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Optimization of oxygen-based CFBC technology with CO_2 capture

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Abstract

O2GEN project was running during more than three years and it was successfully finished in January 2016. The main target was to develop the 2^{nd} generation oxyfuel circulating fluidized bed (CFB) power plants based on higher oxygen concentrations with the aim of decreasing flue gas recirculation and the energy penalty. Remarkable advances have been achieved in Air Separation (ASU) and Compression and Purification Units (CPU) reducing significantly their energy consumption. CFB boiler concept was proposed by scaling-up from past designs. No special drawbacks were found regarding combustion, heat transfer and emissions. Finally, a process integration methodology was applied and overall efficiency was increased by heat integration. Energy penalty was reduced from 10.5 to 7.3 efficiency points. The new power plant lay-out avoids technical restrictions in the use of complex heat exchangers and facilitates the operational flexibility of the system.

Keywords: oxyfuel; CFB; CO_2 capture; efficiency optimization.

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1. Introduction

Oxyfuel combustion is one of the most feasible technologies for capturing CO_2 from power plants and large industrial sources in a short-medium term. For thermal power plants, the combination of oxyfuel technology with

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Circulating Fluidized Bed boiler technology (CFB) offers excellent advantages. It allows a broad fuel flexibility and an excellent combustion efficiency with low levels of pollutant emissions. Integrating oxygen-based combustion into CFB technology makes it an excellent choice for a CO_2 free power plant.

Nevertheless, one of the main drawbacks of the carbon capture is the energy requirement that reduces the overall efficiency of power generation by approximately 12 efficiency points. The consequences are remarkable, an increase in the cost of electricity above 40-50% and in fuel consumption (for the same power production) above 30-40%. Oxygen production by cryogenic distillation is by far the most important cause for the reduction of efficiency in an oxyfuel cycle and it consumes about 60% of the power consumption for carbon capture and it is responsible for the most reduction of the overall efficiency of the power plant. An additional reduction of 1-3% efficiency points is directly associated with the CO_2 purification and compression steps. In the final CO_2 conditioning phase, factors such as compressor efficiency, the amount of impurities in the CO_2-rich stream, and the adequate integration with the overall system, have great potential to reduce the power consumption.

For this reason it is necessary to develop a more efficient and cost competitive Carbon Capture and Storage (CCS) technology. In the case of oxyfuel technology, the use of higher O_2 concentrations in oxyfuel combustion reduces the flue gas recirculation and energy penalty. This is called the second generation oxyfuel power plants. In addition, higher O_2 concentrations enable the reduction of the boiler size and hence, a capital cost reduction. Using a CFB boiler, the temperature profiles inside the furnace are lower than in a PC boiler, since there is a very high solids circulation rate with effective heat transfer.

The O2GEN project objective has been the demonstration of the second generation oxyfuel CFB concept based on the combustion with high oxygen levels (30-50% v/v basis). New designs and improvements of main systems (ASU, CFB boiler, CPU) for oxyfuel combustion have been carried out during the project. They have allowed to reduce ASU requirements, increase boiler efficiency and achieve a high CO_2 purity at CPU. Moreover, a complete process integration of high efficiency and optimized systems has revealed an improvement in the overall efficiency of power plants with CO_2 capture.

To achieve the project objectives, O2GEN has included relevant participation of key industrial partners and technology suppliers (Amec Foster Wheeler, Air Liquide, ENDESA and INERCO), research institutions (VTT, CSM, SUT, USEV, LUT and CIRCE) and state of the art facilities (CIUDEN) that also provide improvements in operational flexibility [1].

2. Improvements and research topics identification

The analysis of the results from previous projects carried out at CIUDEN facilities were used as baseline reference for the definition of the main drawbacks and areas of improvement of oxyfuel technology [2, 3]. Furthermore, experimental data from pilot plant tests under high oxygen levels (up to 42%) shown that the combustion performance was similar under air and oxy conditions. These results were also used as the basis of knowledge for new tests in CIUDEN facilities within O2GEN project.

