CO_2 CAPTURE OPTIONS FOR AN EXISTING COAL FIRED POWER PLANT: O_2/CO_2 RECYCLE COMBUSTION vs. AMINE SCRUBBING

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Abstract
The existing fleet of modern pulverized coal fired power plants represents an opportunity to achieve significant greenhouse gas (GHG) emissions in the coming years providing efficient and economical CO_2 capture technologies are available for retrofit.

One option is to separate CO_2 from the products of combustion using conventional approaches such as amine scrubbing. An emerging alternate, commonly known as O_2/CO_2 recycle combustion, involves burning the coal with oxygen in an atmosphere of recycled flue gas. Both approaches can be retrofitted to existing units, however they consume significant amounts of energy to capture, purify and compress the CO_2 for sequestration.

This paper compares the performance of the two approaches using a commercial process simulation package (HYSYS). The goal of this particular study is to preserve the net power output of the original plant. To accomplish this objective, the internal energy needs of each capture process are met by firing natural gas. The emissions produced as a by-product of supplying these additional energy needs are considered in the determination of the resulting overall plant emissions.

The energy requirements needed to satisfy each approach are compared, pointing to the need to develop different energy integration strategies for each process. Finally, the goals of future research work sponsored by the CANMET CO_2 Consortium in this area are described.

Introduction

Close to half of the electricity generated in North America comes from coal combustion. Modern pulverized coal fired power plants are also some of the largest single point emitters of greenhouse gases, in particular CO_2. With such a large opportunity to impact CO_2 releases to the atmosphere, there is a compelling need to explore the best near term strategy to retrofit the existing fleet to capture CO_2. Retrofit options are becoming even

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more attractive with recent increases in natural gas prices emphasizing the importance of coal resources in North America's long term energy future.

This paper will compare the performance of two different technologies that can be retrofitted to capture CO_2, namely O_2/CO_2 recycle combustion and amine scrubbing. The simulation of each process is done using HYSYS, a commercially available process simulator. This study assumes that the energy required for the CO_2 separation equipment is provided by firing natural gas so that the overall plant maintains its original power output to the grid. It is further assumed that the CO_2 product is delivered at a high purity (98%) to be used in Enhanced Oil Recovery operations (EOR) (McDonald et al., 1999).

Simbeck and McDonald (2000) compared these two technologies and concluded that the capital and operating cost in terms of $/tonne of CO_2 avoided were similar for both cases. The study presented in this paper looks at each process in more detail using a process simulator in order to develop an understanding not only of the differing energy needs of each, but also to lay the groundwork necessary to identify the most appropriate energy integration strategy for each.

Technology Background

The technology currently exists to design, construct and make commercial guarantees for large scale amine scrubbers. In this process the flue gas is scrubbed with an amine based solvent in an absorption column. The solvent is regenerated in a second column thereby releasing a high purity CO_2 product, as shown in Figure 1. Amine scrubbing with application to CO_2 capture is being studied by many groups in the world (Chakma et al., 1999; Desideri et al., 1999; Hendriks, 1994; Riemer 1993). The focus of current research is on developing more efficient solvents and packings. Innovative work is being done by Kvaerner (Herzog, 2000) to combine the use of gas absorption membranes with amine scrubbing. Because it can be argued that the technology currently exists to build large scale amine plants, it is useful to treat amine scrubbing as a benchmark for emerging retrofit technologies.

O_2/CO_2 recycle combustion technology seeks to dramatically increase the CO_2 concentration in the product flue gases, thereby facilitating CO_2 recovery. This combustion technique can be used alone or in combination with other approaches, however this paper considers only the classic case involving the complete substitution of combustion air by oxygen. In applying O_2/CO_2 combustion to retrofit situations, it is common to consider the use of relatively large quantities of flue gas to be recycled in order to moderate the flame temperature and to establish adequate flue gas flowrates through the existing boiler passages (Croiset et al., 1999; McDonald et al., 1999). This study assumes the oxygen is produced in a dedicated on-site facility using cryogenic air separation technology, which is the only technology currently available for very large plants. It is important to note that air leakage in the boiler, as well as the purity of the oxygen significantly impacts the resulting CO_2 content of the flue gases produced (Singh et al., 2000). This paper takes a conservative approach assuming the worst case assumptions of 95% oxygen purity and 3% air infiltration yielding a flue gas with a CO_2 content of 80% (by volume, dry basis). The resulting flue gas is then further purified using a simple low temperature flash (LTF) process, as shown in Figure 2. It is important to note that this additional purification step may not be required for every sequestration opportunity.

