OXY-FUEL COMBUSTION FOR
CO_2 CAPTURE FROM PC BOILERS

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ABSTRACT

The oxy-fuel combustion is gaining more support as a viable CO_2 capture alternative for reducing CO_2 emissions from the power plants. This paper will focus on the process and economic analysis of CO_2 capture from PC (pulverized coal) boilers by oxy-fuel combustion. A sensitivity analysis of the impact of oxygen purity and CO_2 purification requirements on the cost of purification will be shown. In addition, the benefits of co-capture of other pollutants will be reviewed. Finally, key research needs will be identified.

INTRODUCTION

The CO_2 capture and sequestration from major industrial sources such as coal-fired power plants is proposed for mitigating global warming. The captured CO_2 can be either stored underground (e.g. in saline aquifers) or injected in oilfields for enhanced oil recovery (EOR). There are three major pathways for CO_2 capture: 1. Post-combustion capture by absorption (e.g. amines) 2. Oxy-fuel combustion to generate CO_2-rich flue gas 3. Pre-combustion decarbonization in an IGCC (integrated gasification combined cycle) process. The oxy-fuel combustion capture is appealing for two reasons. It is cost-competitive when compared with IGCC in terms of CO_2 capture costs and power plant efficiency and it is applicable for retrofitting old PC boiler plants. To realize its potential, significant R&D and engineering efforts will be required before it can be applied to large scale plants. This paper examines the status of various technology elements and the impact of key process variables on the cost of CO_2 capture and plant efficiency.

TECHNOLOGY OVERVIEW

Figure 1 shows a schematic diagram of the oxy-coal fired PC boiler process that is suitable for retrofitting existing boilers as well as for new boilers. This process involves recycle of a portion of flue gas so as to mimic the performance of the air fired boiler. Oxygen is mixed with the recycled flue gas to produce the oxidant stream. The flue gas is scrubbed to remove SOx. If flue gas is recycled before the scrubber, the volume of flue gas passing through the scrubber is much smaller compared to an air fired boiler. After a majority of water is condensed out, the flue gas stream is rich in CO_2. This stream contains impurities mainly comprising of atmospheric gases (oxygen, nitrogen and argon) and small amounts of SOx and NOx. The flue gas is compressed and purified to prepare the CO_2 stream suitable for sequestration.

