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# Oxy-Combustion Coal Based Power Plants: Study of Operating Pressure, Oxygen Purity and Downstream Purification Parameters

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Oxy-combustion coal based power plants are considered one of the cost effective ways to produce $CO_2$ emission free electricity. Recovery of compression heat and the latent heat from the flue gases can further improve the efficiency of such power plants. Power plants that employ a boiler operating at a pressure higher than ambient pressure avoid air leakage into the boiler and also recover more of the latent heat available in the flue gases. Such power plants require compression of the oxygen stream before the combustor, an entirely new boiler house design and modifications to the downstream flue gas processing systems. Selection of an operating pressure that is energy optimal is the key to design of such systems. Besides the operating pressure, the oxygen purity and the downstream separation parameters have a considerable impact on the overall performance of such power plants. In this paper, the impact of operating pressure, oxygen purity and downstream purification parameters on the performance of oxy-combustion coal based power plants are studied.

## 1. Introduction

The Oxy-combustion method of capturing $CO_2$ is one of the most demonstrated capture methods. Several pilot and demonstration scale power plants employing this technology are being operated around the world. The oxy-combustion method is also suitable for retrofit modifications, as it only requires an upstream Air Separation Unit (ASU) to produce oxygen and a downstream Compression and Purification Unit (CPU) to separate the volatiles. Other existing systems such as the boiler house and the steam turbine generator systems can be used with minimal modifications. Together, the ASU and CPU are responsible for an efficiency penalty of 10 percentage points (Fu and Gundersen, 2010). A conventional state of the art coal based power plant has a boiler operating pressure slightly below the ambient atmospheric pressure. This is a design feature that ensures safety of the power plant operating personnel. This negative gage pressure in the furnace leads to air leakage into the boiler and hence has an impact on the downstream systems such as the loading of the induced draft fans (Bhatt, 2007). In an oxy-combustion set up, this air leakage has an even greater impact due to the downstream purification and compression requirements. Hence it becomes essential to minimize or if possible entirely avoid the air leakage into the boiler of an oxy-combustion power plant. The CPU of an oxy-combustion coal based power plant employs compressor trains to compress the flue gas to the pipeline pressure required for transport. The work consumed by these compressors represents a major portion of the energy penalty related to capture. Design of the compressor trains and recovery of compression heat can reduce the energy penalty associated with capture. In addition to the compression heat recovery, flue gas latent heat recovery must also be considered in case of the oxy-combustion coal based power plant. Recovery of the flue gas latent heat has more relevance in case of the oxy-combustion power plant as the flue gases need to be cooled before the CPU.

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Operating the boiler at a pressure higher than the ambient pressure eliminates the air leakage while increasing the flue gas latent heat recovery (Hong et al., 2010). At the same time, such a design would require a completely new boiler set up and hence may not be suitable for retrofit applications. Increasing the boiler operating pressure increases the useful latent heat recovery, but also increases the net compression work. Other design parameters that have significant impact on the performance of the power plant include the oxygen purity from the ASU and the downstream CPU operating parameters (Li et al. 2013). In this study, the effect of air leakage, operating pressure of the boiler, oxygen purity and CPU operating parameters on the energy performance of the power plant are studied. Power plants utilising a positive gage pressure boiler and incorporating significant levels of heat integration require large capital investments. Such power plants may also pose challenges in terms of reliability and operability as they represent relatively new concepts. The issues related to cost, reliability and operability, however, are out of scope for this work. The parameters are studied purely from the energy efficiency perspective with an objective of finding ways to reduce the energy penalty associated with the capture of $CO_2$.

