System-Level Analysis of Pre-Combustion Carbon Capture in an IGCC Power Plant

Introduction

Pre-combustion carbon capture (Jansen et al., 2015) is regarded as one of the most promising pathways for achieving deep decarbonization in fossil-fuel-based power generation, particularly when integrated with coal gasification and combined cycle systems. In an integrated gasification combined cycle (IGCC) plant, carbon dioxide can be separated from synthesis gas prior to combustion (Giuffrida et al., 2011), where CO_2 is present at high partial pressure and relatively high concentration, offering thermodynamic advantages over post-combustion capture. However, despite these advantages, the incorporation of carbon capture units inevitably leads to efficiency penalties due to additional energy consumption, process integration complexity, and disturbances to the overall power cycle (Raganati and Ammendola, 2024).

Conventional pre-combustion CO_2 capture has been predominantly based on chemical absorption technologies, such as physical or chemical solvents, which are mature and commercially available (Moioli et al., 2014). Nevertheless, absorption-based capture typically requires substantial energy input for solvent regeneration, resulting in significant power efficiency losses. In recent years, adsorption-based carbon capture processes have attracted increasing attention due to their potential for lower regeneration energy, flexible operating conditions, and suitability for integration with high-pressure gas streams (Lassitter et al., 2025). Despite extensive material-level studies on adsorption processes, systematic evaluations at the plant-wide system level remain limited, particularly for large-scale IGCC configurations (Xin et al., 2020).

In this work, a comprehensive pre-combustion carbon capture system is developed and analyzed based on a full-process IGCC model. By integrating air separation, gasification, syngas purification, carbon capture, gas turbine, heat recovery steam generation, and steam turbine units, this study aims to (i) quantify the overall power efficiency penalty induced by carbon capture, (ii) compare absorption-based and adsorption-based capture technologies from a system-level perspective, and (iii) elucidate the influence of adsorption operating temperature on total energy loss and system performance.

IGCC system simulation

A full-scale pre-combustion carbon capture power generation system was constructed using Aspen Plus, representing a typical IGCC plant integrated with carbon capture. The model consists of the following major subsystems:

- Air separation unit (ASU) for oxygen production;
- Entrained-flow coal gasification unit;
- Syngas cooling and purification section;
- Carbon capture unit (absorption-based or adsorption-based);
- Gas turbine (GT) for syngas combustion;
- Heat recovery steam generator (HRSG);
- Steam turbine (ST) power generation system;

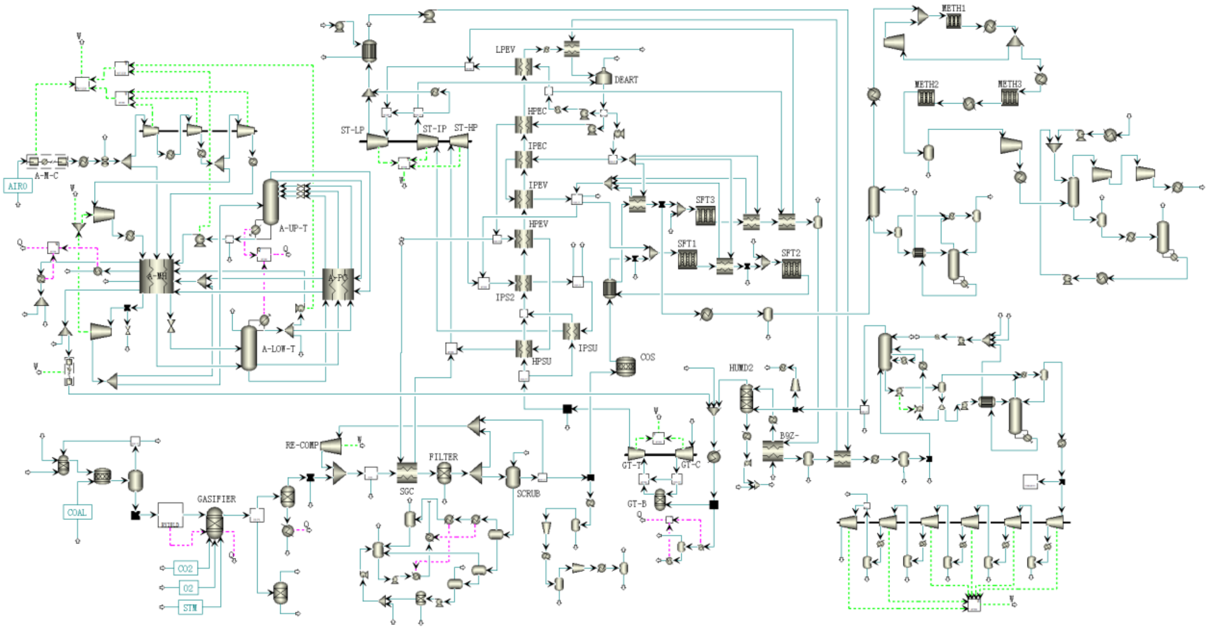

Figure 1 *The flowsheet of IGCC system containing the units of air separation, coal gasification, syngas cooling and purification, carbon capture, gas turbine (GT) for syngas combustion; heat recovery steam generator (HRSG); steam turbine (ST) power generation system.*

Simulation results indicate that the integration of carbon capture units significantly affects the overall energy balance of the IGCC system. In the absorption-based capture case, a pronounced reduction in net power efficiency was observed, primarily attributed to the high energy demand for solvent regeneration and auxiliary equipment. This efficiency penalty is consistent with previous reports on solvent-based pre-combustion capture systems.

In contrast, the adsorption-based capture system exhibited a substantially lower efficiency loss under comparable CO_2 capture rates. The reduced regeneration energy requirement and improved compatibility with high-pressure syngas streams contribute to the superior system-level performance of adsorption-based capture.

