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Conception of a Pulverized Coal Fired Power Plant with Carbon Capture around a Supercritical Carbon Dioxide Brayton Cycle

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Abstract

Power generation efficiency penalty is the main concern about carbon capture technologies. Improvement of power plant efficiency due to higher steam condition is frequently foreseen to outbalance the carbon capture penalty. This work focuses on the conceptual design of two coal-fired power plants using CO_2 as working fluid: one with post-combustion MEA-based CO_2 capture and one with oxy-combustion CO_2 capture with cryogenic air separation. Two maximal supercritical CO_2 temperatures are investigated (620 and 700°C).
The combination of a Brayton supercritical CO_2 power cycle, a coal boiler and a capture process allows significant increase of the overall plant efficiency. Both post-combustion and oxy-combustion capture processes lead to a very high overall plant efficiency: approximately 41.5% for a 620°C power cycle and 44.5% for a 700°C power cycle. Oxy-combustion seems best fitted for supercritical CO_2 Brayton cycle due to a simpler thermal integration and the CO_2 purification devices already integrated in the CO_2 processing unit. Main resulting technological challenges are the very large heat exchanger needed in the CO_2 cycle in order to achieve high power cycle efficiency and the development of supercritical CO_2 turbine significantly different than steam or gas turbine especially because of the very large effort on wheel and the small size of the equipment. Numerous technological developments on process component will be necessary and a representative CO_2 cycle pilot plant will be needed to assess CO_2 leakage, corrosion and flexibility issues.

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Keywords: Post-combustion, Oxy-combustion, supercritical CO_2 Brayton cycle, plant integration

1. Introduction

Power generation efficiency penalty is the main concern about carbon capture technologies. Improvement of power plant efficiency due to higher steam condition is frequently foreseen to outbalance the carbon

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capture penalty. But even with a maximal temperature of 700°C, a power plant designed around a Rankine steam cycle will have around 50% LHV theoretical efficiency. Coupled with an up-to-date and tightly integrated MEA-based post-combustion capture process, a power plant efficiency (CCS plant efficiency) of 42.5% could be achieved at best.

In fourth generation nuclear reactor designs, supercritical helium and supercritical carbon dioxide Brayton power cycles are investigated because of their compatibility with these applications, simplicity, small size and good energetic performances. The main problem is the make-up of working fluid required in all closed-loop thermodynamic cycle. With CCS, a large amount of high pressure CO_2 becomes available and will allow CO_2 to be used as the main working fluid after purification, also for coal-fired power plant. Nevertheless, the use of a supercritical CO_2 Brayton cycle for a coal-fired power plant needs some changes compared to the temperature cycle (450°C) used in nuclear applications at present. The maximal working fluid temperature must be adapted to coal application and the heat integration should be optimized: reheat, low temperature integration and air pre-heating. Moreover the absence of condensable steam leads to a completely new post-combustion carbon capture integration for post-combustion process, the heat must be distributed between the rich solvent and the stripper boiler or in a diabatic stripper.

This work focuses on the conceptual design of two coal-fired power plants using CO_2 as working fluid: one with post-combustion MEA-based CO_2 capture and one with oxy-combustion CO_2 capture with cryogenic air separation. Two maximal supercritical CO_2 temperatures are investigated (620 and 700°C). The issue of energetic integration, power plant efficiency and basic design of the plant are discussed for the four resulting cases.

2. Adaptation of supercritical CO_2 Brayton cycle to coal boiler

Supercritical CO_2 Brayton cycles have already been studied in literature [1,2,3,4] for fourth generation nuclear power plant. Some preliminary basic design of a 750 MWe turbine has been carried out [2]. Supercritical CO_2 is foreseen to produce high efficiency cycle with a rather cheap, abundant and low toxicity fluid. The high efficiency is due to the strongly non ideal behaviour of supercritical CO_2 near its critical point with respect to density and heat capacity. These turbines are in developing stage and a few numbers have been tested at pilot scale (around 1 MWe) [1,3]. The main technological issues are the validation of turbine and compressor efficiency and the control-loop of the power cycle due the sensitivity of the performance to operating parameters. Secondary concerns are linked to engineering developments: thrust load management, rotor cavity pressure control, advanced gas-seal operation, rotor windage [3].

