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Process integration and design for maximizing energy efficiency of a coal-fired power plant integrated with amine-based CO_2 capture process

Se-Young Oh, Seokwon Yun, Jin-Kuk Kim*

Department of Chemical Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea

HIGHLIGHTS

- Process integration for the integrated design of CO_2 capture with power plants.
- System-wide energy analysis for minimizing power generation penalty.
- Identification and optimization of configurational modifications for energy saving.
- Case study for demonstrating the applicability of process integration method.

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ABSTRACT

System-wide integration of post-combustion CO_2 capture process into a coal-fired power plant is an effective and practical strategy to improve cost-effectiveness for capturing CO_2 emissions from the power sector. Considerable reduction of the net energy efficiency of a power plant by 20–40% is inevitable due to energy requirements for the CO_2 capture and power requirement for the CO_2 compression. Hence, this study focuses on minimizing the net efficiency penalty through integrated design of coal-fired power plant with CO_2 capture process in a holistic and systematic manner. In order to analyze the techno-economic impact of integrated process on the net power plant efficiency, overall process models are developed in a commercial simulator Aspen Plus®, in which a 550 MW_{net} supercritical coal-fired power plant is simulated and validated. A pilot-scale post-combustion CO_2 capture process based on MEA, together with CO_2 compression, is modeled and scaled-up to meet the commercial-scale capacity. Simulation-assisted optimization is performed to enhance the overall performance of capture-integrated power generation through fully exploiting system interactions and examining relevant economic trade-offs. A case study is carried out to evaluate the effect of several heat integration options and demonstrate a considerable benefit for reducing the net efficiency penalty.

1. Introduction

Coal-fired power plants are major providers of electricity and heat in the energy sector, which produce significant amounts of CO_2 emissions. CO_2 is known as the main greenhouse gas (GHG) so that reducing the CO_2 emissions has been a global issue to limit average global temperature increase to 2 °C by 2050 [1]. Due to an increase of worldwide electricity demand, coal, which is the largest energy source, still plays an important role in energy generation. Therefore, implementation of carbon capture and storage (CCS) into coal-fired power plants is considered as a realistic near-term technology for mitigating CO_2 emissions.

The CCS technology includes capturing the CO_2 from the CO_2 emitters, and compressing and transporting them to the storage, for example, the injection of CO_2 into a geological oil reservoir for EOR (enhanced oil recovery). There are different ways of applying CCS technology in power and process industries, mainly pre-combustion, post-combustion, and oxy-combustion. Post-combustion CO_2 capture are utilized to not only coal- and gas-fired power plants, but also the iron and steel and cement industries. Among them, coal-fired power plants have accounted for about 40% of global electricity and heat supply [2]. Although natural gas-fired combined cycle (NGCC) power plant has been increasingly focused in the power generation, the CO_2 capture cost of an NGCC power plant with CCS is higher than that of a coal-fired power plant [3]. The post-combustion capture for coal-fired power plants is generally preferred, since it can be easily retrofitted with the existing power plants as well as integrated into new build plants [4].

* Corresponding author.
E-mail address: jinkukkim@hanyang.ac.kr (J.-K. Kim).

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An amine-based chemical absorption process is likely to be the first choice for large-scale CO_2 capture from a coal-fired power plant. Aqueous monoethanolamine (MEA) has been widely recognized as a vital solvent for post-combustion capture technology, due to its fast reaction rate and relatively high separation selectivity with CO_2 [5]. Furthermore, it has already been demonstrated and commercialized in ammonia plant and gas processing industry [6]. Jiang et al. [7] has proposed a promising process of the ammonia-based CO_2 capture process and demonstrated its technical feasibility and economic benefits for commercial application. The chemical absorption CO_2 capture processes using MEA requires heat energy for solvent regeneration in the stripper reboiler. Hence, it is important to evaluate the process performance and energy demands for applying it to large-scale post-combustion capture plants.

In order to enhance technological readiness of the MEA-based CO_2 capture technology integrated with coal-fired power plants, many studies have been carried out to develop rigorous capture process models which are then validated with laboratory- and pilot-scale experimental data [8]. For the application of commercial-scale CO_2 capture process, the rate-based process modeling and simulation has been regarded as an important technique to gain more accurate and detailed guidance for process design and development [9]. With understanding of the absorption/stripping phenomena, such as chemical reactions, mass and heat transfer on the gas and liquid phases, and hydraulic properties, a rigorous model for capture process can be established, for example, by using a commercial simulator, especially Aspen Plus®, known as an effective software to study the CO_2 capture process [10]. The developed model can be used for not only equipment design and scale-up, but also process integration study for the large-scale coal-fired power plant.

When the CCS process is integrated into a coal-fired power plant, it leads to a reduction of the net efficiency of the power plant. As mentioned, an MEA-based CO_2 capture process demands a large amount of steam (typically 3.5–4.5 GJ/tCO_2 about 120 °C) in the stripper reboiler, which can be provided by steam extraction from the steam cycle of a power plant. In addition, power is further required for the compression of captured CO_2 and its auxiliaries [11]. For these reasons, the net power efficiency is decreased by approximately 20–40% and many studies had attempted to reduce the efficiency penalty associated with the introduction of CCS in practice [12].