Approach

The overall assumptions are outlined and discussed below.

Overall Assumptions:

- *The scenario is built around a typical Canadian utility scale power plant burning a low sulphur western sub-bituminous coal*. The plant is equipped with electrostatic precipitators and low NOx burners. The turbine condenser is cooled using evaporative cooling.
- *The steam cycle remains unchanged.* Although some previous amine studies have modified the steam cycle to extract the steam to be used in the CO_2 separation (Desideri et al., 1999; Hendriks, 1994) this study avoids this complication which is judged too capital intensive for most retrofits.
- *Natural gas is used to maintain the power output of the plant.* Natural gas is chosen to provide the additional energy requirements of the CO_2 capture process. This energy may be required in the form of low pressure steam and/or shaft power and will be provided using the most efficient combination of gas turbines and steam generators. The CO_2 generated by the combustion of natural gas will not be captured in this study, however the quantity will be reflected in the calculation of the net plant emissions. This approach avoids the complexity of addressing these dilute emissions and is thought to be acceptable in retrofit situations provided that the total amount of CO_2 avoided represents a significant proportion of the original plant emissions.
- *CO_2 product purity of 98% @ 150 bar.* Near term sequestration opportunities for CO_2 captured from large coal fired power plants favours EOR applications which require relatively high CO_2 purity leading to the selection of a target purity of 98% for this study. A final product pressure of 150 bar was chosen to facilitate transport and sequestration of the CO_2.

Amine Case Assumptions:

- *Capture 90% of the CO_2 from the combustion of coal.*
- *Use a gas turbine to provide shaft power.* In this case a natural gas fired gas turbine is used to provide power for all the compression and electrical power needs.
- *Use a supplementary fired HRSG and an additional natural gas fired boiler to provide the steam load.* The amine process requires a significant amount of low pressure steam for the regeneration of the solvent which is by far the largest energy consumer in this process. A gas turbine sized to provide the necessary shaft power coupled with a fully fired HRSG was found to provide insufficient steam thus dictating the need for an auxiliary natural gas fired boiler.

O_2/CO_2 Recycle Combustion Assumptions:

- *Oxygen Purity limited to 95%.* Commercially available cryogenic air separation plants are capable of providing oxygen at up to 99.5% purity, however since the cost begins to escalate as the purity exceeds 95%, this study limits the purity to 95% in order to take a conservative approach with respect to the performance of the low temperature flash process required for final purification of the CO_2 stream.

- *3% Air infiltration into boiler.* Air infiltration in a well maintained balanced draft boiler is typically 3% of the total combustion air requirement. This value can be improved through the incorporation of improved sealing, however this study has taken a conservative approach and assumed an air infiltration value of 3%. The combination of the 95% oxygen purity and the 3% air infiltration value represents the "worst case" for nitrogen content in the flue gas (~20% N_2 by vol. dry basis). Because a flash process will be used for final purification of the CO_2, the presence of nitrogen in the flue gas will consequently limit the amount of CO_2 that can be captured at any fixed CO_2 purity level (Singh et al.; 2000).
- *Power the ASU & Flash using a GTCC.* The most efficient way to generate the power required by the Air Separation Unit (ASU), the flue gas flash process and the final flue gas compression is by firing natural gas in a gas turbine combined cycle. The dilute emissions from the GTCC will not be captured in this study, however the quantity will be reflected in the net plant emissions.
- *Capture the maximum amount of CO_2 at a purity of 98%.* Thermodynamics limit the capture of CO_2 using the flash process. This study will optimize the flash process for the maximum capture of CO_2 while maintaining a CO_2 purity of 98%.

Case Studies

The two cases selected for comparison are outlined in more detail below. In each case the energy required is quantified in terms of energy per tonne of CO_2 avoided.

