Integrated gasification combined cycle (IGCC) process simulation and optimization

F. Emuna, M. Gadallaa, T. Majozib, D. Boerc

Abstract

The integrated gasification combined cycle (IGCC) is an electrical power generation system which offers efficient generation from coal with lower effect on the environment than conventional coal power plants. However, further improvement of its efficiency and thereby lowering emissions are important tasks to achieve a more sustainable energy production. In this paper, a process simulation tool is proposed for simulation of IGCC. This tool is used to improve IGCC's efficiency and the environmental performance through an analysis of the operating conditions, together with process integration studies. Pinch analysis principles and process integration insights are then employed to make topological changes to the flowsheet to improve the energy efficiency and minimize the operation costs. Process data of the Texaco gasifier and the associated plants (coal preparation, air separation unit, gas cleaning, sulfur recovery, gas turbine, steam turbine and the heat recovery steam generator) are considered as a base case, and simulated using Aspen Plus®. The results of parameter analysis and heat integration studies indicate that thermal efficiency of 45% can be reached, while a significant decrease in CO₂ and SOₓ emissions is observed. The CO₂ and SO₂ emission levels reached are 698 kg/MWh and 0.15 kg/MWh, respectively. Application of pinch analysis determines energy targets, and also identifies potential modifications for further improvement to overall energy efficiency. Benefits of energy integration and steam production possibilities can further be quantified. Overall benefits can be translated to minimum operation costs and atmospheric emissions.

1. Introduction

Strong dependency on crude oil and natural gas and the associated price and supply chain risk increase the need for efficient utilization of existing non-renewable energy sources (e.g., coal, natural gas, nuclear power, etc.) (Kavouridis & Koukouzas, 2008). The emission of different pollutants, especially green house gases, may urge the environmental regulations to be a strong driver for new developments, in particular for decision makers that regulate the energy policies of states and regions. In this context coal has to be considered as energy source for power generation because of its availability and relatively wide geographic distribution. These developments include coal based electric power technologies, where the integrated gasification combined cycle (IGCC) is an alternative to pulverized coal (PC) combustion systems

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References

Jay, Lynn, Jeff, & Massood, 2002; Minchener, 2005; Ordorica-Garcia, Douglas, Croiset, & Zheng, 2006; Park et al., 1999).

In comparison with modern coal combustion technologies (pulverized coal combustion (PCC), fluidized bed combustion (FBC), supercritical and ultra-supercritical technologies), IGCC systems are characterized by lower SOₓ and NOₓ emissions, comparable vapor organic carbon (VOC) emissions, 20% less CO₂ emissions and use of 20-40% less water. They operate at higher efficiencies, thus requiring less fuel and producing less emission (Zheng & Furinsky, 2005). Commercially available IGCC power plant technologies produce substantially smaller volumes of solid wastes (∼1/2) than the new conventional coal plants (Shilling & Lee, 2003). Furthermore, IGCC solid wastes are less likely to cause environmental damage than fly ash from conventional coal plants because IGCC ash melts in the gasification process (Shilling & Lee, 2003).

IGCC has higher fuel flexibility (biomass, refinery residues, petroleum coke, etc.) and generates multiple products (electricity, hydrogen and chemicals like methanol and higher alcohols) and by-products (sulfur, sulfuric acid, slag, etc.) (Jay et al., 2002). In
addition, IGCC technology has the potential for CO₂ sequestration (Minchener, 2005; Ordorica-Garcia et al., 2006). Before CO₂ can be sequestered it must be captured as relatively pure CO₂ from power plants and other sources. In IGCC, as coal is not combusted, the relatively small volumes of synthesis gas (syngas) are easier to clean up than the much larger volumes of flue gases at coal combustion plants (Descamps et al., 2008).

Ongoing research activities focus on IGCC thermal efficiency, including cost related aspects and environmental performance indicators. A higher energy conversion efficiency leads to a better use of the coal resource and contributes to the reduction of greenhouse gases and other pollutants.

Apart from design considerations, IGCC performance depends on numerous integration options and can be improved by process optimization. These considerations include (Christopher & Zhu, 2006):

- Gas turbine air extraction to the air separation unit (ASU).
- Increase the gas turbine power.
- High and low temperature heat recovery.
- Steam generation conditions.
- Utility balance.
- Co-production or polygeneration including steam, hydrogen, and other products.
- Optimization of operating conditions, etc.