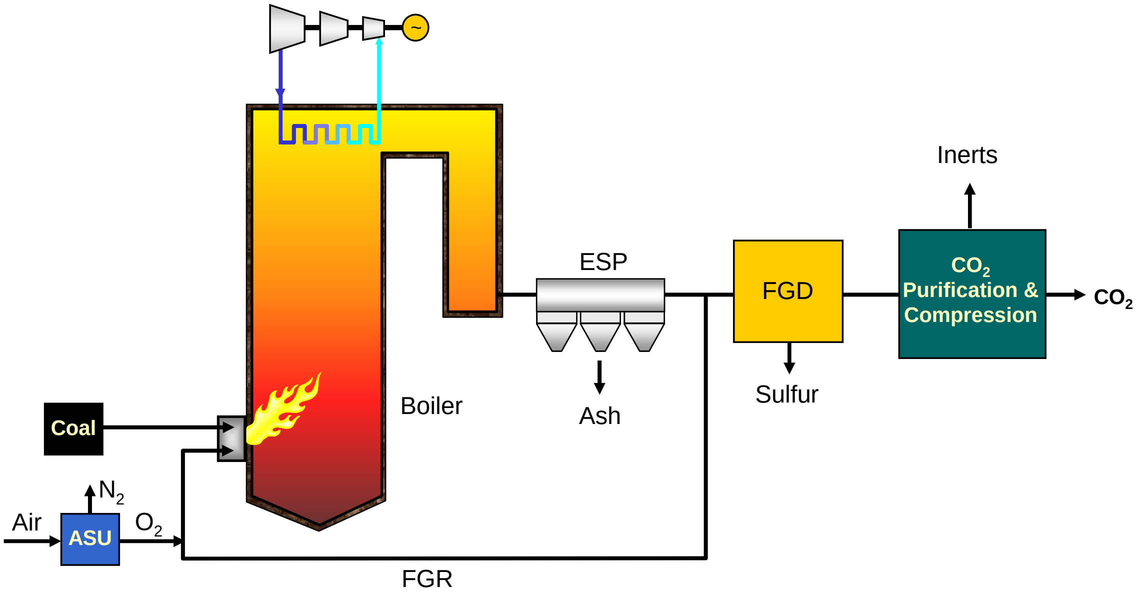

Figure 1. Oxy-Coal Fired PC Boiler for CO_2 Capture

Air Separation Unit

Commercially available air separation technology for large tonnage oxygen production is based on the cryogenic distillation. The cryogenic process typically employs a high pressure and a low pressure distillation columns that are thermally linked. The power consumption in an oxygen plant has a big impact on the efficiency of the oxy-coal fired plant. Therefore, it is important to use the most efficient design. Two variables that has the most impact on the power consumption are oxygen purity and degree of thermal integration between distillation columns.

The oxygen purity required for this application will be determined by the overall optimization of power consumed in oxygen production and CO_2 processing. Figure 2 shows relative power consumption for the distillation system as a function of oxygen purity. The power consumption generally increases with purity. Interestingly, a peak efficiency is obtained at about 97.5% purity. This represents a crossover point where oxygen-nitrogen separation transitions to oxygen-argon separation. And since oxygen-argon separation is more difficult, the efficiency rapidly declines and power consumption climbs, as higher purity oxygen is produced. In a typical operation of oxy-coal PC boiler, power savings in CO_2 processing is insufficient to justify high-purity oxygen (99.5% pure).

The extent of thermal integration employed is determined by economic trade-off between power consumption and capital investment. Figure 3 shows relative separation power as a function of degree of thermal integration. With increased thermal integration, it is possible to reduce the power consumption. However, higher degree of thermal integration results in more complex designs and higher capital costs. Most air separation plants in commercial use today are below 3000 tpd capacity and a majority of them employ at the most two points of thermal integration. With increasing capacity, the cost of power becomes ever more significant as economy of scale reduce the capital component of overall costs. Thus, at 5000+ tpd capacities that would be required for oxy-coal boilers, an opportunity exist to increase the extent of thermal integration and it would pay to design capital intensive system to reduce the power consumption.

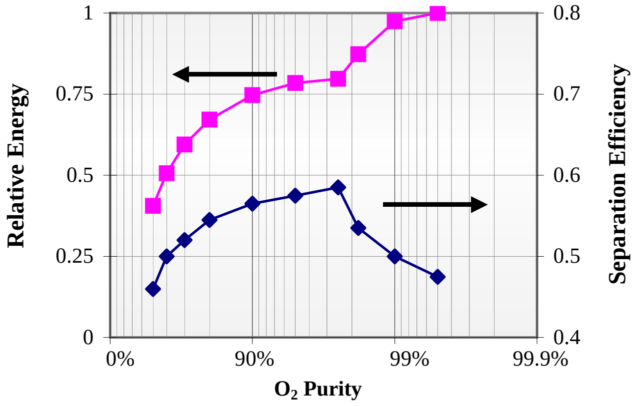

Figure 2. Relative Energy vs. Oxygen Purity

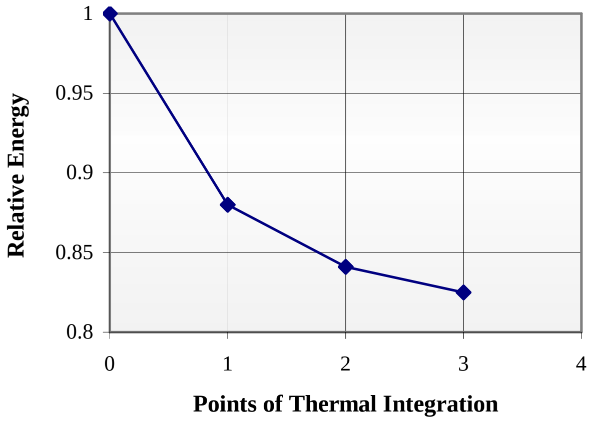

Figure 3. Relative Energy vs. Points of Thermal Integration

Oxy-Coal Fired PC Boiler

The oxy-coal fired boiler has been studied in laboratory and small pilot units of up to 3 MW_{th} [1]. Before this technology can be implemented at commercial scale, further scale-up through larger pilot and intermediate-scale demonstrations will be required. Although in theory, the oxy-coal fired boiler can be operated to mimic the air-coal fired boiler, there are many issues that need further investigation. Several papers have discussed issues and the research and demonstration needs for this technology [2, 3, 4]. Some of the issues that must be addressed are performance of oxy-fuel burners, oxy-fuel flame properties, heat transfer characteristics and materials compatibility due to different chemical environment within the boiler. Larger pilot-scale demonstrations of the entire systems at ~10 and ~30 MW_e, respectively, have been announced by Vattenfall [5] and Australian-Japanese project team [6]. These larger tests will allow verification of mathematical models and provide engineering data useful for designing larger systems.

