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Integrated gasification combined cycle with carbon dioxide capture by elevated temperature pressure swing adsorption

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HIGHLIGHTS

- Design of ET-PSA unit and its integration with IGCC system.
- CO_2 capture energy consumption of ET-PSA and comparison to Selexol process.
- Effects of purge and rinse steps on energy consumption of ET-PSA process.

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ABSTRACT

This paper investigates the CO_2 capture energy consumption via elevated-temperature pressure swing adsorption (ET-PSA) for CO_2/H_2 separation. IGCC power plants with ET-PSA, with the conventional Selexol process and without CO_2 capture are built in Aspen Plus. The CO_2 capture energy consumption of ET-PSA is evaluated by the specific primary energy consumption for CO_2 avoided (SPECCA), which is a function of the net electrical efficiency and the specific CO_2 emission rate. The ET-PSA unit with different processes simulated in gPROMS is coupled into the IGCC model, the operation parameters of which are analyzed to achieve the lowest SPECCA. The results show that the CO_2 capture energy consumption has a tendency to decrease by increasing the adsorption time, the residence time, and the purge-to-feed ratio; reducing the purge ratio; and adding the CO_2 reflux. The SPECCA of ET-PSA with the 5–3–1 process is 2.79 MJ/kg_{CO_2} with a 90.5% CO_2 capture ratio, which is 11.71% lower than that of the Selexol process. An effective way to further reduce the SPECCA of ET-PSA is to add rinse and purge steps, whose energy loss mainly comes from the consumption of high-temperature steam. The calculated SPECCA of ET-PSA with rinse and purge steps is 2.32–2.52 MJ/kg_{CO_2}, which is 20.3–26.6% lower than that of the Selexol process.

1. Introduction

Global warming caused by greenhouse effect has aroused widespread concern in recent years. Governments around the world came to an agreement at the COP21 conference that the world temperature should be kept less than 1.5–2 °C above preindustrial levels by the year 2100 [1]. It is known that CO_2 release from fossil fuel combustion is one of the major sources for greenhouse gas emissions. Currently, various technological approaches are developed to capture CO_2 from power plants, including pre-combustion capture, post-combustion capture, oxy-fuel combustion and chemical-looping combustion [2–6].

Elevated-temperature pressure swing adsorption (ET-PSA) using solid CO_2 adsorbents such as hydrotalcite [7–10] and modified activated carbon [11–14] is a new type of technology for pre-combustion CO_2 capture. Compared with other CO_2 capture technologies, ET-PSA technology is more energy efficient. In the coal-based chemical industries and integrated gasification combined cycle (IGCC) power plants, the syngas produced by coal gasification has a high temperature (250–500 °C) and high pressure (2–7 MPa) [15,16]. However, the operation temperature of the conventional wet CO_2 capture technology is very low (e.g., −5 to 25 °C for Selexol, 40–60 °C for MDEA, −40 to 20 °C for Rectisol) [17,18]. A series of heat exchangers should be used if these technologies are adopted to capture CO_2 from the syngas, increasing the heat loss and the investment cost. In contrast, the ET-PSA technology works at elevated temperature ranges (200–450 °C). Moreover, it can adsorb/desorb the CO_2 in the syngas simply by the pressure swing, which avoids the heat regeneration required for the conventional CO_2 capture technologies [19].

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A series of fundamental research has been performed for ET-PSA. Large quantities of researches indicate that hydrotalcite and its derivatives are suitable CO_2 adsorbents for the application of ET-PSA technology [19–23]. For the process design, Reynolds et al. [24] developed a ET-PSA process based on K-promoted hydrotalcite adsorbent and a simple, 4-step, Skarstrom-type cycle at 575 K. The simulated results showed that CO_2 recovery increased with increasing purge-to-feed ratio, pressure ratio and decreasing cycle step time, while CO_2 enrichment increases with increasing cycle step time, pressure ratio and decreasing purge-to-feed ratio. Zheng et al. [25] proposed a four-bed two-pressure-equalization ET-PSA unit based on the elementary reaction kinetics adsorption model with Elovich equation, which was then verified with experimental data. The effects of detailed operating parameters, including adsorption time, residence time, purge to feed ratio, operating pressure and adsorbents capacity on ET-PSA performance was studied. Zhu et al. [26] analyzed the thermodynamic performance of IGCC with an ET-PSA unit by considering ET-PSA subsystem as a black box. They indicated that the estimated power efficiency of IGCC with ET-PSA process with 90% of CO_2 removal and more than 93.5% of H_2 recovery rate can be higher than that for IGCC with Selexol process. Many works have been conducted for the modeling and optimization of the sorption-enhanced water gas shift reaction (SEWGS) [27–31] and sorption-enhanced methane reformation (SEMR) [32–36] which were typical applications of the ET-PSA technology. Najmi et al. [29] built a dynamic SEWGS system model based on multi-train ET-PSA process. It consists of eleven distinct steps, which each reactor undergoes in sequence. Based on that, they investigated the load-following capacity and controllability of the IGCC integrated with the ET-PSA process [30]. Gazzani et al. [37] studied the thermodynamic performances of SEWGS system with ET-PSA process integration in a 400 MW IGCC power plant. A net electric efficiency of 38–39% with 86–96% of CO_2 avoidance was achieved by ET-PSA, which was higher than that by IGCC with capture via Selexol (36.03%) and Advanced super critical (ASC) boiler with amine scrubbing (33.55%).