Therefore, the optimization of the oxyfuel combustion was based in the increase of the oxygen concentration to higher levels, achieving 30-50% v/v basis concentrations. Nevertheless, there are different topics related to the oxycombustion in CFB that must be analyzed in detail and finally, they have to be overcome, in order to increase the overall power plant efficiency by reducing the CO_2 capture energy penalty. Figure 1 shows the main areas of improvement.

In order to reach the 2nd generation of oxyfuel power plants, oxygen level has been increased (1) and ASU energy requirements have been significantly reduced (2). The inherent characteristics of the CFB technology allow using different fuel mixtures with different reactivity and composition (3) and in addition, boiler size has been reduced (4) and as consequence, capital cost is lower than same power PC boilers. Several commercial materials have also been tested in order to choose the best candidates for boiler manufacturing (5) that are able to withstand the high temperatures inside the furnace. The high oxygen concentration increases the heat flux and the energy release inside the boiler, thus new designs for internal and external heat transfer surfaces have been proposed (6). Regarding pollutants emission, the influence of higher O_2 levels and lower flue gas recirculation (7) has been studied in relation with NOx and SOx formation (8). The CPU performance (9) has been optimized, reducing energy consumption in the compression process and testing new components and designs. Finally, to minimize the energy penalty and increase the overall electric efficiency of the oxyfuel power plant, an energy integration process (10) has been carried out in order to recover energy from flue gases (9) and to design an optimized heat exchanger network.

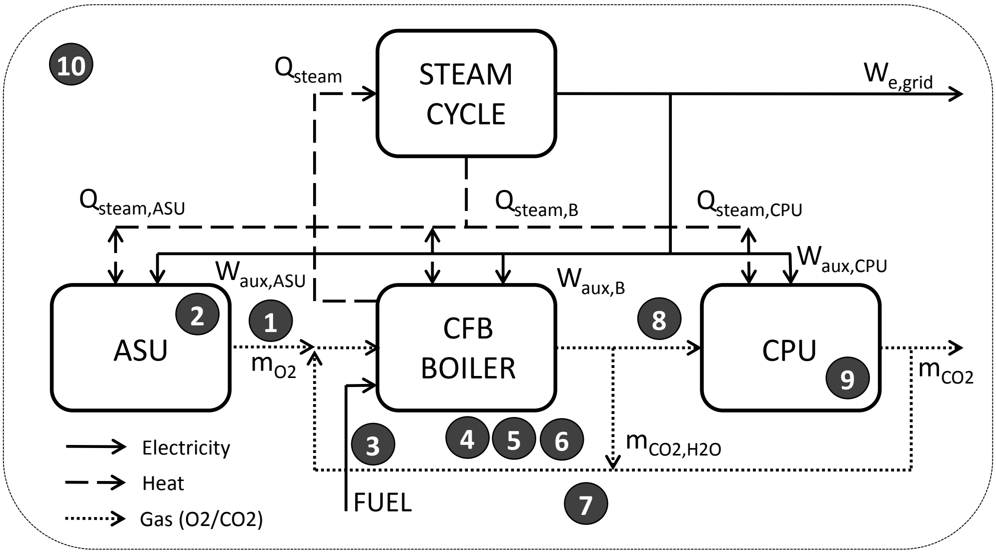

Fig. 1. Areas of efficiency improvement to the 2nd generation oxyfuel power plant

3. Main results: 2nd generation oxyfuel CFB technology features

3.1. High oxygen level in CFB boiler

Experimental work under high oxygen content combustion conditions was firstly carried out at two scales, bench and small pilot scale. Bench scale bubbling fluidized bed (BFB) combustion tests in oxygen combustion conditions up to 50% v/v basis of O_2 in feed gas and pilot scale CFB combustion test campaign up to 42% v/v basis O_2 in feed gas. The fuels in bench scale tests were Spanish anthracite and Polish bituminous coal, and in pilot scale tests Spanish anthracite/petcoke blend and Polish bituminous coal. Two Spanish limestone types were used for in-furnace sulphur capture in pilot scale tests. Finally, in a second phase, the same fuels and limestone types were used in larger scale CFB combustion tests carried out by CIUDEN under the same oxygen conditions (30-40% v/v basis).