This paper presents an optimization scheme for IGCC through process simulation and sensitivity analysis of the key operating parameters. Then, a heat integration scheme is presented for different sections of the process. Finally, pinch analysis is performed for the overall process.

2. Gasification based energy conversion system options

Although there are many available technologies, this paper refers to the power generation schemes based on the combined gas turbines and Rankine cycles (Polyzakis, Koroneos, & Xydis, 2008).

There are three technologies for IGCC, classified according to the gasifier configurations and the flow geometry (Minchener, 2005):

- Entrained flow gasifiers, in which pulverized coal particles and gases flow concurrently at high speed. They are the most common option for coal gasification.
- Fluidized bed gasifiers, in which coal particles are suspended in the gas flow, and therefore coal feed particles, are mixed with the particles undergoing gasification.
- Moving bed gasifiers, in which gases flow relatively slowly upward through the bed of coal feed. Both concurrent and countercurrent technologies are available, but the former is more commonly used.

Each option has advantages and drawbacks. Shell and Texaco entrained flow gasifiers are used in nearly 75% of the gasification plants throughout the world that use coal to produce electric power (Minchener, 2005). They are the most versatile type of gasifiers as they can use both solid and liquid fuels and operate at high temperature to ensure high carbon conversion and a syngas free of tars and phenols (Zheng & Furinsky, 2005). In this work the Texaco process has been selected.

3. IGCC process description

The IGCC process model is developed for a Texaco gasifier with radiant/convective cooling system. The simplified process flow diagram is shown in Fig. 1. The coal (Illinois #6, Table 1), is crushed and mixed with water to produce a slurry (35.5%, w/w) and is pumped into the gasifier with oxygen. The gasifier operates in a pressurized, down flow entrained design and gasification takes place rapidly at temperatures higher than 1200 °C (Zheng & Furinsky, 2005). The raw fuel gas produced is mainly composed of H₂, CO, CO₂ and H₂O. The coal’s sulfur is primarily converted to H₂S and small quantities of COS (intermediate component). This raw fuel gas leaves the gasifier at 1370 °C along with molten ash and a small quantity of unburned carbon.

The gas/molten solids stream enters a radiant syngas cooler (RSC) and convective syngas cooler (CSC) sections. In the Texaco design, the mix of gas/solids from the gasifier enters a radiant syngas cooling (RSC) system where cooling to approximately 815 °C is accomplished by generating a high-pressure steam. A convective syngas cooling (CSC)/gas scrubbing system cools the raw fuel stream to about 150 °C (27.5 bars) by generating additional steam. It uses a gas scrubber and a low temperature gas cooling/heat recovery section to reduce the raw fuel gas stream to 40 °C, prior to entering a cold gas cleaning unit (CGCU) for sulfur removal. Claus/SCOT sulfur recovery section is used to recover sulfur from the sour gas. Then, the clean syngas drives a gas turbine after being combusted in the combustion chamber of the gas turbine. The heat from the gas turbine exhaust is used to generate superheated steam in the heat recovery steam generator (HRSG). The generated superheated steam drives a steam turbine, producing additional power.

The data for the air separation unit (ASU), the steam cycle and the power block are listed in Table 2. Most of the data are taken from a report of the Process Engineering Division of the American Energy Institute (Shelton & Lyons, 2000). The missing data relating to operating conditions and range of operating variables are retrieved from the literature (Booras & Holt, 2004; Christopher & Zhu, 2006; Osama, Akira, & Yoshinori, 2002; Polyzakis et al., 2008; Sugiyama et al., 2005).

Table 1

<table>
<thead>
<tr>
<th>Component</th>
<th>w/w (%)</th>
<th>w/w (%) dry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>11.12</td>
<td>11.12</td>
</tr>
<tr>
<td>Carbon</td>
<td>63.75</td>
<td>63.75</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>4.50</td>
<td>4.50</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>Chlorine</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>Sulfur</td>
<td>5.70</td>
<td>5.70</td>
</tr>
<tr>
<td>Oxygen</td>
<td>6.88</td>
<td>6.88</td>
</tr>
</tbody>
</table>

Fig. 1. Simplified diagram for IGCC [15].
4. Methodology

In this work, sensitivity analysis and process integration are applied in order to improve the efficiency and the environmental performance of the process. The analysis is interpreted by linking Aspen Plus® with MS Excel TM, thereby directly accessing the required parameters from Aspen Plus® for calculation of the performance indicators.