Note that in a coal-fired power plant, the biggest difficulty for the application of CO_2 capture technologies is the large efficiency penalty it causes [38,2–5]. Although researchers have indicated that the ET-PSA technology might be more energy saving than the wet solvent CO_2 capture technologies [13,14,19,21,22,39] the quantitatively calculation of CO_2 capture energy consumption of ET-PSA is lacked, and even the standard of comparison between these CO_2 capture technologies is not so clear. The technical principle and energy consumption source of ET-PSA are completely different from the conventional CO_2 capture technologies. Hence, a unified energy consumption evaluation method should be built to quantitatively compare the energy loss for these two types of CO_2 capture technologies.

In this study, the energy consumption of CO_2 capture units is quantitatively evaluated by analyzing their influence on the overall performance of IGCC system. Selexol process is chosen to represent the conventional normal temperature solvent absorption method. Approximately 600 MW_e IGCC power plants with the Selexol process, with the ET-PSA process, and without a CO_2 capture unit (the reference case) are built based on the Aspen Plus commercial software package. The ET-PSA unit with a 4–2–1 process or a 5–3–1 process adopted in this work is designed and verified in gPROMS, and the effects of the operation parameters (e.g., adsorption time, purge ratio, purge time, CO_2 reflux ratio) on CO_2 capture energy consumption is calculated and analyzed. The performance of the ET-PSA process with steam rinse and purge is also evaluated based on the experimental data. The CO_2 capture energy consumption is evaluated by the power efficiency penalty and the amount of released CO_2 after adopting the CO_2 capture systems.

2. Modeling and parameter setting of IGCC power plant

2.1. Analytical method and parameter definition

The main energy consumption of the conventional wet CO_2 capture technology results from the regeneration of the CO_2-rich solution, so the specific heat duty q_{CO_2} (MJ_{th}/kg_{CO_2}) of the reboiler is generally used to describe the CO_2 capture energy consumption [40,41]. However, it does not reflect information such as CO_2 capture efficiency and temperature range (or the energy quality) of the required heat load [41].

The CO_2 adsorption and desorption of ET-PSA are realized by the pressure change of the CO_2 adsorbent and thermal regeneration step, which is used when the wet CO_2 capture technology is not needed. However, the low-temperature H_2 purge step is adopted in this technology to help regenerate the CO_2 adsorbent [25]. Meanwhile, a small amount of H_2 in the desorbed stream is discharged into the CO_2 gas storage tank, causing a lower H_2 recovery ratio compared with the normal/low-temperature solvent absorption methods (>99%). For a coal-based power plant, the decreasing H_2 recovery ratio will reduce the power output generated by the subsequent power units (gas turbine and steam turbine system), indirectly causing CO_2 capture energy consumption.

Another process adopts the steps of high-pressure steam rinse and low-pressure steam purge to replace the original low-pressure H_2 purge. The concrete method is as follows [39]: after the adsorption step, the high-pressure steam co-currently passes through the column, driving away the remaining H_2 in the gas phase into the product gas storage tank; after the depressurization step, the low-pressure steam is counter-currently added into the column to facilitate the CO_2 desorption on the adsorbent surface and drive the CO_2 stream into the CO_2 gas storage tank. The experimental test results indicate that by using this method, the CO_2 capture ratio and the H_2 recovery ratio can be as high as the wet capture technology or even higher [42,43]. Different energy and chemical engineering industrial processes have different demands for CO_2 capture and H_2 recovery ratio, which can be controlled by adjusting the steam consumption for the rinse and purge steps. The CO_2 capture ratio is more sensitive to the purge step, and the rinse is more sensitive to the H_2 recovery ratio [44]. If the rinse and purge steps are adopted in ET-PSA, then the energy consumption mainly results from the elevated temperature steam consumption. In an IGCC power plant, this part of steam can be provided by the heat recovery boiler (HRSG) in the steam turbine system, whose consumption will reduce the power output of the gas turbines. To distinguish it from the ET-PSA process with the low-pressure H_2 purge, this new process is termed ET-PSA-steam.

Based on the foregoing analysis, the energy consumption of ET-PSA is closely connected to the system, which cannot simply be ascribed to the heat load or the electricity load. A more significant method is to place the CO_2/H_2 separation unit in an actual industrial system (e.g., IGCC power plant) to analyze its influence on the overall performance of the system, then to back-calculate the CO_2 capture energy consumption.

The evaluation indicator of the energy consumption is the specific primary energy consumption for CO_2 avoided (SPECCA), which is defined as follows [37]:

$$\mathrm{SPECCA} = \frac{\mathrm{HR} - \mathrm{HR}_{\mathrm{REF}}}{E_{\mathrm{REF}} - E} = \frac{3600 \cdot \left(\frac{1}{\eta} - \frac{1}{\eta_{\mathrm{REF}}}\right)}{E_{\mathrm{REF}} - E} \tag{1}$$

In the above equation, HR represents the heat rate ($MJ_{th}/MW\,h_e$); E represents the specific CO_2 emission rate ($kg_{CO_2}/MW\,h_e$); η represents the net electrical efficiency (%); and