## 2. Methodology

A conventional (negative gage pressure) air-combustion coal based power plant without $CO_2$ capture is modelled initially to serve as a baseline to estimate capture penalty and emissions avoided by the capture plants. A conventional oxy-combustion counterpart is also simulated as a baseline power plant with capture. Power plants with pressurized boiler (HP-OXY) are derived from the latter by adding a compressor to the oxygen stream before the combustor and making necessary changes to the pressure drop in the gas path and the downstream CPU compressor stages. The ASU itself was not simulated. Instead, the energy required to produce oxygen at the desired purity was based on values from Chao Fu, see acknowledgement. All other systems including the boiler island, the CPU and the steam cycle were simulated. The commercial simulation package Aspen Plus® was used for all the simulations. The Aspen HYSYS® simulation tool was used to estimate the amount of heat recovery between the hot and cold streams. Necessary care was taken to ensure that heat recovery takes place at appropriate temperatures. Minimum temperature differences for various hot and cold stream combinations were assumed and maintained. This was achieved by using multistream heat exchangers (LNG) and simultaneous adjust functions in Aspen HYSYS® to modify the mass flows of the cold streams. The above method was used to simulate complete power plants with boilers at various pressure levels to find the optimal operating pressure.

The boiler island and the CPU of the conventional power plant with capture are linked to Aspen Simulation Workbook (ASW) for the sensitivity cases (16 bars only). Multiple scenarios with various oxygen purities and CPU operating parameters are then fed into the simulation via the ASW to obtain the impact on the overall performance. For all the sensitivity cases, only the flue gas latent heat recovery is considered and not the CPU heat recovery for simplicity purposes. The steam cycle is not simulated in detail for the sensitivity cases and instead, the shaft power produced is estimated using the conversion efficiencies obtained from the base cases. The results from the sensitivity cases are then used to calculate various performance parameters such as the $CO_2$ recovery rate, net efficiency and the specific energy required to avoid one kg of $CO_2$ emitted.

## 3. Process description

The overall process flow diagram of the power plant with capture is shown in the Figure 1. All units of the power plant including the steam cycle, the boiler island, and the CPU are shown in the figure along with the heat integration between various units. The ASU, the coal preparation and handling systems and the ash handling systems are not shown in the figure. The Oxygen from the ASU (S1) goes through a compression and heat exchanger train (C1&HEX1) before entering the boiler (S2). The pressure and temperature of stream S2 depend on the compression mode of the compressor train C1 and the heat recovery/addition assumed which in turn depend on the simulation case. For instance, in the conventional case, the compression (C1) will be skipped and hence the pressure at S2 will be same as that at S1. A major portion of the flue gas S3 is used as a recycle (S4) to control the furnace temperature. A fan is also required to overcome the pressure drop in the gas circulation path. Atmospheric air is assumed to leak into the boiler in cases with negative gage pressure. The flue gas stream S5 is then taken to the downstream CPU for purification and compression to pipeline pressure. Stream S5 needs to be cooled before any compression can take place and this represents a heat recovery opportunity (Q2).