CO_2 Processing

The flue gas from the boiler will contain up to 75 – 85 % by volume CO_2 (on dry basis). The purity required for sequestration is generally > 95%. To achieve this purity, one-stage or two-stage partial condensation can be used [7]. If CO_2 is to be used for enhanced oil recovery (EOR), then oxygen content in CO_2 must be reduced to meet oil producers specification. Current requirement for EOR in the US calls for < 10 ppm O_2 in CO_2. To achieve more stringent specification for the EOR application, it will be necessary to use distillation. The recovery of CO_2 will generally range from 85 to 95% depending on the CO_2 concentration in the feed and final CO_2 purity required.

ECONOMIC EVALUATION

A base case was assumed to be a supercritical PC power plant with 44% efficiency (LHV) with nominal output of 450 MW. This plant includes SCR for NOx control and FGD for SOx control. The oxy-fuel plant with CO_2 capture consumes significant power for ASU and CO_2 processing. To maintain the power supply to grid, the oxy-fuel plant was over-sized. Thus, the gross output of the oxy-fuel plant was much higher. Key operating parameters and assumptions for the economic evaluation are summarized in Table 1. Table 2 shows a summary of performance and cost for these two cases.

Table 1. Assumptions	
Capital cost	\$1200/kW gross
Operating rate	90%
Coal	Illinois #6
Coal Cost	\$2/MMBtu (HHV)
Air Leak	3% of wet flue gas
CO_2 Purity	96%
CO_2 Pressure	1500 psia

Table 2. Performance And Cost Summary		
	Air-Fired PC Boiler	Oxy-Fired PC Boiler
Gross Output, MW	479	635
Auxiliaries, MW	27	183
Net, MW	452	452
Efficiency, % (LHV)	44	34.7
Oxygen, tpd (contained)	-	9671
Oxygen Purity, % v/v	-	95
CO_2 Captured, tpd	0	9800
CO_2 Emitted, tpd	8632	1132
CO_2 Avoided, tpd	-	7500
Total Capital, $MM	575	1018
Capex, $/kW net	1272	2254
COE, $/MWh	45	71.7
Cost of CO_2 Captured, $/ton	-	29.6
Cost of CO_2 Avoided, $/ton	-	38.6

To gain better insight, the CO_2 capture costs were broken down by different processing areas. Major new equipment needed for CO_2 capture are air separation unit (ASU), CO_2 processing and flue gas recycle (FGR). Power consumed in these units was valued such that the cost of electricity (COE) of net output of 452 MW was same as that of the base case ($45/MWh). The ASU and CO_2 processing accounted for majority of costs at 57% and 36%, respectively, while FGR accounted for 7%. It is clear that improvement in ASU cost and performance will have a significant impact. The cost of CO_2 processing is also not insignificant. Although most of the previous studies have identified the need for advancing the oxygen supply system, there is also a need for finding ways to reduce the CO_2 processing costs.

Oxygen Purity

The premise of oxy-fuel combustion is to eliminate inerts from the process and obtain flue gas that contains only CO_2 and water vapor so that pure CO_2 can be obtained by condensing and knocking out water. However, due to excess oxygen required for combustion and air leak into the boiler, the flue gas will contain significant amount of inerts. Thus, even with 99.5% oxygen, the concentration of CO_2 in the flue gas is only 82%. The cost and performance summary for oxygen purities in 90 – 99.5% range is shown in Table 3. Increasing oxygen purity increases the power consumption as well as capital cost, while the CO_2 purification cost goes down. The optimum oxygen purity required to produce is somewhere between 95 and 97.5%.