Selection and comparison of carbon capture technology for pre-combustion system

Two alternative pre-combustion CO_2 capture routes were implemented and compared:

- Absorption-based capture, representing a conventional solvent-based process with CO_2 separation followed by solvent regeneration.
- Adsorption-based capture, in which CO_2 is selectively removed from syngas using solid adsorbents, followed by regeneration through temperature swing operation.

System performance was evaluated using the following key indicators:

- Steam Turbin power (MW);
- Gas Turbin power (MW);
- ASU power consumption (MW);
- Nitrogen compressor power consumption (MW);
- CO_2 compress power consumption (MW);
- Other power consumption (MW);
- Power efficiency (%);

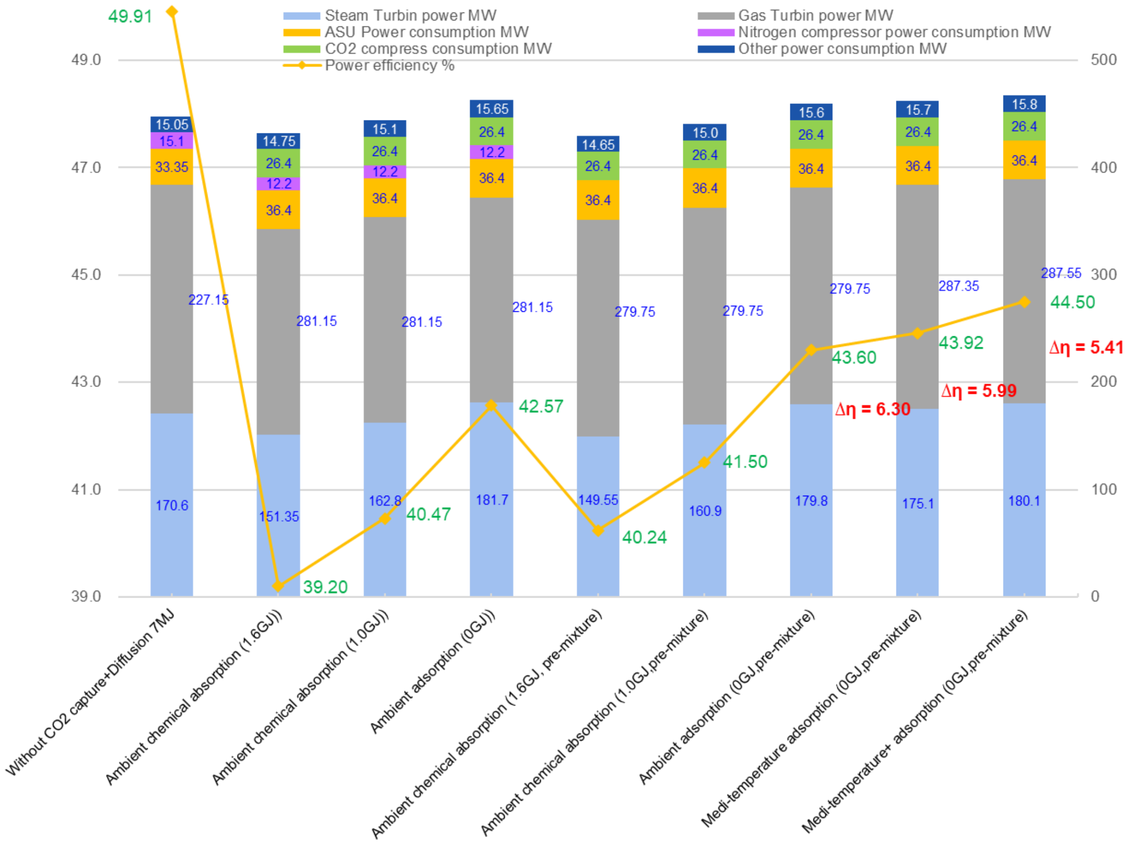

Figure 2 *Comparison of net power efficiency of the IGCC system under different pre-combustion carbon capture technologies.*

A range of operating conditions and carbon capture configurations were systematically evaluated in this study. For the ambient-temperature chemical absorption process, different solvents with distinct regeneration heat duties (1.0 and 1.6 GJ/t CO_2) were considered to represent varying levels of energy sensitivity. In parallel, an ambient-temperature adsorption-based capture process was simulated, in which no thermal regeneration duty was required and only the associated power consumption was accounted for. Different contacting configurations, including premixed and diffusion-based modes, were further examined. In addition, the effect of adsorption temperature on system performance was investigated through comparative simulations.

As shown in Figure 2, the integration of chemical absorption results in a substantial power efficiency penalty, with the maximum reduction approaching 10 percentage points. In contrast, the adsorption-based capture system exhibits a significantly lower impact on overall IGCC performance, with the power loss remaining below 6 percentage points under the investigated conditions. These results indicate that adsorption-based pre-combustion carbon capture offers a clear advantage over conventional chemical absorption from a system-level energy efficiency perspective.

Conclusions

This study presents a comprehensive system-level assessment of pre-combustion carbon capture technologies in an IGCC power plant. By constructing a full-process simulation model, the impacts of absorption-based and adsorption-based CO_2 capture processes on overall power generation efficiency were quantitatively evaluated. The results demonstrate that adsorption-based carbon capture has significant potential to reduce the efficiency penalty associated with pre-combustion CO_2 capture, particularly when operating conditions such as adsorption temperature are carefully optimized.

The insights provided in this work highlight the necessity of integrated material–process–system analysis for the development of next-generation carbon capture technologies and offer valuable guidance for the deployment of low-energy-loss pre-combustion CCUS systems.

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