There are a number of ways to minimize the energy penalty of the power plant integrated with CO_2 capture. Some researchers have focused on improving the performance of absorption process for CO_2 capture, of which the main purpose is basically to lower energy consumption in the reboiler, in order to reduce the amount of steam extraction from the power plant. This can be achieved by the use of advanced solvents and the development of solvents leads to superior performance in terms of high absorption/desorption rate and/or low regeneration energy [13]. However, further study is still needed for these novel absorbents to demonstrate their technical feasibility on a large scale [14]. Additionally, many research studies have been carried out considering parametric optimization and structural modifications of the post-combustion CO_2 capture process for the reduction of the energy penalty. Cifre et al. [15] investigated the impact of process variables, such as column height, lean loading, and stripper pressure in the capture process, on reboiler duty and power consumption through sensitivity analysis. Various process configurations have been evaluated to reduce the energy consumption of amine-based CO_2 capture process [16,17]. Among them, Zhao et al. [18] found that enhancement methods, for example, simple and advanced rich-split, significantly improved the process efficiency. Oh and Kim [19] showed the benefit of operational optimization with full exploitation of part-load characteristics for the operation of power plants, and the system-wide improvement from the structural modifications with the application of superstructure-based optimization technique.

Other researchers have focused on investigating the proper extraction of steam from the power plant to minimize the plant-wide energy penalty. Lucquiaud et al. [20] discussed three capture-ready plant options considering retrofitting of steam turbine systems, that include clutched LP turbine, throttled LP, and floating pressure strategy. It is important to find the optimal location of steam extraction from the steam cycle to provide necessary heat for the CO_2 capture plant, since heat requirements in the reboiler are generally over 130 °C for the case of MEA solvent regeneration [21]. Extracting low-pressure steam at the appropriate pressure can be effective in minimizing energy penalty [22].

Many authors have suggested heat and power integration between the power plant and CO_2 capture process as an effective strategy to improve the net efficiency. Hanak et al. [4] analyzed several heat exchanger network (HEN) designs, among which the most efficient option is to use the flue gas leaving the supercritical high-ash coal-fired power plant for heating up boiler feedwater. A combined pinch analysis and linear programming optimization method was used to reduce the energy penalty by redesigning the HEN of power stations [11]. The utilization of waste heat recovery for the CO_2 capture and compression units is another heat integration option to improve the energy efficiency. In the CO_2 compression process, heat to be rejected from the CO_2 inter-coolers can be useful to preheat the boiler feedwater [22]. Preheating of the condensate can be also achieved by recovering heat from the stripper overhead product stream in the CO_2 capture process [23]. Pan et al. [24] also proposed optimal strategies to minimize the efficiency penalty in retrofitting existing power plants integrated with CO_2 capture. They dealt with both implementing heat transfer intensification techniques and extracting steam in an appropriate manner, which could provide sufficient heat to the capture process. Moreover, with the advanced process integration, the installation of a back-pressure turbine from the IP/LP crossover can be considered to provide the steam at the required temperature, which can be exploited for generating additional power [25].

Several studies have reviewed the performance of coal-fired power plants without CCS in terms of thermal efficiency [26]. As improving the steam conditions (i.e. producing steam at high temperature and pressure) in the boiler, the thermal efficiency of a power plant is increased. For example, the overall energy efficiency of a subcritical power plant is about 35%, and that of a supercritical power plant generating steam, typically, below 600 °C is about 40%. The ultra-supercritical power plant is currently being developed which generates steam over 600 °C temperature, and further target for this area of development is steam conditions over 700 °C by 2021 [27]. The supercritical coal-fired power plant is considered in this study for integrating CCS technology, as it is the most widely used in power industry in these days.

This work aims to show how to minimize the net efficiency penalty of an integrated supercritical coal-fired power plant with post-combustion CO_2 capture process by using a comprehensive heat integration. The integrated overall system is modeled and simulated in Aspen Plus V8.8® environment. A process model for a 550 MW_{net} supercritical coal-fired power plant in this study includes a pulverized coal boiler and steam cycle. Most researchers have focused on only mathematical modeling of the steam cycle and retrofitting an existing process, but it can be also considered that the CO_2 capture process is installed on a new power plant. The inclusion of a flue gas desulphurization (FGD) unit for the model of a pulverized coal boiler can improve overall integrity of the model, as accurate estimation of the required fuel and the flue gas to be treated can be obtained for new design cases. The energy required for the FGD unit is considered to balance the fixed target of net power output in a coal-fired power plant. When integrating the power plant with CO_2 capture, the performance of the CO_2 capture process is dependent on the design of the FGD unit. In this study, new built case is considered as opposed to retrofit, which has greater potential and opportunities in the context of process integration with CO_2 capture leading to significant energy efficiency improvements. Reliable process models are developed, which are then used for evaluating the impact of