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Heat integration of natural gas combined cycle power plant integrated with post-combustion CO_2 capture and compression

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HIGHLIGHTS

- Steady state simulation of natural gas combined cycle (NGCC) power plant.
- NGCC power plant with exhaust gas recirculation (EGR) to increase CO_2 concentration in flue gas.
- Steady state simulation of post-combustion carbon capture (PCC) process and CO_2 compression train.
- Advanced supersonic shock wave compressor used for the CO_2 compression.
- Heat integration of NGCC with EGR, PCC and CO_2 compressors to improve thermal efficiency.

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ABSTRACT

Carbon capture for fossil fuel power generation draws an increasing attention because of significant challenges of global climate change. This study aims to explore the integration of a 453 MW_e natural gas combined cycle (NGCC) power plant with an MEA-based post-combustion carbon capture (PCC) process and CO_2 compression train. The steady state models of the NGCC power plant, the PCC process and compression train were developed using Aspen Plus® and were validated with the published data and experimental data. The interfaces between NGCC and PCC were discussed. Exhaust gas recirculation (EGR) was also investigated. With EGR, a great size reduction of the absorber and the stripper was achieved. An advanced supersonic shock wave compressor was adopted for the CO_2 compression and its heat integration was studied. The case study shows net efficiency based on low heating value (LHV) decreases from 58.74% to 49.76% when the NGCC power plant is integrated with the PCC process and compression. Addition of EGR improves the net efficiency to 49.93% and two compression heat integration options help to improve the net efficiency to 50.25% and 50.47% respectively. This study indicates NGCC including EGR integrated with PCC and supersonic shock wave compression with new heat integration opportunity would be the future direction of carbon capture deployment for NGCC power plant.

1. Introduction

1.1. Background

Greenhouse gas emission may contribute to serious global warming issue and carbon dioxide (CO_2) is a main anthropogenic greenhouse gas. Thus reducing CO_2 emission is vital to achieve the target of limiting average global temperature increase to 2 °C in 2050 [1]. Power generation from fossil fuel (e.g. coal and natural gas) fired power plants is the single largest source of CO_2 emissions [2]. However with the increasing energy consumption requirement, fossil energy is projected to remain a major source of energy in the near future. Gas-fired power generation currently accounts for around 20% of global electricity production capacity [3]. The advent of cheap natural gas provides chances for more NGCC power plants to be built especially in the developed countries.

For NGCC power plants, net LHV efficiency is able to achieve close to 60% whilst the CO_2 per unit electricity generated is only about half of the coal-fired power plant. The blue map of IEAGHG (see Fig. 1) [4] shows NGCC equipped with carbon capture will contribute 5% electricity supply in 2050 to achieve the target of CO_2 emission control. Regarding the technology selection of carbon capture, MEA-based post-combustion chemical absorption is the most likely technology to be implemented for carbon capture from fossil fuel power plants [5,6]. But two main barriers of carbon

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capture process deployment at the full commercial scale are: (a) its massive capital cost; (b) high thermal energy penalty. The cost of electricity will increase from £66 to £144.1 per MW h for NGCC power plant integrated with PCC plant [7]. Considering the great number of power consumption, it is a great cost increment for both industry production and living expense. Therefore potential improvements are needed to reduce the capital investment and the energy penalty to gain a better economic profile of carbon capture process commercial deployment.

1.2. Previous studies

Amine scrubbing, typically using monoethanolamine (MEA) as a solvent, is a proven technology for CO_2 separation from flue gas, but great thermal energy is required for rich solvent regeneration in the stripper [8]. When NGCC power plant is integrated with PCC process, an energy penalty was reported with a reduction of net thermal efficiency of NGCC from 58.5% to 50.6% [9]. This energy penalty is caused by: (1) steam extraction from power plant for solvent generation; (2) power consumption of CO_2 compression and (3) auxiliary power consumption for the PCC process.

The typical thermal energy required to regenerate 1 tonne of CO_2 is between 3.4 GJ and 4.2 GJ [9–13]. Recent research efforts focus on how to improve the PCC process efficiency to reduce its energy requirement. Most early studies are based on a coal-fired power plant. In the study by Abu-Zahra et al. [13], several key parameters such as lean solvent loading, CO_2 capture level, MEA concentration in solvent and stripper operating pressure were examined in the context of a 600 WM_e coal fired power plant. The lean solvent loading was found to have a major effect on the thermal energy requirement. The economic range of lean solvent loading is 0.29–0.32 mol CO_2/mol MEA corresponding to MEA concentration in solvent decreasing from 40 wt% to 30 wt%. High operating pressure in the stripper would lead to a reduction of energy requirement of both solvent regeneration and CO_2 compression. Mac Dowell and Shah [11] conducted a cost optimization study of a capture plant integrated with a 660 MW_e coal fired power plant using dynamic process models. The results showed when the capture level increase from 85% to almost 100%, the optimal energy requirement of per ton of CO_2 decrease from 4.2 to 3.8 GJ with optimal lean solvent loading 0.22–0.18 mol CO_2/mol MEA, which is obviously lower than the result of Abu-Zahra et al. [13]. The results and insights obtained from those studies provide a good base for the later researches on PCC process.

