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Integration of IGCC and methane reforming process for power generation with CO_2 capture

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ABSTRACT

IGCC is a power generation technology which represents a higher thermal efficiency with large scale implementation of CO_2 capture. In this study, two IGCC process models have been evaluated in terms of both the process performance and economics with CO_2 capture. Case 1 is based on the conventional IGCC process, whereas, case 2 presents an idea of integrating methane reforming process with an IGCC technology. The high enthalpy steam generated during coal slurry gasification process is used to assist the reforming process for H_2 generation. The integration of IGCC with methane reforming process not only supplies the heat required for the endothermic reforming process but also increases the heating value of the resulting syngas. This concept also provides an opportunity for process intensification since shared water gas shift reactors and CO_2 capture units will suffice the process needs. In this study, two design cases have been evaluated in terms of their performance, economics and levelized cost of electricity. The integrated process produces high value syngas by making use of heat available from the gasification process. The results show that by integrating the methane reforming process with the coal based IGCC plant improves the overall performance compared to the standalone process design.

1. Introduction

The rapid growth of industry and population during the last few decades increased both the energy demand and pollution in the world. The conventional electricity and heat generation technologies relies on fossil fuels and accounts for nearly 42% of global CO_2 emissions [1]. Among various fossil fuels, coal and natural gas are widely used for electricity generation and are considered as main sources of greenhouse gas (GHG) emissions. Coal alone accounted for 46% of CO_2 emissions in 2013 and its consumption is expected to increase by 33% in 2035 compared to that in 2009 [2,3]. However, coal fired power plants are also considered as one of the prime source of CO_2 emissions which is a primary cause of global warming. Therefore, power generation systems should be designed in a way to meet the world energy demand while addressing the environmental issues.

The reduction in GHG emissions can be achieved by improving the performance of currently operating power plants along with the development of the renewable energy technologies [4]. Due to an ever increasing energy demand, carbon capture and sequestration (CCS) technologies will also play a vital role in controlling and abating GHG emissions [5]. Currently, the most common power generation technologies include ultra-supercritical pulverized coal (USPC), natural gas combined cycle (NGCC) and integrated gasification and combined cycle (IGCC) power plants. However, the efficiency of power plants tremendously drops with the addition of CCS technology to the system. For an instance, NGCC, USPC and IGCC power plants show an efficiency drop of 7.1%, 11.4% and 9%, respectively with a retrofit of CCS technology [6]. The addition of CCS to existing power plants not only affect the performance but also cause an increase in the cost of electricity (COE). For an example, IGCC, NGCC and USPC offer an increase of 39%, 43% and 78%, respectively in the cost of electricity with an

Abbreviations: AGR, acid gas removal; ASU, air separation unit; ATR, autothermal reforming; CAPEX, capital expenditure; CC, combined cycle; CCS, carbon dioxide capture and storage; CCU, carbon capture and utilization; COE, cost of electricity; DRM, dry reforming of methane; GHG, greenhouse gas; GU, gasification unit; HP, high pressure; HRSG, heat recovery steam generation; IGCC, integrated gasification and combined cycle; IP, intermediate pressure; LCOE, levelized cost of electricity; LP, low pressure; MMCFD, million cubic feet per day; NGCC, natural gas combined cycle; O&M, operation and maintenance; OPEX, operational expenditure; PC, pulverized coal; SE, specific emissions; SMR, steam methane reforming; TIC, total investment cost; USPC, ultra-supercritical pulverized coal; WGSR, water gas shift reactor.

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Nomenclature

MW_e	Mega Watt (electrical)
MWth	Mega Watt (thermal)
MWh	Mega Watt hour
η	Efficiency
M€	Million Euro