Case A: Amine Scrubbing

The amine case is shown in Figure 1. In this process five areas of energy consumption have been identified.

A1. Re-boiler Duty: Low pressure (LP) steam is required to provide the heat necessary to separate the CO_2 from the solvent in the re-boiler of the regeneration column.

A2. Flue Gas Compression: The flue gas must be compressed slightly to facilitate the absorption of CO_2 into the solvent.

A3. CO_2 Compression: The CO_2 must be compressed to 150 bar in a multi-stage compressor to facilitate transport and sequestration.

A4. Solvent Cooling: The solvent must be cooled (with cooling water) before being reused in the absorption column.

A5. Partial Condenser: The vapour from the regeneration column must be partially condensed (with cooling water) to allow reflux back to the regeneration column.

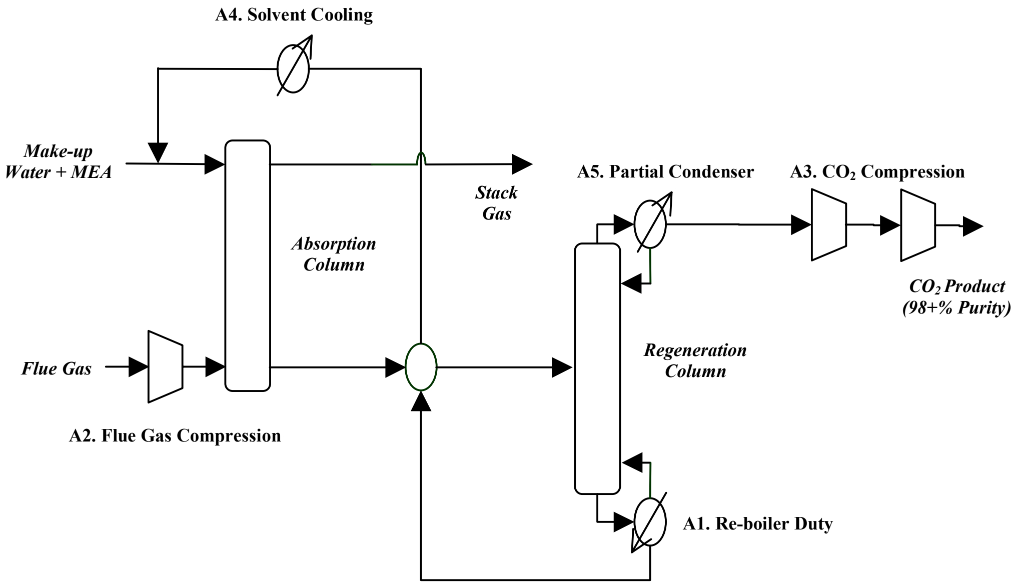

Figure 1: Amine Scrubbing Plant

Case B: O_2/CO_2 Recycle Combustion

The O_2/CO_2 recycle combustion process flowsheet is shown in Figure 2. There are four major areas where energy is consumed in this process.

B1. ASU Shaft Power: The ASU requires shaft power for air compression/separation.
B2. Flue Gas Compression: The flue gas must be compressed before the flash step.
B3. Refrigeration Compression: Cooling for the flash is provided by a mechanical refrigeration system.
B4. Cooling Duty: The ASU, flue gas compressor and refrigeration system require cooling water in order to reject heat.