Table 3. Effect of Oxygen Purity (Air Leak 3%)				
Oxygen Purity, %	**90**	**95**	**97.5**	**99.5**
% CO_2 in flue gas (dry basis)	74.1	78.4	80.6	82.2
% CO_2 Avoided	82.7	86.9	89.0	91.4
Cost of CO_2 Avoided, $/ton	41.1	38.6	38.3	39.7
COE, $/MWh	72.1	71.7	72.1	73.9

Air Leak

A majority of PC boilers in the US operate with balanced draft with slight negative pressure. The air leak can vary from 3% in modern boilers to as high as 15% in the older boilers. The effect of air leak is described in Table 4. It is interesting to note that the COE increases by ~4% when air leak increases from 1% to 10%. However, the cost of CO_2 avoided increases much more significantly. This anomaly results from the fact that the concentration of CO_2 in the flue gas and hence the recovery of CO_2 decreases significantly with high air leaks.

At 10% air leak, the cost of CO_2 avoided is estimated to be $56/ton. This is certainly higher than the cost of CO_2 avoided by alternative capture methods such as amine absorption. This raises the question about economic viability of retrofitting existing power plants with the oxy-fuel technology considering the fact that many aging boilers have high air leak rates. In modern boilers designed for oxy-fuel technology, it should be possible to keep the air leak rates to minimum or even consider maintaining slight positive pressure in the boiler to keep air out.

Table 4. Effect of Air Leak (95% O_2)				
Air Leak, %	**1**	**3**	**5**	**10**
% CO_2 in flue gas (dry basis)	85.0	78.4	72.7	61.4
% CO_2 Avoided	92.3	86.9	81.2	65.3
Cost of CO_2 Avoided, $/ton	35.2	38.6	42.8	56.5
COE, $/MWh	70.9	71.7	72.7	74.4

CO_2 Purity

The CO_2 purity requirements will depend on the application. Table 5 shows the cost of CO_2 capture as a function of CO_2 purity. The CO_2 purity of 96% corresponds to the sequestration application and 99.9% purity corresponds to EOR application where oxygen must be reduced to low levels. A hypothetical case with no CO_2 purification was also examined. The cost of CO_2 avoided was lowest when there was no purification carried out. Also, in that case there are no CO_2 emissions and as a result 100% of base case CO_2 emission is avoided. When purification process is used to meet either sequestration or EOR specification, there is always some CO_2 that is not recoverable resulting in less than 100% CO_2 avoidance. Since a major portion of compression energy is spent before the impurities are removed, the removal of those impurities does not reduce the overall power consumption significantly compared to the hypothetical case with no purification. In fact, incomplete recovery of CO_2 in the purification process results in higher unit cost of CO_2 avoided.

Table 5. Effect of CO_2 Purification

CO_2 Purification	**None**	**96%**	**99.9%**
% CO_2 Avoided	100	86.9	84.9
Cost of CO_2 Avoided, $/ton	32.5	38.6	41.2
COE, $/MWh	71.0	71.7	73.0

Co-Capture of SOx and NOx

One of the appealing feature of the oxy-fuel process is possible co-capture of SOx and NOx. Since the flue gas containing ~80% CO_2 must go through purification first, how much of SOx and NOx can be co-captured will depend on the extent of purification required. The purification of CO_2 is achieved by distillation and/or partial condensation. In this process, a majority of SO_2 in the flue gas remain with CO_2, while NO will get vented. Table 6 shows how much SOx and NOx can be co-captured at CO_2 purities of 96 and 99.9%.

Table 6. Co-Capture of SOx and NOx

CO_2 Purification	**96%**	**99.9%**
% SOx Co-Captured	100	99.7
% NOx Co-Captured	15	0.8

As most of the NOx is vented, it is most likely that SCR will be required for NOx control. It is possible to eliminate flue gas desulphurization (FGD) unit. The benefit of SOx co-capture is significant as the cost of CO_2 avoided will drop from $38.6/ton to $34/ton, which is ~12% reduction. It is however not known how SO_2 will impact the costs of CO_2 compressor and pipeline and whether it will have any other environmental impact where CO_2 is stored. Various issues related to co-capture of different impurities have been reviewed [8].

CONCLUSIONS

The oxy-fuel combustion has a potential for a cost-effective CO_2-capture from power plants. Air leak in the boilers must be minimized to realize this potential. The optimum purity of oxygen is 95 to 97.5%. The co-capture of SOx will make the oxy-fuel even more attractive.

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