According to bench scale BFB combustion tests, the increase in oxygen concentration in primary and secondary gas increased combustion rate and the peak temperature. At low O_2 levels, volatile release and char combustion can be separately observed. However at high O_2 concentrations, the processes occur almost at the same time [4]. The rate of NO formation increased too with oxygen level but in any case, there was not significant change in total nitrogen release. In pilot scale CFB combustion tests, the effect of oxygen share variations on temperature profiles was not significant due to solids densities and circulation rates in furnace.

Regarding tests run in CIUDEN facility, almost 2 weeks continuous operation under different conditions and with high oxygen level in the oxidant streams was carried out. No major problems were encountered during the operation. Combustion process at elevated oxygen concentration in oxidant streams was stable. As a main conclusion, it can be said that any major differences in the results between the high oxygen level cases and the previous oxygen level were not found or were only minor [5]. It is possible to reach the same SO_2 capture figures inside the furnace and, according to the test results, the SO_2 capture efficiency is very similar in both combustion conditions. NO_x emission increases with increasing boiler load, bed temperature and primary oxidant share. Like in air combustion, N_2O emission is very clearly a function of bed temperature and it is well in line with low-O_2 test results previously. CO emission is lower compared with low-O_2 tests at full load operation i.e. when the bed temperature is also high. At other load levels, CO emissions are in line with low-O_2 measurements. CO emission is quite clearly a function of bed temperature (i.e. load) and to some extent, of primary oxidant share.

3.2. Oxygen production optimization

Oxygen production consumes about 60% of the power consumption for oxyfuel CCS and it is responsible of similar percentage in the energy penalty. Simulations for integration studies and exergy analysis have allowed detecting sources of inefficiency. An exergetic efficiency of 18.6% is obtained corresponding to a specific energy of separation of 200 kWh/t of oxygen [6]. Therefore, an important improvement potential was detected in the oxygen production process. The main target for ASU design consists of achieving a specific energy consumption of 120 kWh/t of oxygen in 2020. Figure 2 shows the trend of energy consumption in cryogenic ASU technology development, including an estimation of the energy reduction share corresponding with heat integration.

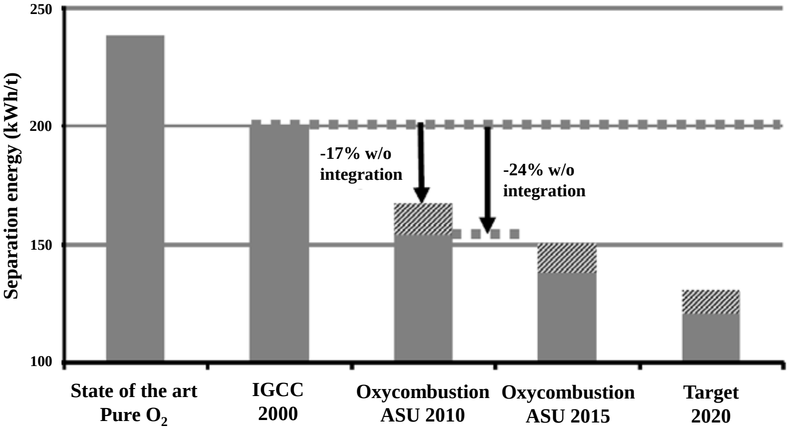

Fig. 2. Trend of the reduction of specific separation energy consumption of cryogenic ASU [7]

The main advances were focused on the implementation of an adiabatic compression with heat recovery, the optimization of the Pressure Swing Adsorption process (PSA), development of a membrane contactor and the design of an advanced structured packing.