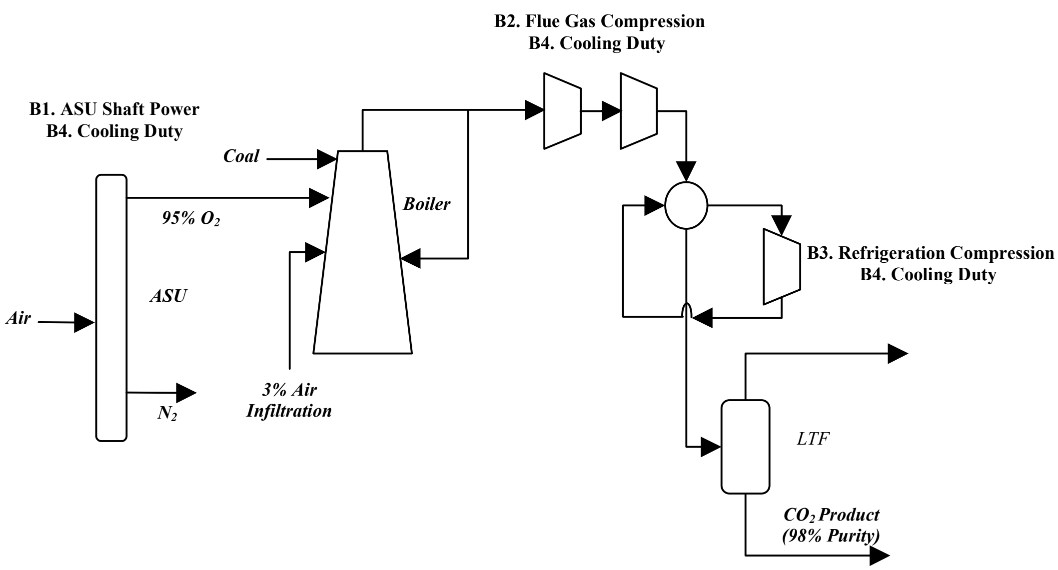

Figure 2: O_2/CO_2 with ASU and Low Temperature Flash (LTF)

Results & Discussion

A summary of the results is outlined in Table 1. The energy per tonne of CO_2 avoided is presented for the respective cases. A fuel equivalent duty is calculated for the shaft power and the heating duty in order to compare both cases on common basis.

Table 1: Energy Comparison of O_2/CO_2 and Amine Scrubbing

	Case A: Amine	**Case B: O_2/CO_2**
Shaft Power (MW/tonne CO_2 avoided)	0.17	0.57
Heating Duty (MWth/ tonne CO_2 avoided)	2.00	-
Tonnes of steam / tonne CO_2 captured	2.10	-
Fuel Equivalent : Heat +Shaft (MWth/ tonne CO_2 avoided)	**2.80**	**1.32**
Cooling Duty (MWth/ tonne CO_2 avoided)	2.00	0.52

By comparing these two approaches it is obvious that the type of energy required for each process is quite different. For the O_2/CO_2 case, 1.32 MWth/tonne of CO_2 avoided of natural gas is required to generate the shaft power (0.57 MW/tonne of CO_2 avoided). An additional 0.52 MWth/tonne of CO_2 avoided of cooling is also required.

In the amine case, 2.80 MWth/tonne of CO_2 avoided of natural gas is required to generate the required shaft power (0.17 MW/tonne of CO_2 avoided) and the heat for re-boiler (2.0 MWth/tonne of CO_2). The amine case also requires an additional 2.0 MWth/tonne of CO_2 avoided for cooling. The largest energy sink with the amine process is by far the solvent regeneration step, which requires more heat duty than the total fuel equivalent duty of the O_2/CO_2 recycle combustion process. The heating duty for the re-boiler in the regeneration column translates to approximately 2.1 tonnes of steam per tonne of CO_2 captured from the combustion of coal which is consistent with other published values (Mimura et al., 1998).

The heat required in the form of steam for the amine process is constrained by the tendency of the solvent to degrade at temperatures greater than 125^{o}C (Riemer, 1993), therefore limiting the pressure of the steam that can be used. The use of natural gas to generate low pressure steam directly is highly inefficient, pointing to the strong need to explore novel energy integration strategies for the amine process.

Conversely, the main energy input for the O_2/CO_2 recycle combustion process is shaft power. In this study it has been assumed that the shaft power is delivered by a GTCC. Since modern GTCC's are very fuel efficient, the need to explore energy integration strategies for this approach is much reduced.

These two cases also differ greatly in the total amount of cooling required. The amine process requires approximately three times the cooling duty of the O_2/CO_2 recycle combustion process, which is not surprising due to the fact that the large amine regeneration duty must be rejected at some point in the cycle. Since water utilization is a major issue for plants in Western Canada, this finding reinforces the significant need to explore novel energy integration strategies for the amine process.