2.1. Classical regenerative supercritical CO_2 cycle

A Brayton supercritical CO_2 cycle is based on a regenerative Brayton cycle in which a fraction of the CO_2 is pumped at high pressure without prior cooling [1]. This arrangement maximizes the cycle performance and is named part flow cycle. It is composed of (figure 1):

- A main heater where the CO_2 is heated to its maximal temperature.
- A turbine where the CO_2 enthalpy is converted to mechanical power, the minimal pressure being around 80 bars in order for the CO_2 to stay supercritical despite the pressure drop in the downstream heat exchangers.
- A main economizer where the cold, high pressure CO_2 is preheated before the main heater by cooling down the hot, low pressure CO_2.
- An auxiliary economizer where a portion of the cold, high pressure CO_2 is preheated before the main economizer by further cooling down the hot, low pressure, CO_2.
- A cooler where the low pressure CO_2 is cooled down to 31°C.

- A main compressor where most of the CO_2 is pumped to 200 bar.
- An auxiliary compressor where the rest of the CO_2 is pumped to 200 bar, the feed of this auxiliary compressor being taken before the cooler and mixed back after the auxiliary economizer.

The amount of CO_2 sent to the auxiliary compressor is adjusted in order to keep the pre-heated temperature constant. Most supercritical CO_2 Brayton cycles have been designed for nuclear application with a heat source with constant temperature comprised between 450 and 600°C.

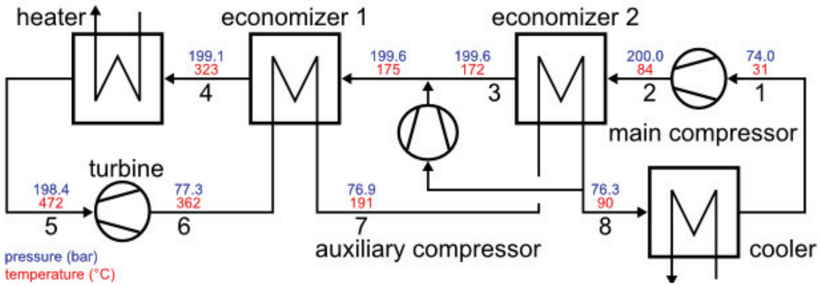

Figure 1: typical supercritical Brayton CO_2 power cycle with part flow recycle (pressure and temperature data are taken from [7])

2.2. Basic boiler design

In coal-fired power plants, the temperature in the boiler is around 1400°C; approximately half the total heat duty is delivered at this temperature through radiative heat transfer, the other half is the sensible heat of flue gas leaving the boiler. The CO_2 cycle heating system must be redesigned specifically for a coal-fired boiler coupled with a CO_2 capture process.

The part-flow design [1] is not adapted: the heat needed for the cycle is delivered at high temperature (i.e. above 500°C) consequently, with this configuration, a large part of the duty in the flue gas below 500°C cannot be valued in the CO_2 cycle or by air preheating. In order to circumvent this issue, an additional CO_2 heater has been added in parallel to the primary air pre-heater. Moreover, in order to maximize efficiency and use the high heat transfer in the boiler, two reheats have been added. The maximal cycle temperature is 620°C which is equal to the maximum temperature in most advanced supercritical steam/water power cycle. Double reheat is feasible for CO_2 cycle because the CO_2 density does not change drastically in the cycle and therefore does not need large tubes and high pressure drop resulting in a compact heat exchange surface area in the boiler.

Sensitivity analysis on the optimal compression ratio of the Brayton cycle shows that 4 seems the best technological compromise. With the CO_2 cooler operating near the critical point, this leads to a 300 bar maximal temperature.

CO_2 turbines efficiency of 93% and CO_2 compressors efficiency of 90% have been assumed accordingly to the literature [1,4]. Pressure drops of 15 bars and 5 bars have been assumed, respectively, in the main CO_2 heater and both economizers.

2.3. Low grade heat integration

In order to improve plant efficiency and to decrease flue gas temperature up to 110°C, two parallel heat exchangers are needed to recover heat from flue gases exiting the boiler. One of these exchangers, the larger, preheats the combustion air, the other, preheats the CO_2 of the power cycle through a bypass of both economizer 1 and 2 (figure 1).