One-stage adiabatic compression and recovery of compression heat for boiler feed water preheating increases power plant net power output. The most common air compressor technology for ASU application is the centrifugal technology. In the case of heat integration no intercooling is required and axial compressors would be the preferred technology. Axial compressors can achieve larger volume flow capacities, better stage polytropic efficiencies and less shaft losses. The use of axial compressor and corrosion resistant brazed aluminum heat exchanger reduces ASU net power consumption by more than 10% in comparison to nonintegrated compression. H_2O and CO_2 contained in the air must be removed before entering cryogenic distillation process to prevent freeze up of ASU. For that purpose, it is generally used a Temperature Swing Adsorption (TSA). Within project, a PSA process was proposed instead of TSA. Since the sorbent is regenerated at ambient temperature by depressurization there is no heat requirement for this system, providing significant energy saving over TSA. In addition, different contactors were proposed for distillation: membrane contactor and an advanced structured packing. The latter was finally selected for the second generation ASU due to its technological maturity, reducing distillation pressure drop by 15%. The new ASU configuration net power consumption was reduced by 23% in comparison to reference ASU configuration. The specific energy of separation of the improved ASU configuration is 150 kWh/t with integration credits.

3.3. CFB boiler design

Conceptual boiler design for high oxygen conditions was based in the state-of-the-art of supercritical CFB technology and the structural materials available in the market were taken as a basis of the process design. Increasing the oxygen concentration in oxidant up to 40% v/v basis implies that the volume of RFG is strongly reduced, resulting in significantly more compact construction and also reduced auxiliary power consumption. Figure 3 shows a comparison of the main boiler features with other relevant reference units.

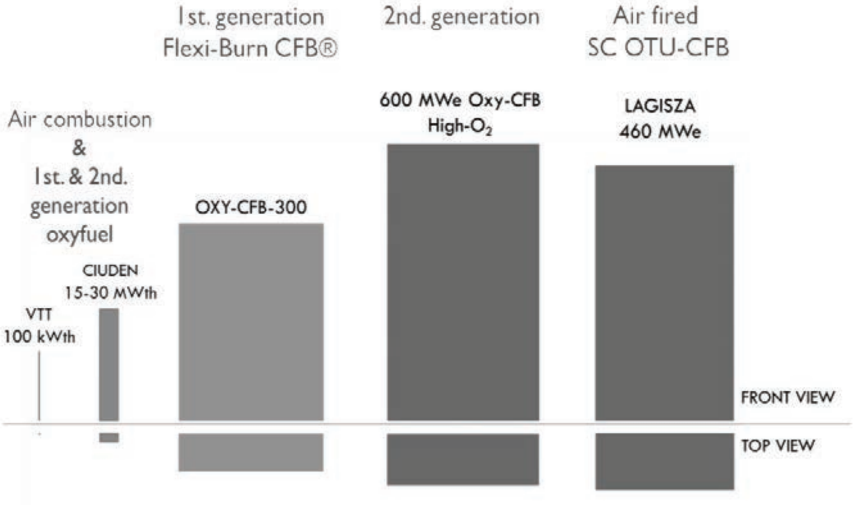

Fig. 3. Comparison of furnace geometry from test facilities to large power plants designs [8] [9] [10]

The thermal power of the 600 MWe oxy-CFB high O_2 concentration boiler is 1439 MWth, which twice the thermal power of the Oxy-CFB-300 boiler and ~50 % higher than the thermal power of the Lagisza plant. In spite of the higher thermal power, the furnace cross section (9.5 x 29.7 m^2) is slightly smaller (3.6%) than in Lagisza (10.6 x 27.6 m^2) and the height of the furnace is 53 m compared to 48 m in Lagisza.

