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Operational optimization for part-load performance of amine-based post-combustion CO_2 capture processes

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ABSTRACT

It is typical to assume that the capture system operates at the full working load of the power plant. This study aims to develop systematic design framework which can provide a cost-effective strategy for operating CO_2 capture plant under different operating load. The part-load performance of CO_2 capture process together with power plant is modeled and evaluated with a process simulator UniSim®. This study considers both natural gas-fired combined cycle (NGCC) and coal-fired plants, in which optimization is carried out for finding an economic operating strategy to minimize regeneration energy without compromising process efficiency of the capture system. The multi-period modeling approach is applied to accommodate discontinuous nature of part-load performance, with which techno-economic impacts of part-load operation is investigated in a holistic manner. The case study is presented to demonstrate the usefulness of proposed design and optimization framework and to provide practical guidelines and conceptual insights for part-load operation in practice. From the case study, the specific reboiler duty is reduced through the superstructure optimization at full-load operation, which is about 3% lower than one without structural modifications. Also, the operational optimization for part-load achieves energy savings by 2–3% in NGCC and 3–5% in coal-fired power plant.

1. Introduction

Industrial power plants burning fossil fuels, such as coal and natural gas, produce large amounts of carbon dioxide (CO_2) emissions, having a great effect on the global warming. Demand for energy has been considerably increased due to worldwide economic growth and development and hence reducing CO_2 emissions from power plants has become one of major issues for achieving sustainable development over the last decade [1].

Carbon Capture and Storage (CCS) is considered as one of key technologies for minimizing CO_2 emissions from process industry. CCS refers the process of removing the CO_2 released into the atmosphere and transporting the captured CO_2 to a storage or conversion. Although the world's electricity demand is expected to increase for future and CCS is considered as one of key options for reducing CO_2 emissions [2], attentions have been paid to minimize potential economic burdens associated with the introduction of CCS to the power industry and hence to reduce energy efficiency penalty on the power plants and/or cost of CO_2 avoided on the capture plant [3].

Methods for CCS are in general categorized as pre-combustion, oxy-fuel combustion and post-combustion technologies. Among these, the post-combustion CO_2 capture process using chemical absorption has become one of the most promising and mature capture methods to remove CO_2 from the flue gases produced by fossil fuel power plants. This option can be implemented without modification of existing configuration of power plants for the retrofit [4]. Since the CO_2 partial pressure in exhaust gases is relatively low, a chemical reaction is favored for post-combustion capture processes, in terms of efficiently and economically removing CO_2 [5]. Furthermore, amine solvents, such as monoethanolamine (MEA), are commercially available for capturing CO_2 from the flue gases, due to relatively fast absorption rate and high purity of CO_2 recovered [6]. However, one of main drawbacks of chemical absorption for CO_2 capture from power plant is a large amount of heat required for solvent regeneration and the large amine solution flow rate needed for CO_2 Capture [7].

It is widely believed that the main challenge for the development of amine-based CO_2 capture technologies is to reduce energy consumption for solvent regeneration. In order to improve energy

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efficiency of and reduce costs of CO_2 capture, a large number of studies have been carried out, which are mainly focused on the use of alternative solvents [8], the evaluation of degradation performance [9], or process modifications with parameter optimization [10]. Damartzis et al. [11] focus on the systematic evaluation of amine solvents/flowsheet structures combinations for the efficient CO_2 capture. Also, the process optimization of amine-based CO_2 capture was carried out by superstructure-based approach using multiple process modifications [12], leading to greater energy savings.

When post-combustion CCS technologies are implemented to power plants, the CO_2 capture unit is typically integrated with power plants in order to extract steam from power plant steam cycle and use steam for capture process (e.g. regenerating solvent), which results in considerable penalty in power generation efficiency for power plants [13]. However, for most of studies carried out for CO_2 capture processes, fixed flue gas conditions operating at steady-state and full working load conditions have been taken [14], and accordingly the performance of CO_2 capture unit has been evaluated at full gas load of power plants [15], although flexible operation could have significant impacts on energy efficiency and economics of CO_2 capture. Previous studies also assumed constant CO_2 emissions rates for natural gas-fired or coal-fired power plants, and are based on fixed emissions reduction targets [16].

As power plants usually operate with different working loads to satisfy changing electricity demand, it is necessary to understand the part-load performance of CO_2 capture unit and analyses its impact on capture cost and energy consumption. The coal-fired power plants are expected to be operated in part load environment further in the future than in the past, due to the introduction of renewable electricity sources to the grid as well as implementation of stricter environmental regulations [17]. In the meantime, natural gas (NG) is the second largest fossil fuel used in conventional power industry, following coal and is expected to play an important role in electricity generation in the world [18]. The existing power plants will be more frequently operated in part load, because its operation is subject to fluctuating supply and demand of electricity under smart grid environment.