An additional economizer is added to the power cycle, in parallel of economizer 2 (figure 1) in order to recover the CO_2 compression heat for both post and oxy-combustion cases and the ASU compressor heat in the oxy-combustion cases.

3. Integration of capture process

3.1. Amine based post-combustion process

The absence of steam implies the absence of large quantities of heat at constant temperature which is the common mode of heating for CO_2 stripping; therefore the thermal integration of the CO_2 capture plant with the power plant must be adapted. There are two large source of sensible heat at the required temperature level: the flue gas between the SCR (Selective Catalytic Reduction of NOx) and the ESP (Electrostatic Precipitator) and the CO_2 exiting the main economizer. The flue gas does not contain enough energy therefore a part of the CO_2 will be extracted at 210°C and 80 bars from the power cycle in order to boil the solvent. The amount of CO_2 extracted is set in order to keep a 5 K minimal temperature pinch in the boiler. The conception of the capture process is based on anterior study on process modification [8]. A block diagram of the overall process is shown in figure 2.

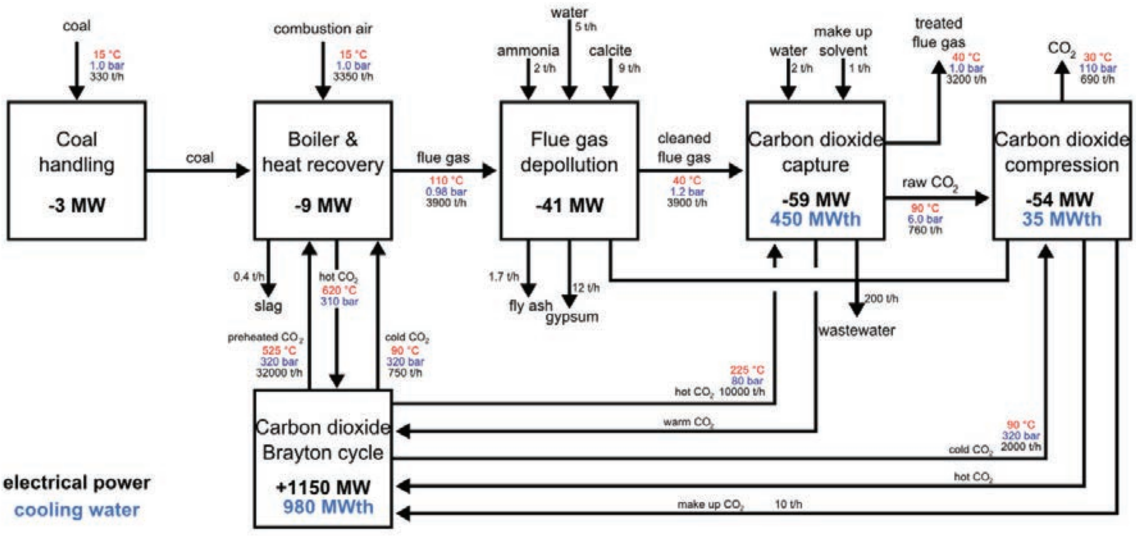

Figure 2: bloc diagram of the power plant with post-combustion capture

Capture process is based on standard 30%-wt MEA solvent process with a simple absorber (without intercooling nor split flow) and a highly thermally integrated stripper. Both columns are equipped with 15 m structured packing bed. The CO_2 stripper is designed to operate at 2 bar, the regeneration heat is provided by hot supercritical CO_2 and the condensation of the stripper overhead after compression, the solvent feed is preheated with the remaining heat contained in the supercritical CO_2 exiting the boiler. The steam produced by flashing the stripper overhead flow exiting the boiler is compressed back in the stripper. The raw CO_2 at 6 bars exiting the capture unit is then compressed up to 110 bars and resulting low quality compression heat is integrated into the power cycle.

3.2. Cryogenic based oxy-combustion process

The oxy-combustion process is simpler to couple with a CO_2 cycle plant. Indeed, the interface between cryogenic air separation unit (ASU), CO_2 processing unit (CPU) and power plant is limited to electric power and low grade heat-integration, the later being integrated in the same way than the compression heat in the post-combustion case. The flue gas recirculation needed to control the boiler temperature does not change significantly the integration pattern between the boiler and the power cycle. A block diagram of the overall process is shown in figure 3.