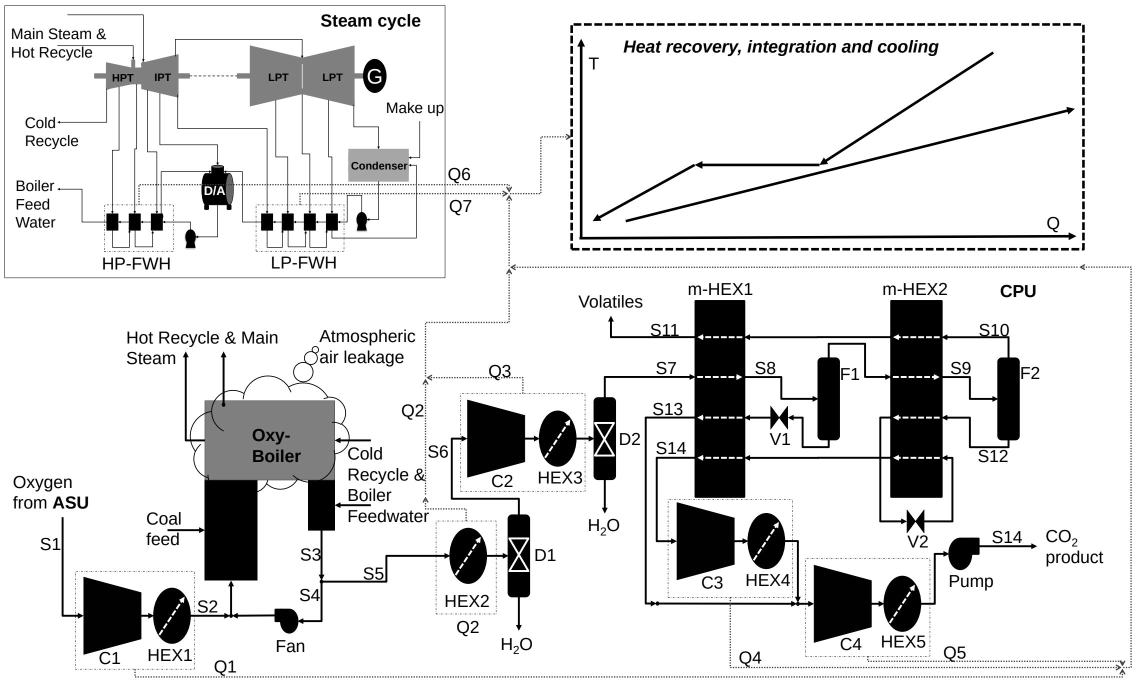


*Figure 1: Overall process flow diagram with heat integration*

As the oxy-combustion flue gas contains a lot of moisture, flue gas latent heat recovery is carried out in heat exchanger unit HEX2. Moisture is removed via a drier unit D1. The dry flue gas is compressed (C2) to a pressure of 30 bar and any heat recovery opportunities arising from the compression are fully exploited (Q3). Isothermal compression is employed in compressor train C2. Flue gases are then cooled to 15 $^oC$, remaining moisture is removed using the drier D2 and then fed into the first multi stream heat exchanger (m-HEX1). Stream S7 undergoes partial condensation in the heat exchanger and enters the flash drum F1 for vapour liquid separation. The liquid portion is rich in $CO_2$ and is expanded in valve V1 to satisfy the cooling needs of the incoming stream S7. The vapour stream is lean in $CO_2$ and hence undergoes one more stage of partial condensation (m-HEX2) and separation (F2) to improve the recovery rate of $CO_2$. The vapour stream S10 is then emitted to the atmosphere after utilising the stream for cooling purposes. The streams S13 and S14 undergo final compression in the compressor trains C3 and C4 respectively. Isothermal compression is used and heat recovery (Q4 & Q5) is carried out. The final product is achieved by pumping the liquid $CO_2$ to pipeline pressure. Stream S14 satisfies both the pipeline purity requirement and pressure level. A model of the steam cycle used in the simulation is also shown in the figure. The steam cycle receives the main steam and the hot recycle from the boiler, and these are expanded in the turbines to generate power. The exhaust from the low pressure turbines are condensed in a condenser and the condensate is then pumped to higher pressures. The condensate, referred to as Boiler Feed Water (BFW) is heated through a series of heat exchangers by extracting steam from the steam turbines. This regenerative feedwater preheating results in a high steam cycle efficiency. The BFW and the cold reheat are then fed to the boiler for heat transfer. This feedwater preheating train represents opportunities for heat integration (Q6 & Q7). Low grade heat recovered from other units of the power plant, such as the oxygen/flue gas compressor trains and the flue gas latent heat, can be used to supply a part of this preheating requirement. Heat integration reduces the steam extraction from the turbines, thereby increasing the electricity generated. Flue Gas Desulphurization is not included in the simulation for simplicity reasons. All the simulation parameters are taken from previous work by the authors (Soundararajan and Gundersen, 2012).