Regarding materials, high Cr austenitic stainless steels, as Ni alloy, present a protective behaviour when exposed in typical oxy environment (3% O_2 / 30% H_2O / 60% CO_2 / 6000 ppm SO_2) at 600 and 700°C. Thus, it might be concluded that the tested high Cr austenitic stainless steel seems to be a promising alloy to be used for application at 700 °C in oxyfuel in alternative to Ni alloys. However, longer exposure tests might be necessary for a full qualification.

As conclusions CFB boiler start-up appeared to be easy regardless of the increased heat transfer surface in furnace. CFB boiler combustion performance under high oxygen levels is similar to 1st generation performance technology (low-O_2). Emissions are low and sulphur dioxide can be controlled by furnace limestone injection. Under high oxygen content in oxidant streams, the CFB boiler behaves in the same way that as in previous oxygen values with the exception of the difference resulting from higher thermal power and distribution of heat duty in furnace and backpass.

3.4. CO_2 Compression and Purification Unit

Around 4% of the total exergy losses for an oxyfuel power plant correspond with the CPU [5] hence, a reduction of 1-3% efficiency points are directly associated with CO_2 processing. Recommendations for process optimization include: (1) the implementation of low pressure driers, (2) heat integration between the compression units and the steam cycle, (3) recovery of non-condensable gases mechanical exergy and (4) coupling of cryogenic separation and permeation processes. With optimum operation conditions, the four main recommendations have made possible to decrease CPU power consumption by 14% [11]. A specific energy of separation in the range of 120 kWh/t (with integration credit) is obtained for second generation CPU. Regarding impurities behaviour in the CPU, test campaigns perform in CIUDEN facilities revealed HCl and SO_2 concentrations near zero at scrubber inlet even when operating with SO_2 concentration above design conditions [12]. In addition, mercury concentration was drastically reduced, particles were well captured and finally, driers perform a good drying of the process gas. The concentration of CO_2 produced was above 98.8% even if the cold box set point was not optimized. It is important to notice that these performances were measured during small time periods, during which the plant operating parameters were not fully optimized. Therefore, it is necessary to increase the quantity of experimentation hours on large pilot plants such as CIUDEN in order to further optimize the technology and reduce CAPEX uncertainty [13].

3.5. Process integration and optimization

One of the main milestones in 2nd generation oxyfuel CFB is to achieve a significant reduction of the overall efficiency penalty of CO_2 capture. To reach this objective it is necessary, not only to optimize processes and components throughout the power plant, but also to accomplish a complete heat integration of the whole plant for diminishing external heating and cooling demands.