The performance indicators used are either economic (efficiency) or environmental (emissions). Thermal efficiency, cold gas efficiency and carbon conversion efficiency are among the economic indicators while emission levels of CO₂, SO₂ and NOₓ per unit of net power output are the environmental indicators (Christopher & Zhu, 2006; Sugiyama et al., 2005). Cold gas and carbon conversion efficiencies are measures of performance of the gasification section. However, the thermal efficiency is an indicator of efficiency of the overall process.

The calculation procedure to obtain the efficiencies is presented in Eqs. (1)–(5)

$$\eta_t(\%) = \frac{P_{NET}}{M_{Coal} \times LHV_{Coal}} \times 100 \quad (1)$$

where $\eta_t$ is the thermal efficiency, $P_{NET}$ is the net power output (MW), $M_{Coal}$ is the mass flow rate of coal (kg/s) and $LHV_{Coal}$ is the lower heating value of coal (MJ/kg).

$$P_{NET} = P_{GT} + P_{ST} - P_{AUX} \quad (2)$$

where $P_{GT}$ is the net power output from the gas turbine (MW), $P_{ST}$ is the power output from the steam turbine (MW) and $P_{AUX}$ is the auxiliary power consumption in pumps, compressors, etc. (MW).

$$\eta_{cc}(\%) = \frac{M_{RC}}{M_{IC}} \times 100 \quad (3)$$

where $\eta_{cc}$ is carbon conversion efficiency, $M_{RC}$ is mass flow rate of the reacted carbon in the gasifier (kg/s) and $M_{IC}$ is mass flow rate of the input carbon to the gasifier.

$$\eta_{CG}(\%) = \frac{M_{Syn}}{M_{Coal} \times LHV_{Coal}} \times 100 \quad (4)$$

where $\eta_{CG}$ is cold gas efficiency, $M_{Syn}$ is mass flow rate of syngas (kg/s) and $LHV_{Syn}$ is the lower heating value of the syngas (MJ/kg).

$$LHV_{Syn} = x_{H_2} \times LHV_{H_2} + x_{CO} \times LHV_{CO} + x_{CH_4} \times LHV_{CH_4} \quad (5)$$

where $LHV_{H_2}$, $LHV_{CO}$, $LHV_{CH_4}$ are lower heating values of H₂, CO and CH₄ respectively, $x_{H_2}$, $x_{CO}$ and $x_{CH_4}$ are mass fractions of H₂, CO and CH₄ respectively. The emissions are retrieved from the mass balance of the process performed by the process simulator and normalized by the net power output obtained from the process.

Finally, Pinch analysis provides a simple methodology for systematically analyzing chemical processes and the surrounding utility system. Pinch analysis is applied to the process to evaluate the overall standing of the process with respect to the hot and cold utility requirements and explore further potentials of heat integration and energy production.

5. Simulation approaches

The flowsheet has several naturally grouped sections: coal preparation, gasification, gas cooling and cleaning, acid gas removal, gas turbine, HRSG, steam cycle, etc. All these sections were rigorously modeled using Aspen Plus® (Aspen Technology, 2008).

5.1. Physical properties

Process simulation does not alleviate the need for accurate physical property data and models (Agarwall, Li, Santollani, Satyro, & Vieler, 2001; Satyro, Agarwall, Li, Santollani, & Vieler, 2001). This issue becomes particularly important when the product properties have a high impact on the process performance.

Peng–Robinson equation of state with Boston–Mathias alpha function (PR–BM) is used to estimate all physical properties (Aspen Technology, 2008) for the gasification and downstream unit operations. The SOLIDS property option is used for the coal crushing and screening section as it is recommended for size reduction, crushing, grinding, solids separation and cleaning.

The enthalpy model for both COAL and ASH, the non-conventional components, is HCOALGEN and the density model is DCOALIGT (Aspen Technology, 2008). The HCOALGEN model includes a number of empirical correlations for heat of combustion, heat of formation and heat capacity. All other values used were retrieved from the Aspen Plus® database (Table 3).

5.2. Chemical reactions

The chemical reactions involved in the IGCC process are very complex as many components are involved, and there is a network of irreversible consecutive and competitive reactions. The model uses a relatively simple approach to represent the reaction set as some trace reaction products, like CS₂, are not considered. The reactors are modeled with the Aspen Plus® built in models RStoic, RYield and RGibbs.