## 4. Results and Discussion

### 4.1 Influence of the boiler operating pressure:

Raising the operating pressure of the furnace and the boiler requires compression of the oxygen fed into the boiler. This essentially transfers part of the compression work from the downstream flue gases to the upstream oxygen. As a result of this, the flue gases coming out of the boiler will be at elevated pressures with increased dew point temperatures. Latent heat of the water vapour available in the flue gases is available at a higher and more useful temperature (Q2) for better heat recovery. A higher than atmospheric pressure inside the boiler area also avoids air leakage. This has a twofold advantage, first being the reduced mass flow through the CPU compressors and the second being the reduced $NO_X$ formation in the boiler. The compression of oxygen can either be done isothermally or adiabatically. In the former case, the compression train must have multiple stages of intercooled compression to save work whereas in the latter, the compressed oxygen is available at a higher temperature. Although adiabatic compression of oxygen consumes more work, the compressed oxygen is available at a much higher temperature and this recovers all the compression work as thermal energy through the boiler. In the isothermal case, most of the work consumed in compressing the oxygen is degraded into thermal energy of much lower temperature and can only be partly recovered and integrated into the steam cycle. Isothermally compressed oxygen can also be preheated by using the flue gases. In the CPU compressors, it is better to carry out the compression process isothermally and recover as much heat as possible via steam cycle feedwater preheating integration (Fu, 2012). The oxygen purity and CPU operating parameters are kept the same for the various cases. Figure 2 shows the impact of the boiler operating pressure on key performance indicators of the plant.

Figure 2(a) shows the compression work required by the upstream oxygen and the downstream CPU compressors. Adiabatic C1 and Isothermal C1 represent adiabatic and isothermal compression schemes in the oxygen compression train C1. Total compression work remains fairly constant for the isothermal case whereas it increases with pressure for the adiabatic case. Even though the work consumed by the CPU falls rapidly with increasing pressure, the total compression work keeps increasing in the adiabatic case. Figure 2(b) shows the gross power output from the steam turbines for various pressures and oxygen compression and preheating combinations. Isothermal300 stands for isothermal compression of oxygen and then preheating the compressed product to 300 $^oC$ before the boiler using flue gases. The increase in

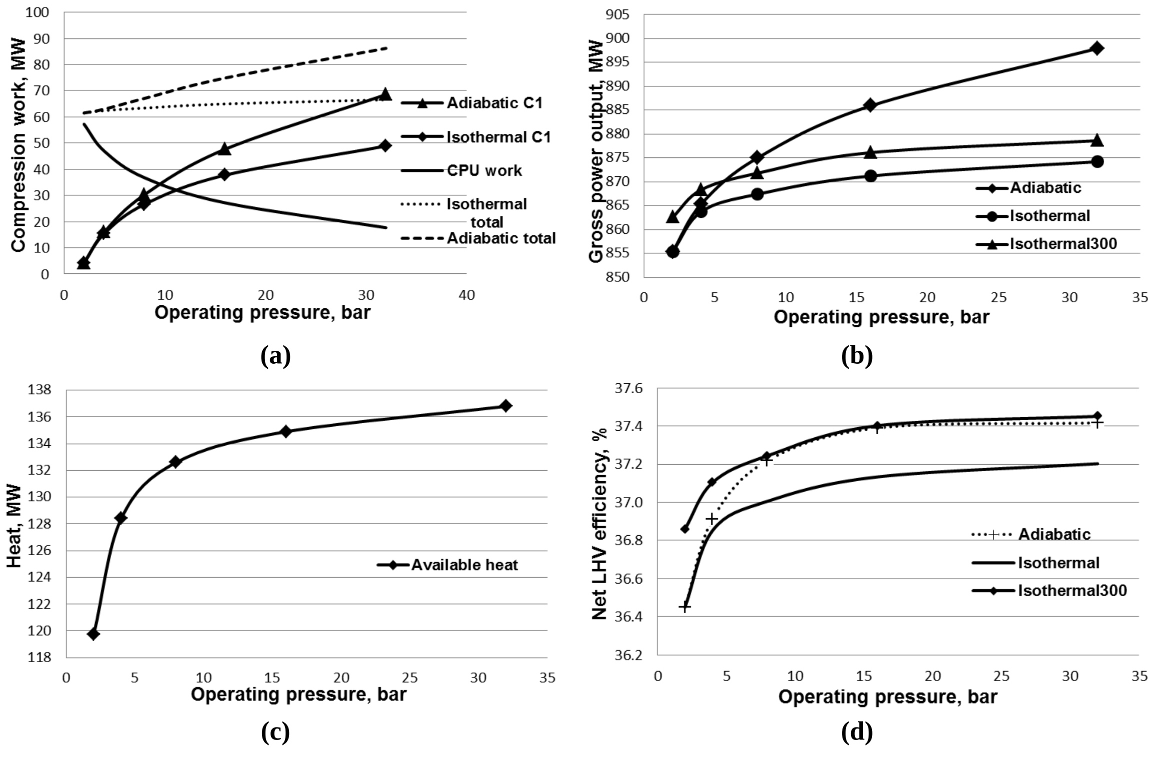


*Figure 2: Influence of the boiler operating pressure on the performance of the power plant*

