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Heat Integration of an Oxy-Combustion Process for Coal-Fired Power Plants with CO_2 Capture by Pinch Analysis

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This paper presents a detailed exergy analysis of an oxy-combustion process for a supercritical pulverized coal power plant with CO_2 capture. The results from the exergy analysis show that the power efficiency penalty related to CO_2 capture is 10.2% points and is caused by two units: the air separation unit (ASU) and the CO_2 purification & compression unit (CPU). The composite curves are applied to study the sub-ambient heat exchangers in the ASU & CPU. The power efficiency can be improved by heat integration between the ASU & CPU. The CO_2 recovery rate is also an important factor for the net power efficiency.

1. Introduction

Carbon capture and storage (CCS) is an important way to mitigate the man-made CO_2 emissions into the atmosphere. Oxy-combustion is a promising option for CO_2 capture especially for coal-fired power plants, since the reduction in efficiency and the increment of investment cost according to IEA (2007) and Kanniche et al. (2010) are less than for natural gas based power plants. In addition, a considerable technical challenge for oxy-combustion capture in natural gas based power plants is the design of oxy-combustion gas turbines.

Oxy-combustion processes have been widely studied recently, with a focus on the modification of individual units and process configurations (Hong et al., 2009, Wilkinson et al., 2001). It is commonly realized that the power efficiency reduction related to CO_2 capture in coal-based power plants is mainly caused by two units: the air separation unit (ASU) and the CO_2 purification & compression unit (CPU). However, only a few studies have focused on the integration of such complex processes. Harkin et al. (2009) use Pinch Analysis to integrate the steam cycle and the steam extraction process for flue gas purification and solvent regeneration in a coal based power plant with post-combustion CO_2 capture. The pre-drying process of coal is also included in their integration study. Romeo et al. (2008) present an integration study of the CO_2 compression process, the amine regeneration and the steam cycle. The study is also based on a supercritical pulverized coal-fired plant with CO_2 capture by post-combustion. There is apparently no literature available on integration studies for the sub-ambient temperature level in oxy-combustion power plants.

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This paper first performs an exergy study on a supercritical pulverized coal-fired power plant with CO_2 capture. The coal to power process is based on an NETL report (DOE/NETL, 2008), while the ASU and CPU are based on other common cases from literature. The distribution of exergy losses in the entire process is presented. The composite curves are applied to integrate the ASU and CPU at sub-ambient temperature levels. The relationship between the power penalty and the CO_2 recovery rate (kg of CO_2 in the product per kg of CO_2 in the flue gas) is also presented. The simulator Aspen Plus has been used to simulate the entire process in this work. The software tool PRO_PI1 is used to perform Pinch Analysis.

2. Process Description

Figure 1 shows the flowsheet of a 571 MW (net) supercritical pulverized coal power plant with CO_2 capture (base case). The steam cycle and the system of flue gas desulfurization (FGD) are simplified in the figure. The high pressure (HP) steam is heated to 242 bar/ 599^oC with single reheat of the medium pressure (MP) steam to 49 bar/ 621^oC.

The conventional cryogenic double-column air separation process is applied in this work to produce O_2 (1.5 bar) with a mole fraction of 95%. Ambient air is compressed to 5.6 bar and enters a front-end temperature swing adsorption-type (TSA) pre-purification unit (PPU) to remove H_2O and CO_2. The dry compressed air is cooled down to near dew point temperature in the main heat exchanger. The air is separated into O_2 and N_2 in the double distillation column. The reboiler in the low pressure (LP) column is integrated with the condenser in the high pressure (HP) column. The temperature difference of the condenser/reboiler match is maintained at 1.5-2^oC. A minimum temperature difference of 2^oC is chosen for the sub-ambient heat exchangers in this study. The waste N_2 first enters the PPU to cool down the process air and is then vented to the atmosphere. The O_2 product with molar composition: O_2-95%, Ar-3.2 %, N_2-1.8 %, is split into two streams. A minor part of the O_2 (2.3 %) enters the FGD and is used as oxidant, while the major part reacts with coal in the combustor.