The RGibbs model is used to simulate gasification of the coal and combustion of the syngas. RGibbs models chemical equilibrium by minimizing Gibbs free energy. However, the Gibbs free energy of coal cannot be calculated because it is a non-conventional component. Therefore, before feeding the coal to the RGibbs block it is decomposed into its element (C, H, O, N, S, etc.). This is done using the RYield model with calculations that are based on the component yield specification. The heat of reaction associated with the decomposition of coal is considered in the coal gasification using a heat stream to carry the heat of reaction from the RYield block to the RGibbs block. The most important coal gasification reactions are given in Eqs. (6)–(8), while the main syngas combustion reactions are shown in Eqs. (9) and (10)

$$C + CO_2 \rightarrow 2CO \quad (6)$$

$$C + H_2O \rightarrow CO + H_2 \quad (7)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (8)$$

$$2CO + O_2 \rightarrow 2CO_2 \quad (9)$$

$$2H_2 + O_2 \rightarrow 2H_2O \quad (10)$$

The RStoic model is used to simulate the COS hydrolysis unit, the Claus and SCOT processes in the sulfur recovery section of the flow.
Table 3
Representative unit operations used in the simulation of the IGCC process.

<table>
<thead>
<tr>
<th>Unit operation</th>
<th>Aspen plus® model</th>
<th>Comments/specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal crushing</td>
<td>Crusher</td>
<td>Rigorous simulation of particle size distribution</td>
</tr>
<tr>
<td>Coal particles screening</td>
<td>Screen</td>
<td>Rigorous simulation of the separation efficiency of the screen</td>
</tr>
<tr>
<td>Coal gasification</td>
<td>RGIBS</td>
<td>Specification of the possible products: H2O, N2, O2, NO2, NO, SO2, SO3, H2, O3, HCl, Cl, CO, CO2, CH4, COS, NH3, HCN, H2S</td>
</tr>
<tr>
<td>Dust removing</td>
<td>Sep</td>
<td>Simplified simulation of gas/solid separation by fixed split fraction specification together with the temperature drop</td>
</tr>
<tr>
<td>Syngas purifying</td>
<td>Absorber, distillation column, RStoic</td>
<td>Rigorous simulation of the H2S, NH3 and chloride removal with COS hydrolysis</td>
</tr>
<tr>
<td>Syngas combustor</td>
<td>RGIBS</td>
<td>All components may appear in the product stream</td>
</tr>
<tr>
<td>Air compressor, O2 compressor and N2 compressor</td>
<td>Compressor, Heater</td>
<td>Calculates the power required</td>
</tr>
<tr>
<td>Boiler</td>
<td></td>
<td>Simplified simulation of the generation of HP, IP and LP steam in the boiler</td>
</tr>
<tr>
<td>HRSG</td>
<td>Counter current multiple stream heat exchanger</td>
<td>Rigorous simulation of the steam cycle with heat recovery of the GT-exhaust</td>
</tr>
<tr>
<td>Gas and steam turbines</td>
<td>Compressor</td>
<td>Calculate power produced</td>
</tr>
</tbody>
</table>

Sheet. RStoic models stoichiometric reactor with specified reaction extent (or conversion). The stoichiometric equations are given in Eqs. (11)–(17). 95% conversion is considered in these units.

- COS hydrolysis reaction:
  \[
  \text{COS} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2\text{S} \tag{11}
  \]

- Claus process reactions:
  \[
  \text{H}_2\text{S} + 3\text{O}_2 \rightarrow \text{SO}_2 + \text{H}_2\text{O} \tag{12}
  \]
  \[
  2\text{COS} + 3\text{O}_2 \rightarrow 2\text{SO}_2 + 2\text{CO}_2 \tag{13}
  \]
  \[
  2\text{H}_2\text{S} + \text{SO}_2 \rightarrow 3\text{S} + 2\text{H}_2\text{O} \tag{14}
  \]

- SCOT process reactions:
  \[
  \text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2\text{S} + \text{CO}_2 \tag{15}
  \]
  \[
  \text{SO}_2 + 3\text{H}_2 \rightarrow \text{H}_2\text{S} + 2\text{H}_2\text{O} \tag{16}
  \]
  \[
  \text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 \tag{17}
  \]

5.3. Design specifications, calculator blocks and convergence

Simulation is controlled using three FORTRAN routines (calculator blocks) and six design specifications to reduce the number of independent specifications and to adjust automatically those associated variables, i.e. the dependent variables are automatically adjusted when independent input variables are modified by the user, a calculator block or a design specification. The main functional relationships (control structures) of the simulation are: the amount of coal input as a function of the gas turbine net power (272 MW), the amount of slurry water as a function of the coal input (35.5%), the makeup water for the steam cycle depends on the temperature of the stack gas (125 °C), the air input to the ASU is determined by the gasifier net duty and air to the gas turbine (GT) combustor is fixed by the combustor net heat duty or the stoichiometric amount of air required. The basic user defined specification is the value of the gas turbine power output which is 272 MW.

