly reduced and no external heating demands are needed. Table 4 includes a complete summary of the main results

PARAMETER	Aire-fired reference	Oxy-fuel reference	Optimized HEN		Final feasible HEN	
Boiler efficiency (%, LHV basis)	90.0	90.0	90.0	93.3	90.0	93.3
Heating demand (MW)	-	52.5	0.0	0.0	0.0	0.0
Cooling demand (MW)	-	312.7	24.8	24.4	60.9	52.9
Gross electric power (MW)	705.7	690.4	722.7	745.1	718.1	741.2
Gross electric efficiency (%)	45.59	44.23	46.30	47.73	46.00	47.48
Net electric power (MW)	672.5	513.8	546.2	568.5	541.5	564.6
Net electric efficiency (%)	43.45	32.91	35.00	36.42	34.69	36.17
Efficiency points penalty	-	10.54	8.45	7.03	8.76	7.28

Table 4. Simulation results and efficiency penalty reduction

Considering a conventional supercritical power plant (air-fired mode) with a net electric efficiency of 43.45%, CO_2 capture process efficiency penalty can be calculated. This penalty has been reduced from 10.5 to 7.0 efficiency points (more than a 30% of reduction). The complexity of the optimized heat exchanger network makes it economically unfeasible. However, a different feasible solution has been proposed, with a minimum number of heaters and a minimum net electric efficiency reduction. Figure 9 compares the energy penalty of each configuration.

Finally, some issues must be taken into account regarding efficiency variation of each individual equipment. For instance, an efficiency increase in compressors will modify the streams temperature and thus, the optimized heat exchanger network should be recalculated in order to obtain a better solution. In this sense, an overall power plant efficiency increase could be achieved but the external heating and cooling demands could be increased. A sensitivity analyses must be performed in order to look for a trade-off.

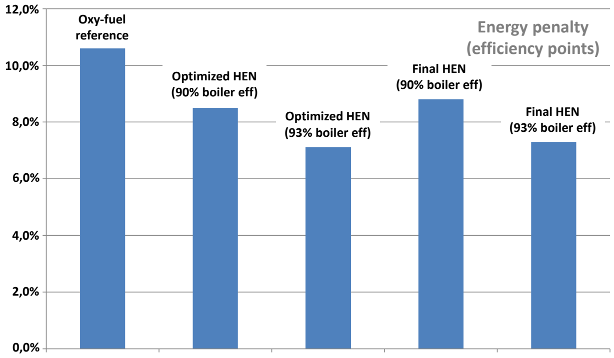


Fig.9. Efficiency penalty reduction by heat integration process optimization

Boiler efficiency becomes a more significant parameter for the whole HEN optimization process. An increase in steam production not only raises the overall power plant efficiency, but also it modifies the heating and cooling demands. When boiler efficiency changes due to the variation of O_2 concentration in oxidant, the heat integration configuration could be different. Although the boiler efficiency increase prevails over any other integration action, some analyses included in this work have yielded very promising conclusions (e.g. a better integration can be achieved in the high pressure zone of the steam cycle with a lower boiler efficiency). In general, the heating demand and the boiler efficiency grow simultaneously. On the other hand, the opposite is noticed in the total cooling demand. Cooling demand decreases when the steam mass flow increases, since cold and heat streams integration is enhanced. Nevertheless, some cooling demands still remain since there are some needs of cooling at very low temperature. This limitation will exist in any case.

Currently, O2GEN project is still running and new features and improvements are being under consideration. According to all the partners, especially boiler and ASU and CPU manufacturers, new technical and economical criteria are going to be considered and included in the final 2nd generation oxy-fuel power plant design.

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