The boiler and power cycle have the same features than in the post-combustion case, the main differences are the addition of a direct contact cooler (DCC) to cool down the flue gases and a 73% flue gas recycling after the DCC in order to keep the O_2 concentration near 28%-vol. 25% of the recycling flow is sent to the coal mill to transport pulverized coal and the complement is used as "secondary air". The oxygen flow is set in order to have an oxygen excess of 3.5% at the boiler outlet.

The ASU is a standard double-column cryogenic distillation process with a specific energy consumption of 220 kWh/t_{O2}. The compression is performed in one stage in order to produce medium (220°C) quality heat which is integrated in the power cycle. Compressor isentropic efficiency is assumed equals to 85%, the higher pressure in the ASU process is set to 5.6 bars.

The CPU is a double-flash standard cryogenic process producing a 98% purity CO_2 flow. Its specific energy consumption is 115 kWh/t_{CO2}. The pre-compressor (from 1 to 18 bars) is a one-stage compressor; the medium quality compression heat (340°C) is integrated in the power cycle. The final compression from 11.9 to 110 bars) waste heat (180°C) is also integrated. Compressors isentropic efficiency is assumed also equal to 85%.

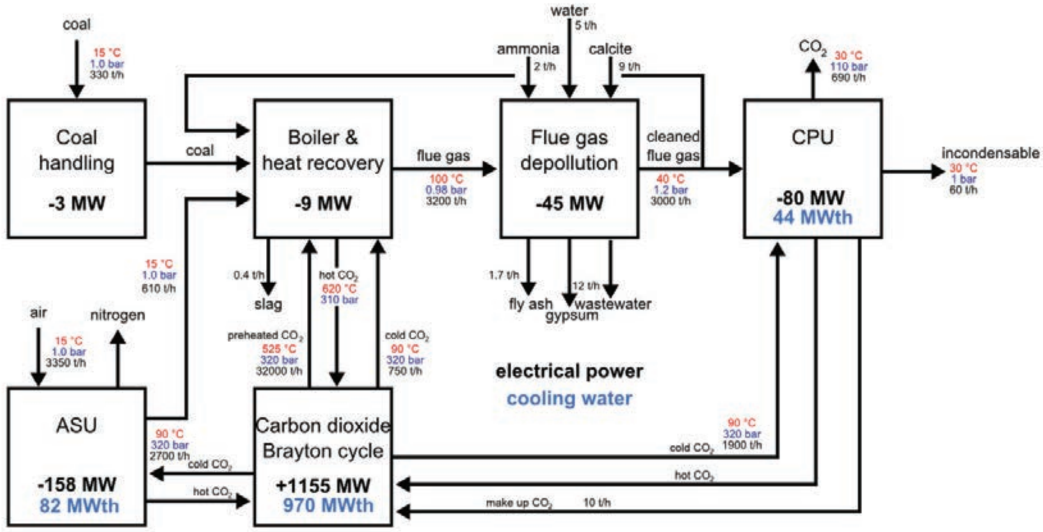

Figure 3: bloc diagram of the power plant with oxy-combustion capture

4. Results and discussion

The studied processes have been simulated with ASPEN-Plus software. Redlich-Kwong-Soave (RKS) equation of state have been used to represent the flue gas path, Peng-Robinson (with Boston Mathias mixing rules) (PR-BM) for the cryogenic processes and Lee-Kesler-Plocker (LKP) equation of state for the CO_2 power cycle.

4.1. Performance evaluation

The base efficiency of the coal power plant with supercritical CO_2 power cycle at 620°C main temperature is 50.3%, which is approximately 5%pt higher than a reference supercritical steam power plant. In the post-combustion case, the waste heat integration yields a CCS power plant efficiency of 41.4% (0.8%pt efficiency gain) whereas in the oxy-combustion case, the waste heat integration yields a CCS power plant efficiency is 41.6% (1.8%pt efficiency gain). The gain obtained on the oxy-combustion case is significantly higher than in the post combustion case because of the higher amount of total available compression waste heat (approximately 105 MW for post-combustion and 240 MW for oxy-combustion).