To ensure complete combustion, the excess O_2 in the combustor is around 19 wt%. The combustion process takes place at 1.1 bar. To avoid a too high temperature in the combustor, a major part of the flue gas (72 %) is recycled to the combustor after desulfurization. The molar composition of the flue gas is: CO_2-70.7 %, H_2O-15.3 %, N_2-8.5 %, O_2-2.5 %, Ar-3.0 %. The rest of the flue gas is compressed to 32 bar after water removal in a direct contact cooler and dried in a molecular sieve twin bed drier to avoid ice formation in the sub-ambient heat exchangers. The inert gases are removed in two flash drums and vented to atmosphere after power recovery (Pipitone and Bolland, 2009). The operation temperatures of the two flash drums are -26 ^oC and -54 ^oC. The purified CO_2 from the bottoms of the two flash drums is expanded to 9 bar and 18 bar respectively. After exchanging heat with other streams, the CO_2 is further compressed to 78 bar in the second compressor and pumped to 150 bar for transportation and saline formation storage. The molar composition of the captured CO_2 is: CO_2-96.2 %, N_2-1.9 %, O_2-0.7 %, Ar-1.2 %. The recovery rate of CO_2 is 95.1%.

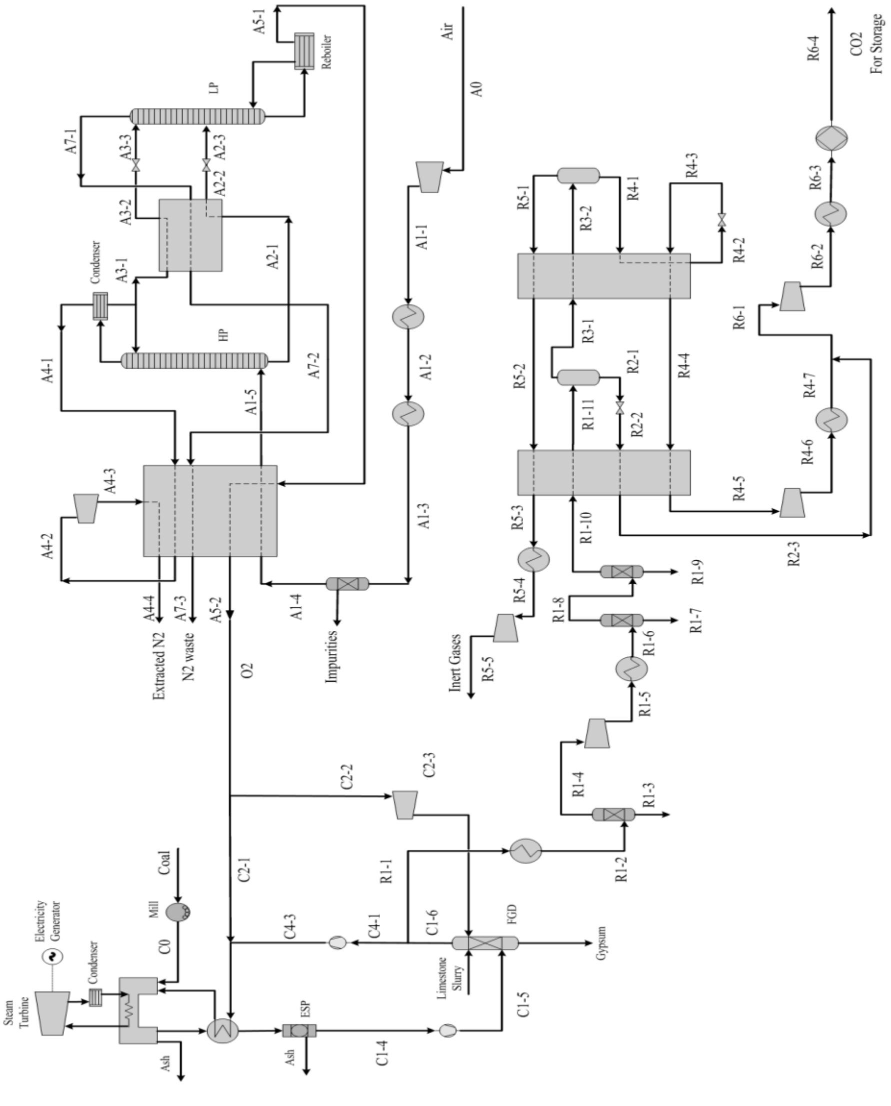


Figure 1: Flowsheet of the studied power plant.