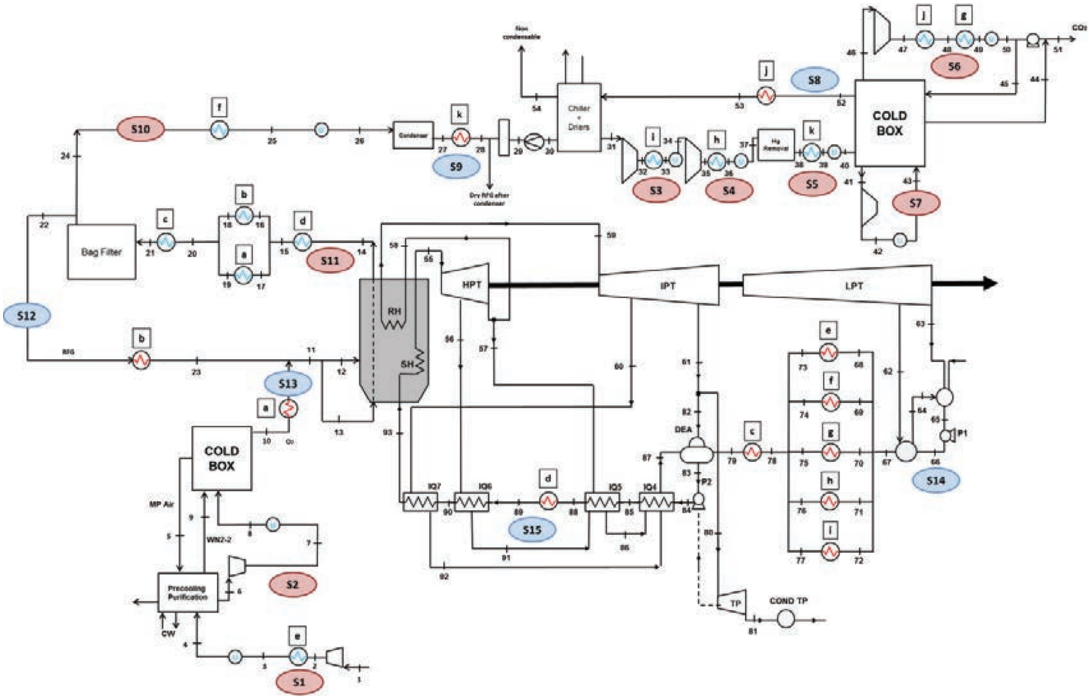

Fig. 4. Second generation oxyfuel power plant layout [14]

A heat integration methodology based on pinch analysis together with Aspen Plus modelling has been developed and applied to the second generation oxy-fuel power plant concept. The main integration options were those in which the low pressure turbine bleedings are avoided. Moreover, the optimum integration allows reducing the high pressure steam extraction to minimum, while keeping zero external heating demands to the overall system.

Nevertheless, the number of heat exchangers in such cases is so large that we have looked for a trade-off between efficiency and complexity. Thus, a new feasible concept looking for a balance between efficiency optimization and complexity of the associated power plant has been proposed, figure 4 [14]. Results show an important increase in power plant net efficiency (36.4%, LHV basis) regarding oxy-fuel reference power plant (32.9%). Finally, the energy penalty has been reduced from 10.5 to 7.3 efficiency points.

Additionally, some studies including high humidity coal pre-drying with by-product N_2 stream have been carried out [15]. Within the O2GEN project, an improvement of 0.3 efficiency points was reported by means of application of fuel dryer for those special cases with this kind of high humidity coals.

Finally, dynamic simulations were developed by using the Apros and Aspen co-simulation system. Mode switch was carried out in 30 minutes, which was only 10 minutes slower compared to the OXY-CFB-300 (50% smaller power plant) project results [16, 17]. The simulation study shows that smooth switching from air to oxy firing is possible to perform by ramping main gas flows. Also load change is possible to carry out smoothly and controlled. The load change from maximum to minimum was carried out in 15 minutes which corresponds 3%/min load change rate. Heat integration between these three main process areas were implemented with intermediate water circuits where concept efficiency decreases little but usability increases remarkable. With developed ASU it is also obvious that oxygen buffer vessels are needed in normal operation. The results show that the control strategies applied worked properly and all the process areas were following the load change including flue gas O_2 content.

4. Conclusions

O2GEN project has been ongoing from 2013 to 2016. The project was totally aligned with one of the main objectives of the European Strategic Energy Technology Plan (SET-Plan) [18], which aims to accelerate the innovation in European low carbon technologies to facilitate the achievement of the 2020 targets and the 2050 vision of the Energy Policy for Europe. While the efficiency of conventional air-fired thermal power plants is typically 45%, the efficiency significantly reduces by 12% when the oxyfuel CCS components are added to capture the CO_2. The project was focused on the use of higher O_2 concentrations in oxyfuel combustion reducing the flue gas recirculation and energy penalty. This high oxygen level concept was named as 2nd generation oxyfuel combustion.

During these three years, new achievements have reached in the different systems. High oxygen levels (30-50% v/v basis) have been successfully proved at several scales (bench, pilot and industrial scale), the specific power consumption in oxygen generation has been reduced around 23% regarding ASU state-of-the-art, CFB boiler was scaled-up from previous designs keeping its features with these new combustion conditions, CPU power consumption was decreased by 14% and an accurate heat integration methodology has allowed reducing energy penalty more than 3 efficiency points together with good flexibility operation conditions.

Acknowledgements

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