For the 700°C power cycle, the plant efficiency is 54.1% leading to 3.8%pt increase compared to the conservative 620°C case. In the post-combustion case, the waste heat integration yields a CCS power plant efficiency of 44.5% (0.75%pt efficiency gain) whereas in the oxy-combustion case, the waste heat integration yields a CCS power plant efficiency is 44.8% (2.0%pt efficiency gain).

4.2. Discussion and technology development issue

Both options show a large increase of CCS power plant efficiency. Nevertheless, numerous technological issues are not discussed in this work: CO_2 turbine technology, boiler design, CO_2 purity and loss in the cycle, etc.

Especially, the CO_2 cycle make-up purity is a specific issue: the CO_2 must be pure enough for the power cycle, a dedicated purification device could be necessary. This additional cost has not been considered. The rectification of almost pure CO_2 (99.98%) to pure CO_2 (>99.99%) can be performed at 60 bar in order to have CO_2 in liquid phase. At this pressure, the CO_2 boils at 22°C, which allows the use of the waste heat to perform the rectification. The pure CO_2 is pumped back to the main compressor inlet at 80 bars. The overall energy consumption for the CO_2 rectification is approximately 2 kWh/tCO_2 and has no significant impact on the plant efficiency. Oxy-combustion seems better suited to this application than post-combustion because of a slightly higher plant efficiency and the availability of the purification equipment, which is already included in the process scheme.

5. Conclusion

The combination of a Brayton supercritical CO_2 power cycle, a coal boiler and a capture process allows significant increase of the CCS power plant efficiency. Both post-combustion and oxy-combustion capture process lead to very high CCS power plant efficiency: approximately 41.5% for a 620°C power cycle and 44.5% for a 700°C power cycle. Oxy-combustion seems best suited for supercritical CO_2 Brayton cycle due to a simpler thermal integration and the CO_2 purification devices already integrated in the CO_2 processing unit. Main resulting technological challenges are the very large heat exchanger needed in the CO_2 cycle in order to achieve high power cycle efficiency and the development of supercritical CO_2 turbine significantly different than steam or gas turbine especially because of the very large effort on wheel and the small size of the equipment. Numerous technological developments on process component will be necessary and a representative CO_2 cycle pilot plant will be needed to assess CO_2 leakage, corrosion and flexibility issues.

Bibliography

[1] Viswanathan, Coleman, K., Rao, U., 2006, Materials for ultra-supercritical coal-fired power plant boilers. *International Journal of Pressure Vessels and Piping*, **83**:778-783.
[2] Utamura, M., 2010, Thermodynamic analysis of part-flow cycle supercritical CO_2 gas turbines. *Journal of Engineering for Gas Turbines and Power*, **132**:1-7.
[3] Sarkar, J., 2009, Second law analysis of supercritical CO_2 recompression Brayton cycle. *Energy*; **34**:1172-1178.
[4] Wright, S.A., Radel, R.F., Fuller, R., 2010, Engineering performance of supercritical CO_2 Brayton cycles. International Congress on Advances in Nuclear Power Plants (ICAPP), San Diego, 17 June.
[5] Muto, Y., Ishizuka, T., Aritomi, M., 2010, Conceptual design of a commercial supercritical CO_2 gas turbine for the fast reactor power plant. International Congress on Advances in Nuclear Power Plants (ICAPP), San Diego, 17 June.
[6] Jeong, W.S., Lee, J.I., Jeong, Y.H., 2011, Potential improvements of supercritical recompression CO_2 Brayton cycle by mixing other gases for power conversion system of a SFR. *Nuclear Engineering and Design*; **241**: 2128-2137.
[7] Dostal, V., Driscoll, M.J., Hejzlar, P., 2004, a supercritical carbon dioxide cycle for next generation nuclear reactors. MIT Advanced Nuclear Power Technology Program, available at: http://stuff.mit.edu/afs/athena/course/22/22.33/www/dostal.pdf
[8] Le Moullec, T., Kanniche, M., 2011, Screening of flowsheet modifications for an efficient monoethanolamine (MEA) based post-combustion CO2 capture, *International Journal of Greenhouse Gas Control*; **5**(4): 727-740