3. Exergy Analysis

This work uses the reference environment model defined by Kotas (1995). The reference state (marked as “0”) is T_0= 25°C, p_0= 1.01325 bar (i.e. 1 atm). A detailed route to perform exergy analysis has been described by Hinderink et al. (1996) and implemented by JACOBS Consultancy (2009). Figure 2 shows the distribution of exergy losses in the entire process. The exergy input of the feed coal (feed rate: 69.232 kg/s) is 2,169,964 kW. The combustor has the largest exergy loss (692,196 kW). Other large exergy losses are the steam generation & reheat process and the steam turbines. The net power output is 571,115 kW and the power efficiency is 30.4 % (HHV: 27,135 kJ/kg). The power input to the ASU is 132,012 kW and the power recovered from the waste N_2 is 8,727 kW. The net power consumed in the ASU is then 123,285 kW. The theoretical minimum work consumption for the ASU is calculated to be 26,906 kW. The main air compressor (42,399 kW) and the distillation process (29,103 kW) are responsible for the two largest exergy losses. The exergy loss in the main heat exchanger is small (5,648 kW) due to low temperature differences. The power input to the CPU is 74,153 kW and the power recovered from the tail inert gases turbine is 5,770 kW. The net power consumed in this unit is then 68,383 kW and the theoretical minimum work consumption has been calculated to be 37,041 kW. Again the main exergy losses take place in the CO_2 compressors. If the power consumed in the ASU & CPU is added to the net power output, the power efficiency without CO_2 capture is calculated to be 40.6% (HHV). The power efficiency penalty is thus 10.2% points, where the ASU contributes 6.6% points and the CPU contributes 3.6% points. The theoretical power efficiency penalty related to CO_2 capture is calculated to be 3.4% points (ASU and CPU together).

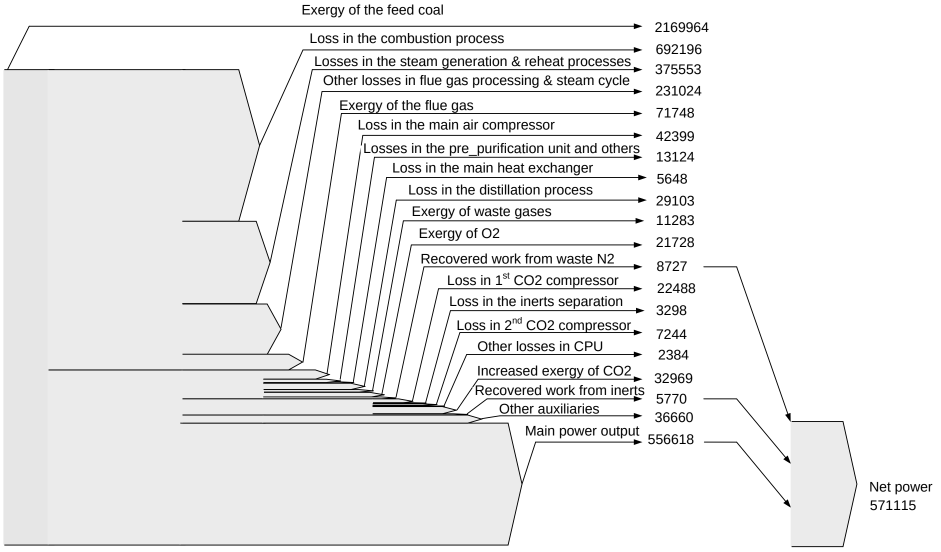
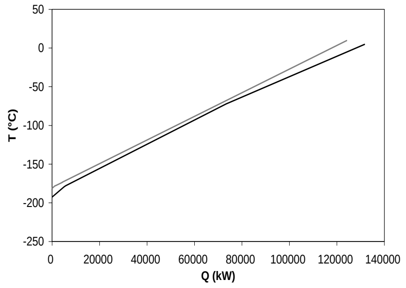


Figure 2: Exergy distribution [kW] in the entire process.