Since this is a large and intricate simulation, with ten nested convergence loops, it is very sensitive towards the loop’s break points and their initial conditions. To fix the initial conditions, an integration of the practical knowledge of the process and the trial runs of the model are very important. After detailed analysis, a specific computational sequence was set up for the model, and the ranges of initial conditions were established to improve the convergence of the model. The design specs are nested inside tear loops. In doing so, the sequence of the blocks was determined.

5.4. Unit operation models

The most important unit operations represented by Aspen Plus® models are shown in Table 3.

6. IGCC process optimization by sensitivity analysis

The sensitivity of the process for different operating conditions is analyzed. After preliminary analysis, just the variables with a high impact in the results were selected: gasification temperature, combustion temperature, level of N2 injection and solid concentration of the coal slurry. The main parameters analyzed within each analysis are thermal efficiency based on the low heating value of coal (\(\eta_{\text{LHV}}\)), cold gas efficiency (\(\eta_{\text{CG}}\)), carbon conversion efficiency (\(\eta_{\text{cC}}\)) and emission levels of CO2, SOx and NOx (Christopher & Zhu, 2006; Sugiyama et al., 2005).

6.1. Effects of gasification temperature

The results in Table 4 illustrate the effect of the gasification temperature (\(T_{\text{gas}}\)) on the IGCC process performance. The sensitiv-

Table 4
Variation of key process variables to the change in gasification temperature.

<table>
<thead>
<tr>
<th>(T_{\text{gas}}) (°C)</th>
<th>Coal (kg/s)</th>
<th>Net power (MW)</th>
<th>(\eta_{\text{CG}}) (%)</th>
<th>(\eta_{\text{cC}}) (%)</th>
<th>Air:syngas ratio</th>
<th>CO2 emission (kg/MWh)</th>
<th>SO2 emission (kg/MWh)</th>
<th>NOx emission (kg/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1250</td>
<td>44.3</td>
<td>427</td>
<td>36.4</td>
<td>68.3</td>
<td>6.47</td>
<td>784</td>
<td>187</td>
<td>10.3</td>
</tr>
<tr>
<td>1300</td>
<td>44.9</td>
<td>431</td>
<td>36.2</td>
<td>67.3</td>
<td>6.32</td>
<td>790</td>
<td>188</td>
<td>10.1</td>
</tr>
<tr>
<td>1350</td>
<td>45.8</td>
<td>436</td>
<td>35.9</td>
<td>66.3</td>
<td>6.18</td>
<td>796</td>
<td>189</td>
<td>10.0</td>
</tr>
<tr>
<td>1400</td>
<td>46.6</td>
<td>439</td>
<td>35.6</td>
<td>65.3</td>
<td>6.08</td>
<td>800</td>
<td>190</td>
<td>9.80</td>
</tr>
<tr>
<td>1450</td>
<td>47.5</td>
<td>444</td>
<td>35.3</td>
<td>64.3</td>
<td>6.01</td>
<td>802</td>
<td>191</td>
<td>9.60</td>
</tr>
<tr>
<td>1500</td>
<td>48.4</td>
<td>449</td>
<td>35.0</td>
<td>63.3</td>
<td>5.87</td>
<td>808</td>
<td>192</td>
<td>9.40</td>
</tr>
<tr>
<td>1550</td>
<td>49.4</td>
<td>455</td>
<td>34.8</td>
<td>62.3</td>
<td>5.70</td>
<td>814</td>
<td>193</td>
<td>9.20</td>
</tr>
</tbody>
</table>
Table 5
Variation of some key variables with combustion temperature.