The captured CO_2 needs to be pressurized to 100–150 bar for pipeline transportation and geologic sequestration normally by a multistage compression train. The CO_2 compression train is not only an expensive equipment but also a big power consumer [14]. Witkowski et al. [15] dissected the power requirements of different configurations of CO_2 compression train are from 57.8 to 31.3 MW_e for a capture-ready 900 MW_e hard coal-fired power plant. Compared with coal fired power plants, NGCC power plants emit about half CO_2 per unit electricity output. But energy requirements of CO_2 compression are still as high as 11–13.1 MW_e [9,16] for pressurizing the CO_2 captured from 400 to 450 MW_e NGCC power plants to a pressure of 110 bar. Most of this power consumption causes a big temperature increment during the compression process [17]. To recover this heat from compression train as well as other heat sources, Marchioro Ystad et al. [9] investigated a low-temperature Rankine cycle turbine utilizing CO_2 as working fluid. Compared with the base case (no heat recovery), Rankine cycle case achieved 1.62% points net LHV efficiency improvement. One notice is that Rankine cycle turbine system requires a major capital investment. An economic assessment is needed for such a trade-off between the capital cost and energy recovery.

An advanced supersonic shock wave compression technology [18] was developed for the CO_2 compression. The shock wave compression only needs two stages of compression (vs. 6–16 stages for the conventional multi-stage approach) and the potential capital cost saving for compression chain is up to 50% [19]. Another advantage is that the discharge temperature of compressed CO_2 is as high as 246–285 °C [15] due to higher pressure ratio of each stage, providing an opportunity for heat integration between the compression and the steam cycle of power plant to generate more steam for power generation or the stripper reboiler for MEA solvent regeneration in PCC process.

1.3. Aim and novel contributions

This paper aims to evaluate integration options of NGCC power plant with PCC process and compressors to improve the thermal efficiency of the power plant and to reduce the cost of CCS deployment. Servicing this aim, the objectives of this study are: (1) to develop detailed steady state models of NGCC power plant, PCC process and compression process and to conduct model validation with experimental data or published data. (2) To carry out a case study for different integration options, including compression heat integration options, of NGCC power plant with PCC process.

There are three novelties claimed in this study: (1) the study is built upon a better reference NGCC power plant. It employs a triple-pressure with reheat HRSG (heat recovery steam generator) with higher pressure and temperature steams (170 bar/600 °C steam for IP steam turbine and 40 bar/600 °C steam for IP steam turbine), which would be potential operational conditions of new build NGCC power plant by 2020. (2) The study dissected that size reduction of absorber and stripper was achieved by using exhaust gas recirculation (EGR) technology for NGCC integrated with PCC, which contributes to a significant capital cost saving. (3) This study points out the integration option, NGCC with EGR integrated with PCC and supersonic shock wave compression with new heat integration opportunity, would be the future direction of carbon capture deployment for NGCC power plant.

2. Model development

Use of commercial process simulation software package can provide an important base for modelling of such an industrial scale NGCC power plant integrated with a PCC process considering both good accuracy and appropriate computational loading. For modelling of a power plant, some professional software packages such as GE's GateCycle® [20,21] and Thermoflow's GT-Pro® [22,23] offer a good prediction of the plant performance. For PCC process modelling, AspenTech's Aspen Plus® [24,25] and PSE's gPROMS® [26–29] were validated to have a good accuracy after comparing model predictions with experimental data. In this study, the model accuracy of PCC process is key to provide an accurate prediction for the energy performance of the whole system. In the previous works [12,30], a rate-based model of MEA-based PCC process was developed using Aspen Plus® and was validated by experimental data. Considering the integration with PCC process, the model of NGCC power plant in this study was also developed using Aspen Plus® and was validated with the results of GT Pro® of a benchmark IEAGHG report [6] (see Fig. 1).

2.1. NGCC power plant model

A 453 WM_e NGCC reference model with a GE 9351FB gas turbine and a triple-level pressures reheat HRSG was developed using Aspen Plus®. Peng–Robinson [31] with Boston Mathias modifications [32,33] (PR–BM) equation of state (EOS) is used for the gas