Exergy analysis of CO₂ capture from syngas at pre-combustion in IGCC power plant

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Abstract: Base on the energy and exergy analysis, the efficiency penalties and the energy required for CO₂ capture in IGCC power plant has been investigated. AS PEN PLUS was used for process simulations with various conditions. From the simulation results, it can be concluded that the largest component of energy expenditure in CO₂ capture is caused by CO₂ liquefaction, followed by CO conversion and gas separation. Furthermore, exergetic efficiency of IGCC power plant achieves 47.4% with a gas turbine inlet temperature of 1250°C. The largest exergy losses in IGCC plants, result from combustion of the syngas in combustor, gasification and syngas cooler.

Keywords: IGCC, CO₂ Capture, Exergy, Energy

Introduction

IGCC power plant allows the possibility of separating the CO₂ from the fuel gas at intermediate scrubbing with low efficiency loss among coal-fired power plant. Efficiency penalties due to CO₂ capture in IGCC are caused by the energy requirements of individual CO₂ separation process steps, moreover, the separated CO₂ has to be compressed, liquefied, transported and disposed. The potential contributions causing efficiency penalties and change of process parameters rendered by CO₂ capture are examined in the various investigations [1-2]. However, analysis of first law cannot identify and quantify the sources of loss which lead to efficiency loss [3]. Accordingly, a detailed second law analysis or exergy analysis has been performed in order to analyze the complex energy system more thoroughly. Although some energy analysis is required to improve efficiency in CO₂-reducing power plant, most of the exergy analysis of in IGCC power plants doesn't include detailed CO₂ capture [4-5]. Therefore, the objective of present paper is to determine the effect of CO₂ capture on the irreversible losses of IGCC and to compare the each irreversibility types, which occurring in CO₂ capture power plant. Furthermore, an exergy analysis assessing the magnitude of exergy destruction identifies the location, the magnitude and the source of thermodynamic inefficiencies in IGCC power plant.

Process Description

IGCC system is composed of gasifier island feeding pure O₂, open Brayton cycle using air and combustion products as working fluid and conventional sub-critical Rankine cycle. Pulverized coal and O₂ yielded in Air Separation Unit (ASU) are fed into gasifier, which operates above more than 1200°C to ensure the flow and removal of molten slag. A metal candle filter is used to remove any particulate material exiting gasifier. This material (tars, oil and fly ash), is recycled back to the gasifier. The produced syngas is mainly composed of CO, H₂, CO₂, H₂O and minor portion of H₂S. H₂S is preferentially removed from the product stream and CO present in the raw gas is converted to CO₂. Once concentrated, CO₂ can be removed during the desulfurization process through use of a double-staged selective unit. CO₂ is then liquefied and compressed to supercritical conditions for pipeline transport. Clean fuel gas from the selective unit, now rich in H₂, mixed with air compressed in a single spool compressor at a pressure ratio of approximately 23:1, are injected into the gas turbine. These components are fired in the combustion turbine, then expanded in the four-stage turbine-expander. The heat recovery system (HRSG) thermally couples the combined mixture heat rejected by the gas turbine (GT) with the steam turbine (ST). Steam generated from HRSG cooperated with another high pressure steam produced by gasifier are used to work in a steam turbine.

A bituminous coal was selected to feed gasifier. It was crushed and milled into three nominal classes of particles, 0-0.5 mm, 0-1 mm, and 0-2 mm. Its proximate and ultimate analyses are given in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Proximate and ultimate analyses of bituminous coal</th>
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<tr>
<td>Proximate analysis (wt%) &amp; Ultimate analysis (wt%)</td>
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<tr>
<td>(air dry basis) &amp; (dry ash free basis)</td>
</tr>
<tr>
<td>Moisture</td>
</tr>
<tr>
<td>Ash</td>
</tr>
<tr>
<td>Fixed Carbon</td>
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<td>Volatile</td>
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<td>Sulphur</td>
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Coal gasification is a process that converts the pulverized coal from a solid to a gaseous fuel trough partial oxidation. Once the fuel is converted into gaseous state, such as sulfur compounds and fly ash, may be removed from the raw gas. The net result is a clean, transportable gaseous energy source. In contrast to combustion process, where fuel is combusted with excess air, the gasifier utilizes partial combustion of coal with the controlled oxygen supply (generally 20-70%) of the amount of O₂ theoretically required for complete
combustion) such that heat and syngas are produced as the coal is consumed.

Methodology

Exergy model
The process arrangement, on which the calculations are based as well as the exergy analysis of IGCC with CO₂ capture are simplified in Figure 1.