4. Integration Study

The results of the exergy analysis show that the compression processes in the ASU & CPU are responsible for the largest exergy losses related to CO_2 capture. The losses can be reduced by improving the performance of the compressors. Although the exergy losses in the sub-ambient heat exchangers are small, they can be further reduced by heat integration between the ASU and CPU. Figures 3 and 4 present the composite curves for the ASU and CPU in the base case. It can be found that the temperature difference in the temperature range above -56°C in the ASU is considerably larger than 2°C. The additional temperature driving forces can be utilized in the CPU, so that the purified CO_2 from the bottoms of the two flash drums can be expanded to higher pressures (both are 22 bar, instead of 9 bar and 18 bar in the Base Case) and less work will be consumed in the second CO_2 compressor. The composite curves for this integration case are shown in Figure 5. The pinch temperature is -19/-21 °C. Compared with the base case, the net power consumed in the CPU in this case is 65,298 kW. The power output increases 3,085 kW and the net power efficiency increases to 30.6 %.



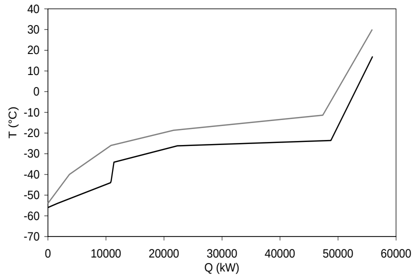


Figure 3: Composite curves for the ASU.

Figure 4: Composite curves for the CPU.

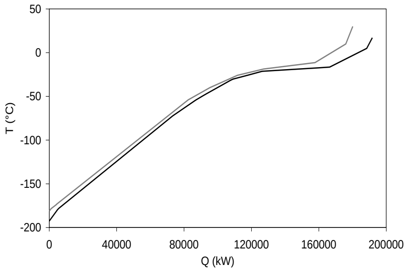


Figure 5: Composite curves for the integrated case.

The power efficiency penalty is also depending on the CO_2 recovery rate. The operating pressure of the two flash drums should be high enough to obtain a high CO_2 recovery rate. However, this causes considerable work to be consumed in the first CO_2 compressor. Table 1 summarizes the effects of CO_2 recovery rate on the power output and net power efficiency. Note that in Cases 3 & 4 only one flash drum is used since the CO_2 cannot be liquefied at -26°C and the corresponding operating pressure. The CO_2 liquid from the bottom of the flash drum in Case 3 is expanded to lower pressure than in Case 2 in order to exchange heat with other streams with a minimum temperature difference of 2°C. As a result, more power is consumed in Case 3 than Case 2.

Table 1: Effects of CO_2 recovery rate.

	Base Case	Case 1	Case 2	Case 3	Case 4
Operating pressure [bar]	32	25	20	18	15
CO_2 recovery rate [%]	95.1	93.3	91.5	90.2	86.9
Purity of captured CO_2 [mol%]	96.2	97.2	97.0	97.4	98.0
Power used in the CPU [kW]	68,383	66,901.5	63,469.5	63,766.7	60,699.2
Net power output [kW]	571,115	572,596.5	576,028.5	575,731.3	578,798.8
Net power efficiency [%]	30.4	30.5	30.7	30.6	30.8

5. Conclusions

Exergy analysis has been applied to investigate an oxy-combustion coal-fired power plant with CO_2 capture. The power efficiency penalty related CO_2 capture is 10.2 % points, where the ASU contributes 6.6 % points and the CPU contributes 3.6 % points. The theoretical power efficiency penalty is 3.4 % points. The main exergy losses related to CO_2 capture take place in the compressors in the ASU & CPU. The composite curves have been used to study the sub-ambient heat exchangers in this study. If the CO_2 recovery rate decreases from 95.1 % to 91.5 %, the power efficiency can be increased 0.3 % points. The net power efficiency can be increased 0.2 % points by heat integration between the ASU & CPU. The power efficiency can be further improved by an optimal design of the sub-ambient heat exchanger network.

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