<table>
<thead>
<tr>
<th>$T_{comb}$ (°C)</th>
<th>Coal (kg/s)</th>
<th>$\eta_{LHV}$ (%)</th>
<th>Air:syn</th>
<th>NOx emissions (kg/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1250</td>
<td>46.1</td>
<td>35.3</td>
<td>8.58</td>
<td>7.49</td>
</tr>
<tr>
<td>1300</td>
<td>45.4</td>
<td>35.7</td>
<td>7.85</td>
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</tr>
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<td>1350</td>
<td>44.8</td>
<td>36.1</td>
<td>7.21</td>
<td>9.18</td>
</tr>
<tr>
<td>1400</td>
<td>44.4</td>
<td>36.4</td>
<td>6.64</td>
<td>10.0</td>
</tr>
<tr>
<td>1450</td>
<td>44.0</td>
<td>36.6</td>
<td>6.13</td>
<td>10.8</td>
</tr>
<tr>
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<td>5.67</td>
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<td>43.5</td>
<td>37.1</td>
<td>5.26</td>
<td>12.2</td>
</tr>
</tbody>
</table>

The rectification of the process for the gasification temperature is done under the operational range of temperatures where gasification can take place with slagging of the ash (1250 and 1550 °C) (Zheng & Furinsky, 2005). As the gasification temperature increases, the thermal efficiency decreases due to a decrease in the cold gas efficiency. This decline in cold gas efficiency is due to a rise in the O2:C ratio in order to combust more carbon to reach high temperature. On the contrary, the total net power increases because the steam turbine power output rises due to a higher amount of the slurry input for the same quantity of gas turbine output. However, the net power output per ton of coal consumed and the thermal efficiency have a decreasing trend.

The CO2 and SOx emissions per unit of power output increase due to the rise in the coal consumption for the same level of GT power output. But the NOx emission per unit of power output drops off very slightly due to a decline in the air:clean syngas ratio, thereby lessening the thermal NOx formation.

### 6.2. Effects of gas turbine inlet temperature (syngas combustion temperature)

The analysis is performed for temperatures ($T_{comb}$) around the base case (1370 °C) and the results of the analysis can be seen in Table 5. For an increase in $T_{comb}$ between 1200 and 1550 °C, thermal efficiency ($\eta_{LHV}$) boosts by 5%. Along with a rise in $\eta_{LHV}$, the CO2 and SOx emissions per unit power output also drop off. This is due to the decline in the level of coal consumption for the same GT power output. But, the NOx emission rises because of the increase in thermal NOx formation at higher temperatures. The carbon conversion efficiency, the cold gas efficiency and the O2:C ratio remain almost constant as they are independent of the combustor operating temperature.

### 6.3. Effects of level of N2 injection

As the fraction of N2 injection to the GT combustor increases:

- The thermal efficiency increases, due to a decrease in the slurry requirement, as more N2 is used to drive the turbine.
- The net power output declines because of a decrease in the steam turbine power output owing to the decrease in coal flow, thereby lowering the amount of exhaust gas from the gas turbine.
- The net power output per ton of coal input is enhanced because the coal requirement for the same level of GT output gets reduced.
- The CO2, SOx and NOx emissions lessen due to the decline in the coal consumption and the diluting effect of the N2 that decreases thermal NOx formation.

### 6.4. Effects of solid concentration in coal slurry

With the rise in solids concentration, the O2:C ratio decreases because of the reduction in required energy to vaporize and superheat water. The syngas heating value increases because less coal is used to supply energy for the gasification. Therefore, there is a boost in the thermal efficiency and the net power output per ton of coal used. The emissions per unit power of CO2, SOx and NOx slightly increase because of the small decrease in the total net power, owing to decline in the steam turbine power output. The steam produced in the HRSG is minimized as the coal consumption drops off. This is because a relatively small amount of coal is utilized to produce the 272 MW of electricity from the gas turbine thereby lowering the GT exhaust feed to the HRSG.

### 6.5. Simultaneous analysis of the effects of level of N2 injection and syngas combustion temperature

The thermal efficiency increases almost linearly with the increase in the combustor temperature for all levels of N2 injection to the combustor (Fig. 2). Therefore, the power augmenting effect of the N2 flow is greater than its diluting effect in the combustor. No trade-off between these two effects was found.

N2 injection level of 98% is the upper bound on the total amount of N2 available for injection, as venting is inevitable and N2 can be used as a coolant in the gas turbine. Therefore 98% of N2 injection to the combustor operating at the highest pos-

Fig. 2. Effects of simultaneous variations of the level of N2 injection and combustor temperature on thermal efficiency.
sible temperature (depending on the turbine inlet temperature specification) produces power with relatively high thermal efficiency.