Table 2 presents a summary of the overall emission reductions for the two processes.

Table 2: CO_2 Emissions Comparison of O_2/CO_2 Recycle Combustion and Amine Scrubbing

	$O_2/C0_2$	Amine
% CO_2 captured from coal combustion	79%	90%
% CO_2 avoided from the overall plant	66%	58%

Based on the "worst case" assumptions stated previously, the O_2/CO_2 process is capable of capturing 79% of the CO_2 generated from the burning the coal. The overall amount of CO_2 avoided in the O_2/CO_2 case is calculated to be 66%. This value accounts for the emissions from the GTCC. The avoidance of two thirds of the CO_2 emissions may be reasonable enough to justify not going after the CO_2 emissions from gas firing in this retrofit scenario.

By increasing the oxygen purity to 99.5% and reducing the air infiltration to 1% the amount of CO_2 captured would be increased to as high as 90%, translating into an overall amount of CO_2 avoided of approximately 78%. This improvement to the performance of the O_2/CO_2 recycle combustion process represents a "best case" scenario for the performance of this technology in real retrofit situations, at least in the foreseeable future. Interesting developments are underway to reduce the energy penalty of producing oxygen using ceramic membranes (Dyer et al., 2000) which, when commercialized will have a direct impact on improving the energy efficiency of the O_2/CO_2 combustion process.

The simulation of the amine scrubbing case showed that it was possible to capture 90% of the CO_2 from the coal plant. Since the amount of CO_2 captured for the amine process is proportional to the heat duty required by the re-boiler there is some freedom in balancing the captured amount verses the energy needs of this process. Nevertheless, after accounting for the natural gas required to provide the necessary steam and shaft power, the overall amount of CO_2 avoided in the amine case is calculated to be 58%, a figure somewhat less than the overall performance of the O_2/CO_2 recycle combustion performance.

It is important to emphasize here that there may be significant opportunities to improve the energy integration of the overall amine process and the energy efficiency of the amine solvents themselves. These efforts will contribute directly to an improvement in the overall amount of CO_2 avoided for this approach.

It should also be noted that the present study does not consider the capital costs of these retrofit cases thereby limiting the conclusions that can be drawn about the two processes studied.

Conclusions

Within the constraints imposed on this study and based on the simulations performed using HYSYS, the following conclusions about the energy needs of the O_2/CO_2 recycle combustion process and amine scrubbing process can be drawn:

- Both processes would appear to be capable of avoiding about 2/3 of the CO_2 emissions of the original coal fired power plant. Using "worst case" assumptions for oxygen purity (95%) and air infiltration (3%) the O_2/CO_2 recycle combustion case was able to avoid 66% of the original CO_2 emissions. When operating at 90% capture the amine case was shown to be able to avoid 58% of the original CO_2 emissions.
- There are major differences in the quantity and type of energy required for each capture process. The O_2/CO_2 process relies heavily on shaft power to produce the oxygen. The amine process requires large amounts of low grade heat in the form of steam to regenerate the solvent. On a fuel equivalent basis (heat input + shaft power) the O_2/CO_2 process requires 1.32 MWth/tonne CO_2 avoided as compared to 2.8 MWth/tonne CO_2 avoided for the amine process. As a consequence, the amine process also requires a significantly higher cooling duty.
- While both processes appear to offer significant potential for capturing CO_2 from existing coal fired power plants, final conclusions cannot be drawn until each process is fully optimized and capital costs are considered. The conclusions made in this study are sensitive to the assumptions, in particular the constraint to maintain the original power output to the grid and to fire natural gas to provide the additional energy needs of the CO_2 capture process.
- The O_2/CO_2 process will benefit significantly from breakthroughs in oxygen separation technology, leading to lower shaft power requirements.
- The amine process will benefit significantly from novel energy integration strategies and the availability of more energy efficient solvents.

Future Work Planned

Having determined that process simulation is a useful tool to compare the relative performance of these two CO_2 capture technologies, further work is planned to explore the energy integration potential of each process.

Efforts will also be made to secure "benchmark" cost estimates for each process in order to understand the capital cost differences of each approach in a typical retrofit situation.

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