gross power production seen in the adiabatic oxygen compression case corresponds to the additional compression work consumed by the oxygen compressors. This shows that the adiabatic compression recovers all of the compression work as heat through the boiler. Figure 2(c) shows the flue gas heat recovery. As the boiler operating pressure increases, the dew point of the flue gases increases and hence results in the increased condensation and recovery of latent heat available. Most of the latent heat available in the flue gases can be recovered at an operating pressure of 8 bars. Further compression yields only marginal improvement in flue gas heat recovery. The combination of flue gas latent heat recovery and the efficient recovery of adiabatic oxygen compression work results in net efficiency improvements. Figure 2(d) shows that an operating pressure of around 16 bars is best suited to exploit all the benefits of boiler pressurization. A similar study by Hong et al. (2010) has shown that 10 bars is the optimal operating pressure. A constant pressure drop across the recirculation fan is assumed in this study, which shifts the optimum to 16 bars. Isothermal compression of oxygen requires preheating to achieve similar efficiencies as the adiabatic compression scheme. Hence the much simpler adiabatic compression is recommended for the oxygen compression.

***4.2 Influence of oxygen purity and CPU operating parameters:***

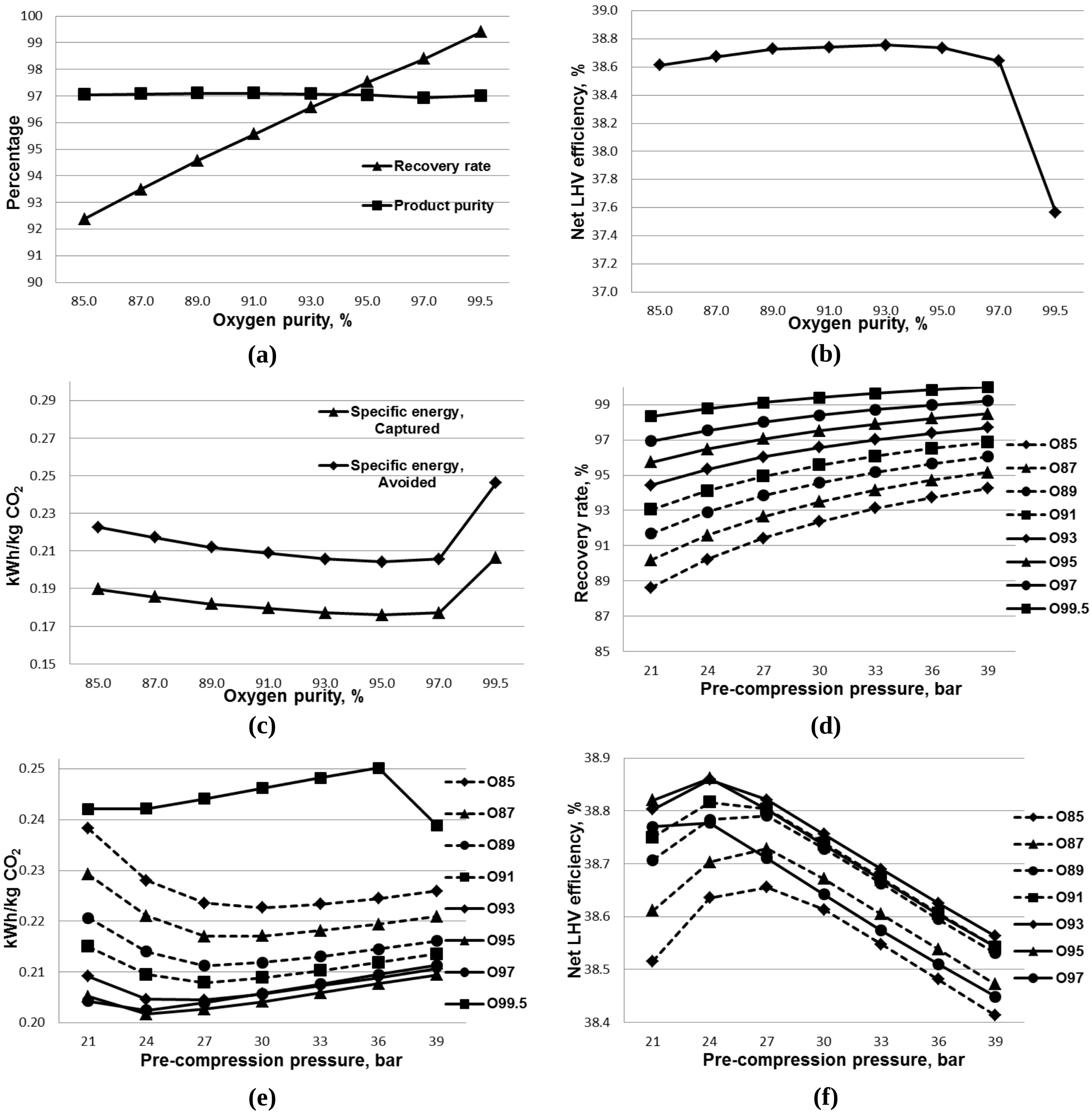


*Figure 3: Influence of the oxygen purity and CPU operating parameters*

The energy required to produce oxygen from air increases with the product purity. The energy requirement increases substantially beyond the purity level of 97 %, as argon needs to be separated from oxygen (Darde et al. 2009). The impurities present in coal and the air leakage brings in volatile components such as nitrogen into the boiler. In a high pressure boiler, even though the air leakage is avoided, impurities are introduced via coal and the oxygen stream. Hence, there is always a need for a purification unit downstream. Two stage flash type CPU has been shown to be an economical choice that also meets the pipeline purity requirement (Fu and Gundersen, 2012). The energy consumption of the CPU and hence the overall separation energy requirement, however, depends on the CPU operating parameters such as the pre-compression pressure (outlet of C2) and the temperature of stream S8.