7. Heat integration

With the aim of improving thermal efficiency and environmental performance, the effects of heat integration of the gasifier and GT combustor are analyzed. The result is supplemented by heat integration of air separation unit (ASU) and gas cleaning unit. With the objective of evaluating the overall process utility consumption and further potential of heat integration and energy production, pinch analysis is applied to the process.

7.1. Heat integration of the gasifier and the GT-combustor

In this analysis, the gasifier is heat integrated with the GT-combustor. The level of integration is optimized by varying the oxygen and air requirements of the gasifier and combustor, respectively. As the gasification reaction is endothermic, its net heat duty is kept zero, i.e. adiabatic operation, so that no external heat is added to the system, except from the combustor. Basically the gasifier gets heat for gasification from the combustion of part of the carbon feed. But, this results in a decline in the thermal efficiency because the heating value of the syngas is reduced. In this analysis, the objective is to minimize the amount of carbon burnt by supplying external heat to the gasifier from the combustor because the reaction in the combustor is exothermic.

With the increase in the level of heat integration, the net power output increases, but the net power per ton of coal consumed increases until it reaches a maximum (Fig. 3a). The decrease in the O₂:C ratio with the increase in the level of integration has a positive effect on the thermal efficiency at first, because it favors the gasification reaction (compared with the combustion reaction) and increases the cold gas efficiency. Then, with further decrease in the O₂:C ratio, the carbon conversion efficiency and, in turn the cold gas efficiency, start to decrease (Fig. 3b), thereby lowering the thermal efficiency. The air requirement in the combustor also decreases as the net heat duty of the combustor increases. This is to minimize the heat absorbed by the excess air, to maintain the operating temperature. The maximum in Fig. 4 represents an optimal trade-off between these two opposing scenarios.

7.2. Heat integration of the air separation unit (ASU) and the gas cleaning unit

The oxygen stream from the ASU to the gasifier is heat integrated with the condenser of the amine regenerator (condenser regeneration) in the gas cleaning unit. This is proposed due to the availability of high quality heat from the amine regenerator unit. Fig. 4 shows a similar trend: the maximum is shifted to the left and the efficiency is improved. The maximum efficiency is
reached at a combustor duty of 150 MW (a value that differs from the 200 MW found in the previous case) due to the further decrease in the O₂:C ratio as the O₂ inlet temperature to the gasifier increases. Therefore, it is possible to minimize the oxygen requirement by heating the inlet oxygen to the gasifier using process heat. This modification increases the overall efficiency, as less energy is used in the ASU to compress oxygen and air.

7.3. Pinch analysis

Pinch analysis is performed to compare the energy consumption of the optimized model with the energy consumption of the process analyzed at a certain fixed pinch approach temperature. The hot and cold composite curves for the process are constructed with a minimum approach temperature of 15 °C (Fig. 5). From these curves, the total net heating and cooling requirements of the process when designed optimally can be identified on each of the hot and cold ends. Also, the total amount of heat recovery that can be achieved within the process can be determined by the overlap-area between the two curves. These values are known as energy targets. The problem table algorithm is used to construct the grand composite curve (Fig. 6). From this curve, the hot energy target is indicated as 225 MW with a temperature level of more than 440 °C (this is the case when all hot requirements are added by only one utility). On the other hand, the cold utility target is 450 MW, at a temperature lower than −160 °C. Pinch temperature is at almost 380 °C. Fig. 6 shows some potential schemes for improving the energy efficiency of the overall basic design. For example, instead of utilizing an external hot utility, an exhaust steam from steam turbines at a temperature level close to 440 °C can be used to fulfill the heat-
ing requirement. On the cooling energy requirement, a possible scheme of utility placement is also suggested in Fig. 6. For this scheme, saturated steam at 230 °C can be produced with a flow rate of 123 ton/h. The heat load on boiler feed water BFW preheating will be 22 MW. Then, the rest of cooling utilities will be provided by cooling water with a cooling duty of 50 MW, and a refrigerant medium at a temperature of −160 °C at a load of 312 MW.

As for heat integration opportunities, the composite curve provides details of how much and at what level these energies are available, e.g., above the pinch temperature two heat sources are available in excess of 50 and 100 MW at temperature levels of 1240–760 and 760–570 °C, respectively. On similar manner, excess heat sources below the pinch can heat cold processes or streams that require energy; e.g., heats of 70 and 60 MW at temperature intervals of 320–240 and 30 °C, respectively, are available.