On the other hand, power plants are typically designed to achieve maximum energy efficiency at full working load and CO_2 capture processes are also designed to achieve optimized performance for CO_2 removal at fixed flue gas flowrate. Hence, it is of great significance to investigate the part-load performance of CO_2 capture plant, because operating at other loads than full working load leads to a certain degree of penalty in the energy efficiency and separation performance. Ideally, post-combustion CO_2 capture processes should be designed and optimized such that the process can be operated at different working loads in a cost-effective manner.

Efforts have been being made to develop the flexible operation of capture units in order to improve energy efficiency and the economics power plants [19]. Several studies on operating strategies for flexible operation of CO_2 capture units in literature have been reported, including investigation of a dynamic performance in terms of various electricity demand [20]. A rigorous dynamic model was developed to evaluate the performance of retrofitted system [21], but not including the effect of flue gas variations in CO_2 capture plant [22]. On the other hand, Chalmers and Gibbins [23] have proposed two flexible operating methods for post-combustion CO_2 capture units. One is venting flue gas directly into the atmosphere, which is referred to as capture by-pass, the other is installing solvent storages to delay solvent regeneration. These studies showed the results of evaluation on performance of overall CCS power plants, subject to part-load behavior, which focused on reducing the energy penalty and the cost of CO_2 emissions against electricity demand and price.

Steady-state models can be applied to predict part-load performance and behavior for post-combustion CO_2 capture process [13]. As seen in previous literature, the part-load performance of a coal-fired power plant with CO_2 capture process has been analyzed and evaluated at different steam conditions to the reboiler using steady-state process model [17]. With the aid of steady-state models, the influence of a reduced turbine load on total plant efficiency was investigated for a natural gas combined cycle (NGCC) power plant integrated with an MEA-based CO_2 capture was investigated with regards to the total plant efficiency [24].

The aim of this study is to evaluate the performance of amine-based CO_2 capture process with a reduced operating load of power plant and investigate the optimal operating strategy for improving the process efficiency of the capture plant at the part-load.

The power plant models for part-load analysis in the context of CCS implementation have been considered in both NGCC (Natural Gas-fired Combined Cycle) and coal-fired plant as shown in Fig. 1. Natural gas combined cycle (NGCC) power plant has two integrated thermal cycles, which consists of a gas turbine cycle and a steam cycle. The gas turbine cycle is operating in a higher temperature range than the steam cycle is. Air is compressed in the compressor, which is then burned with the fuel (natural gas) to produce a hot gas in the combustion chamber. The natural gas feed can be preheated before the combustion and the burned gas is expanded in the gas turbine which generates power. In a steam cycle, a Heat

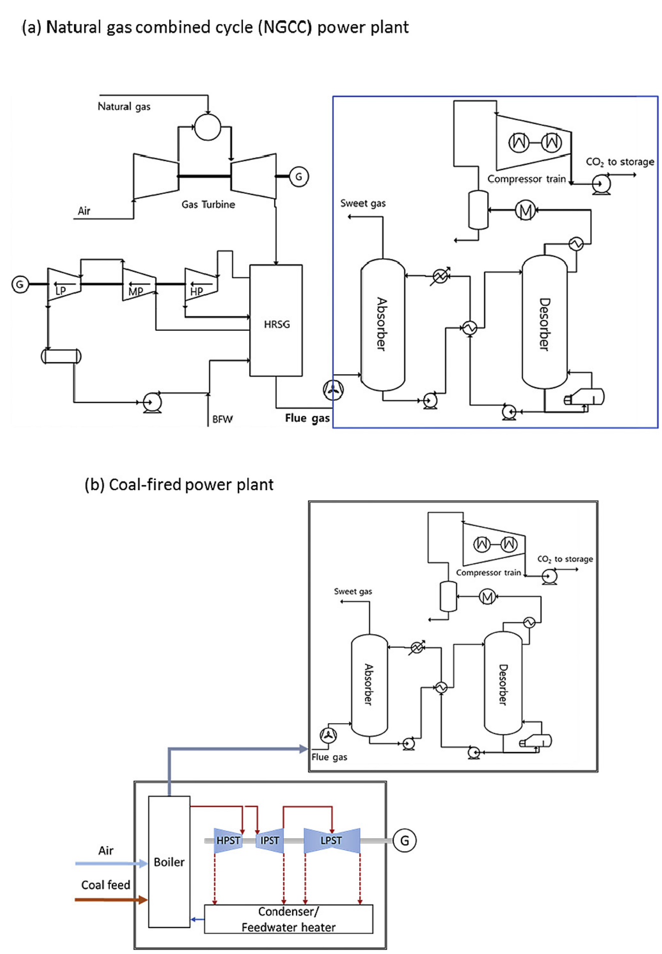

Fig. 1. A simplified diagram for conventional power plant integrated with post-combustion CO_2 capture.

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