![Figure 1. Analysis model of exergy for calculating IGCC with CO₂ capture](image)

where \( E_{\text{as}} \) is physical exergy of steam and \( E_{\text{ch}} \) is the chemical exergy. It should be noted that the \( E_{\text{ch}} \) is calculated with reference to the atmosphere. The exergy input \( (E_{\text{in}}) \) to a component is the sum of the exergies of the streams and the work supplied \( (W_{\text{in}}) \). Similarly, exergy coming out of it \( (E_{\text{out}}) \) is also calculated. Accordingly, the exergy loss \( (I) \) is the difference between these two conditions [7]:

\[
I = E_{\text{in}} - E_{\text{out}}
\]

The exergetic efficiency \( (\zeta) \) of the component is defined as:

\[
\zeta = \frac{(E_{\text{in}} + W_{\text{in}})/(E_{\text{in}} + W_{\text{in}})}{E_{\text{out}}}
\]

The steady state control volume exergy analysis for each component of the plant is done to calculate the losses due to irreversibility and also the exergetical efficiencies and determined. The exergy of coal is estimated based on its composition and net calorific value.

Exergy Analysis of IGCC with CO₂ Capture
To calculate gas generation with CO₂ capture, special program modules were designed individually, which determine energy conversion, exergy conversion and substance conversion in the gas generation process with raw gas CO shift and CO₂ capture (see process diagram in Figure 1). The heat required to humidify the raw gas prior to CO conversion, and the useful component of the lost heat from CO conversion, both play a part in determining heat value \( q_{\text{hr}} \) given off in the heat recovery steam cycle, extracted heat value \( q_{\text{hr}} \), and their exergies. The CO₂ capture is simulated either through the exergetic efficiency of the gas separation process with input of the capture ratio, or through a membrane calculation with input of the relative permeabilities of all the gas components, the pressure ratios and the quantity of permeating gas.

The CO₂ capture ratio \( S_{\text{CO}_2} \) in the condensing or subliming of CO₂ from synthesis gases or flue gases is dependent on saturation or sublimation pressure \( p_i \), total pressure \( p \) and molar fraction \( y_i \):

\[
S_{\text{CO}_2} = 1 - \left( \frac{y_{\text{H}_2} + y_{\text{CO}}}{y_{\text{H}_2} + y_{\text{CO}} \frac{p_i}{p}} \right)
\]

In Eq.(4) clearly shows that, aside from a low temperature, high overall pressure together with a high initial content of CO₂ also play an important role in achieving a high rate of separation.

The exergetic efficiency of a gas separation process is defined as the ratio of reversible separation work \( (w_{\text{rev}}) \) to actual work \( (w_{\text{act}}) \), plus isothermal compression work \( (w_d) \). It is given by Eq.(5) [8]

\[
\zeta_{\text{sep}} = \frac{w_{\text{rev}}}{w_{\text{act}} + w_d} = \frac{x_i R_i T_0 \ln(p_i/p)}{w_{\text{act}} + w_d + x_i R_i T_0 \ln(p_i/p)}
\]

where \( i \) is the gas component to be separated, \( x_i \) is the mass fraction, \( R_i \) is the gas constant, \( w_{\text{act}} \) is the specific energy requirement of the gas separation process, \( w_d \) is the reversible separation work, \( w_d \) is the isothermal compression work to compress separated gas from desorption pressure \( p_i \) to total syngas pressure \( p \).
Results and Discussion

IGCC without CO₂ capture

The conventional IGCC without CO₂ capture was simulated corresponding to the base case. The gasifier is operated with oxygen (95% volume fraction O₂) as an oxidant. It achieves a carbon conversion rate of 99.6% and at a raw gas temperature of 1300°C. Raw gas cooler basically consists of a steam generator and a raw gas/clean gas heat exchanger for reheating the cleaned fuel gas to around 360°C. The air separation unit is fully integrated, i.e. the air required is included in the compression process of the gas turbine compressor, and a portion of the nitrogen is re-mixed into the generated fuel gas prior to the gas turbine combustion chamber. The nitrogen and the cleaned fuel gas are humidified with the required water component in the saturator, prior to mixing, at the lowest possible temperature. The saturator columns are heated with hot water. TIT is fixed at 1250°C, AC outlet pressure 15.6bar, and main steam turbine inlet temperature at 560°C, respectively.

More detailed distribution of exergy losses in IGCC are shown in Figure 2. As expected, it can be seen in Figure 2 that the largest exergy losses result from combustion of the generated gas in the gas turbine combustion chamber. Following major contributors to the increased irreversibility are gasification and partial combustion of the coal in the gasifier. Steam cycle and the heat transfer in the raw gas cooler are ranked third class. Compared with exergy losses in HRSG and GT, the GT compressor and syngas cooler are playing insignificant roles among the exergy losses of IGCC system. Anyway, IGCC power plant achieves an efficiency of 51.5% (exergetic efficiency: 47.4%) when reforming of CO₂ capture is canceled.