Comparing the utility requirements of the optimized process and the process at the pinch point, the hot utility consumption efficiency is calculated to be 94% and that of the cold utility efficiency is 97%. These values show that the optimized process operates nearly at the pinch point.

8. Conclusions

A base case of integrated gasification cycles has been simulated using Aspen Plus®. Sensitivity of the process for different operating variables was then studied. As result of this analysis, thermal efficiency (LHV) as high as 45% was attained, and the corresponding CO₂ and SOₓ emissions were 698 kg/MWh and 0.15 kg/MWh, respectively. This result corresponds to a gasification temperature of 1250 °C, a combustion temperature of 1550 °C, 98% of N₂ injection to the GT combustor, and a slurry solid concentration of 80%. For the practical application of this improvement, other considerations like the capacity of the equipment and its cost, the flowability of the slurry at the high level of solids concentration have to be considered.

Heat integration of the gasifier and the combustor revealed that the best value of the combustor heat duty for the integration is around 200 MW. However the analysis for the heat integrated case of the ASU and the CCGU shows that the best value of the combustor net duty for the integration is 150 MW. The latter case is preferred because the thermal efficiency is higher due to lower power consumption in the ASU compressors. According to the results shown in Figs. 3a, b and 4, it is advisable to operate at combustor net heat duties slightly below the optimum value in order to avoid a significant loss in the efficiency during operation.

The optimum design of the gasification cycle was further analyzed according to pinch analysis principles. The analysis was able to provide further opportunities of heat integration above and below the pinch temperature. Multiple utilities levels can be used for minimum operation costs. Also steam can be produced by the excess heat available, leading to reductions in atmospheric emissions.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>ASU</td>
<td>air separation unit</td>
</tr>
<tr>
<td>BFW</td>
<td>boiler feed water</td>
</tr>
<tr>
<td>CCGU</td>
<td>cold gas cleaning unit</td>
</tr>
<tr>
<td>CSC</td>
<td>convective syngas cooler</td>
</tr>
<tr>
<td>FBC</td>
<td>fluidized bed combustion</td>
</tr>
<tr>
<td>GT</td>
<td>gas turbine</td>
</tr>
<tr>
<td>HRSG</td>
<td>heat recovery steam generator</td>
</tr>
<tr>
<td>IGCC</td>
<td>integrated gasification combined cycle</td>
</tr>
<tr>
<td>LHVᵢ</td>
<td>lower heating value of component i (MJ/kg)</td>
</tr>
<tr>
<td>Mᵢ</td>
<td>mass flow rate of component i (kg/s)</td>
</tr>
<tr>
<td>PC</td>
<td>pulverized coal</td>
</tr>
<tr>
<td>P_AUX</td>
<td>auxiliary power consumption (MJ)</td>
</tr>
<tr>
<td>P_GT</td>
<td>gas turbine net power (MJ)</td>
</tr>
<tr>
<td>P_NET</td>
<td>net power output (MJ)</td>
</tr>
<tr>
<td>RSC</td>
<td>radiant syngas cooler</td>
</tr>
<tr>
<td>T_comb</td>
<td>syngas combustion temperature (°C)</td>
</tr>
<tr>
<td>T_gas</td>
<td>coal gasification temperature (°C)</td>
</tr>
<tr>
<td>x_CH₄</td>
<td>mass fraction of CH₄ in syngas</td>
</tr>
<tr>
<td>x_CO</td>
<td>mass fraction of CO in syngas</td>
</tr>
<tr>
<td>x_H₂</td>
<td>mass fraction of H₂ in syngas</td>
</tr>
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Greek symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>η</td>
<td>thermal efficiency (%)</td>
</tr>
<tr>
<td>ηᶜᵉ</td>
<td>carbon conversion efficiency (%)</td>
</tr>
<tr>
<td>ηᶜ</td>
<td>cold gas efficiency (%)</td>
</tr>
</tbody>
</table>

Acknowledgements

The authors wish to acknowledge support of this research work from the Spanish Ministry of Education and Science (DPI2008-04099) and the Spanish Ministry of External Affairs (A/016473/08, A/020104/08 and HS2007-0006). The authors also express their gratitude to F. Emun for carrying out some of the simulations.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.compchemeng.2009.04.007.

References