A sensitivity study of the oxygen purity and the CPU operating parameters is therefore required to find the energy optimal combination to achieve the desired product purity while capturing at least 90 % of the $CO_2$ produced. The sensitivity analyses are carried out by running the simulation for various combinations of oxygen purity ranging from 85 % to 99.5 % and the CPU parameters. The range for temperature in stream S8 was -22 $^oC$ to -34 $^oC$, while the range for pre-compression pressure was 21 to 39 bars. The results were then compared to the baseline air fired power plant without capture to arrive at the energy required to avoid one kg of $CO_2$ emitted. The temperature of stream S8 has little impact on the purity and the recovery rate, whereas the pre-compression pressure has a profound impact on the recovery rate and hence the overall performance of the system. A combination of higher oxygen purity and a lower outlet pressure from C2 ensures a high recovery rate combined with high overall plant efficiency. This results in low specific energy consumption for capture as shown in figure 3(e). At very low pre-compression pressure (21 bars for 95 % oxygen purity), there will be little or no condensation in heat exchanger m-HEX1 and hence the dual flash CPU essentially functions as a single flash CPU.

## 5. Conclusion

The baseline power plant without capture has a net LHV efficiency of 44.7 % and the baseline oxy-combustion power plant with capture has a net LHV efficiency of 37.9 %. The high efficiency of the capture plant is due to flue gas heat recovery and CPU heat integration. Increasing the boiler operating pressure to 16 bars recovers the flue gas latent heat and the compression heat thereby resulting in a net LHV efficiency of 38.7 %. A study of the impact of oxygen purity and CPU operating parameters provides a near optimal combination of these parameters (~97 % oxygen purity and 24 bars pre-compression pressure) resulting in a final net LHV efficiency of 38.9 %.

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