![Exergy losses in conventional case of an IGCC power plant without CO₂ capture (TIT 1250°C)](image)

Figure 2 Exergy losses in conventional case of an IGCC power plant without CO₂ capture (TIT 1250°C)

IGCC with CO₂ capture

The purpose of this study is to investigate the thermal process and the integration between the reforming process and the power cycles. For the CO₂ separation process, a relatively simple model was used. The exergy that was available for the separation is seen as the sum of the chemical exergy of the captured CO₂ and the irreversibility of the absorption process. Figure 6 shows that how the CO₂ capture ratio influences the contribution made by individual steps in the CO₂ capture process towards the efficiency penalty and specific energy requirements (exergetic efficiency of the scrubbing process: 30.5%).

![Efficiency penalty and specific energy demand varied with CO₂ capture ratio at TIT=1250°C](image)

Figure 3 Efficiency penalty and specific energy demand varied with CO₂ capture ratio at TIT=1250°C

From Figure 3, it can be seen that at a high CO₂ capture ratio, a high level of CO conversion must be achieved; this increases the concentration of CO₂ and the specific work required for gas separation drops (Figure 3a). Specific energy expenditure is virtually independent of CO₂ capture ratio for all other process steps (Figure 3b). This makes it more advantageous to strive for a high CO₂ capture ratio in a split stream, than to remove only a small portion of CO₂ from the total stream. It can be obtained also from Figure 3 that the largest component of energy expenditure in CO₂ capture is caused by CO₂ liquefaction, followed by CO conversion, gas separation and lost turbine work resulting from the CO₂ which is not expanded in the gas turbine.

![Change in output and changes in exergy conversion as a result of increasing the CO₂ capture ratio](image)

Figure 4 Change in output and changes in exergy conversion as a result of increasing the CO₂ capture ratio (exergetic efficiency of scrubbing: 30.5%, TIT 1250°C)

In the simulations, a higher percentage of captured CO₂ could have been assumed. However, the carbon present in the form of CO or hydrocarbons will in any case end up as CO₂ in the atmosphere after the combustion. The corresponding breakdown of irreversibility is also shown in Figure 4. At higher CO₂ capture ratios, exergy losses increase, primarily due to the higher exergy of the separated CO₂ and the greater energy requirement in the CO₂ scrubbing process (Figure 4). Therefore, higher
concentrations of a species reduce the exergetic cost of CO₂ separation.

Details of the energy and exergy utilization for the base case (AC outlet pressure 15.6 bar) with increased TIT are shown in Figure 5. Increasing the gas turbine inlet temperature has the effect, above all, of reducing exergy losses in the gas turbine combustion chamber, while simultaneously causing gas turbine power output and overall efficiency to increase. As expected, the increased TIT reduced the irreversibility both in the combustor and the rest of the GT cycle. Due to the higher turbine-outlet temperature, the reforming process also showed a reduction in irreversibility. All the exergy losses due to CO₂ capture, related to the exergy of the feed coal, remain virtually unchanged (Figure5).

![Figure 5 Change in output and changes in exergy conversion as a result of increasing gas turbine inlet temperature (CO₂ capture ratio of 90%)](image)

Compared with Figure 4 and 5, a general observation for both variation on the IGCC plant with reforming of CO₂ capture, is that the combustor and other reactors continue to be a dominating cause of irreversibility in a power plant. However, the effects of increased TIT on irreversibilities in the base case were somewhat different with CO₂ capture rate, as seen in Figure 5. The reductions in the combustor and the gas turbine were larger than in the plant with reforming of CO₂ capture. On the other hand, the HRSG showed a marked increase, contrary to the power plant with reforming. A major reason for the latter was that the limit imposed on the steam turbine inlet temperature (560°C) prevented the increased flue gas temperature to be fully utilized. Therefore, increasing the effective TIT, and thus reducing the combustor irreversibility, seems to be the most prominent measure for improving the efficiency for IGCC cycles with CO₂ capture (from 39.6% to 42.2%). This is an ongoing development in the GT industry. Nevertheless, it is worth noting that although there were some improvements, the combustor remained the main source of irreversibility in both the IGCC power plant with and without CO₂ capture.

**Conclusion**

An IGCC power plant with CO₂ capture has been investigated. An energy and exergy analysis has been performed, and the influences of some parameters have been studied. This system has also been compared to a conventional IGCC without CO₂ capture process, some conclusions have been reached:

1. For the conventional IGCC power plant without CO₂ capture, a TIT of 1250°C and air compressor outlet pressure of 15.6 bar, the net electric power was 51.5%.

2. The exergy method, contrary to first-law analysis, localizes and quantifies the thermodynamic losses. The main contributions to irreversibility were the GT combustor. Following major contributors to the increased irreversibility are gasification and partial combustion of the coal in the gasifier, steam cycle, and the heat transfer in the raw gas cooler.

3. An increase of the TIT from 1190 to 1250°C and 1500°C increased the net electric power production to 39.6% and 42.2%, respectively.

4. The combustor appears to be the greatest source of irreversibility both with and without fuel reforming of CO₂ capture, and its reduction seems to be the primary action for increased efficiency.

**Reference**