addition of a CCS technology [6]. Although, NGCC power plants with CCS have the highest operational efficiencies, yet the increase in COE together with the fluctuating cost of natural gas limits its extensive utilization over the coal based power plants. IGCC has been identified as one of the most viable options among other coal based power plants in terms of lower environmental impacts with the better control on GHG emissions. It offers higher process efficiencies with lower COE compared to the conventional USPC power plants with CCS technologies [7]. Therefore, improving the performance of IGCC process to make them more reliable and sustainable has been under research for the last many decades. Amirabedin et al. [8] evaluated the performance of IGCC power plants using exergy analysis for various type of coals and compared the results in terms of CO_2 emissions. Kawabata et al. [9] proposed an exergy recuperation technique for enhancing the cold gas efficiency of syngas using exhaust heat from steam and gas turbines in the gasification section. Man et al. [10] compared the IGCC power plants in terms of technical, economic and environmental aspects with CCS and CCU (carbon capture and utilization) technologies for reducing the carbon footprint. Gharaie et al. [11] optimized the operating conditions and integrated the utility system with IGCC for maximizing the power generation capacity. Ferguson et al. [12] and Carbo et al. [13] enhanced the IGCC process performance by improving the heat exchanger network design. Urech el al. [14] and Paduran el al. [15] evaluated the specific heat requirements for various solvents (Selexol, Restisol, Purisol, MDEA) used for CO_2 capture and compared their effect on overall IGCC process performance. Similarly, co-gasification of coal with other feed stocks and with an option of poly-generation processes helped in improving the reliability and economics of the process [16–19].

Another technology for syngas generation is the methane reforming process. The most commonly used methane reforming processes include steam reforming (SMR), dry methane reforming (DMR), mixed reforming (SMR + DMR) and auto-thermal reforming (ATR). The selection of a particular reforming technology depends on many considerations such as feedstock, process parameters, catalyst and downstream product quality requirements. Most of the previous studies focused on the standalone modelling and simulation of IGCC and reforming processes for the syngas and power generation. However, little attention has been paid towards their integration in a single process to improve the process performance and/or economics. Process optimization [20,21], intensification [22,23] and integration [24] with the already existing technologies can help in developing a more sustainable energy production systems with CO_2 capture that can improve the process economics in terms of COE. Recently, an integration of IGCC and natural gas reforming processes are gaining a lot of attention for increasing the H_2/CO ratio in the syngas. Qian et al. [25] coupled the coal gasification with tri-reforming process to increase the H_2/CO in the syngas for methanol production. Similarly, Yi et al. [26] performed the techno-economic assessment of integrating coal gasification and DMR processes for enhancing the syngas production which can be used in various poly generation processes. Adams et al. [27] explored the design routes for integrating IGCC with methane reforming processes and compared them in terms of both process performance and economics. It has been further seen that the integration of coal gasification and reforming processes has a potential to enhance the design robustness and process sustainability [27]. Most of the previous studies referring IGCC integration with reforming processes utilized an additional steam and CO_2 to carry out SMR and DMR reactions, respectively. Also, by integrating gasification and reforming process, process intensification opportunities have not been explored in the previous studies. In this study, the conceptual design of integrating IGCC and natural gas reforming process is proposed where the steam in the syngas is utilized to assist the reforming process without an external source. Furthermore, the results obtained from the simulations are also compared with the other existing technologies (UCPC + CCS, NGCC + CCS) in terms of COE. This study includes the techno-economic investigation of proposed process and its comparison with the existing technologies to understand the effect of process intensification on economics. This paper contains five sections. After introduction section, second section briefly explains the conventional IGCC technology and its integration with the natural gas reforming process. The following section discusses the specific techniques used to model each section along with the important plant performance and economic indicators. The next section presents a detailed comparison between case studies in terms of electricity generation capacities, process efficiencies and CO_2 emissions. The last section discusses the economic feasibility with an assessment of levelized cost of electricity (LCOE) with CCS technology.

2. Process description

2.1. Conventional IGCC process with CO_2 capture (Case 1)

IGCC technology is the complex integration of five major unit processes namely gasification unit (GU) to generate syngas, air separation unit (ASU) to provide high purity oxygen, water gas shift reactor (WGSR), acid gas removal (AGR) unit to remove CO_2 and H_2S from the syngas and the combined cycle (CC). The sequential integration of these units is shown in Fig. 1. Among various gasification technologies, entrained flow gasifiers are currently the most advanced type of gasifier that can operate at high temperature (1200–1600 °C) and pressure (20–80 bar) ranges with an ability to handle wide variety of feedstocks (coal, biomass, liquid fuel) [28]. Syngas produced in the gasification unit is at a very high temperature (~1600 °C) and contains high concentration of H_2 and CO. The temperature of the syngas is reduced in the radiant and convective heat exchangers to carry out WGS reactions. The shifted syngas contains acid gases, therefore it is processed through AGR section where most of the CO_2 and H_2S is removed. The separated CO_2 is then further processed and compressed to an elevated pressure for its transport and storage, whereas, H_2S is further treated in a Claus unit to recover elemental sulfur. The syngas leaving from AGR section contains high concentration of H_2 which is directed towards CC section. CC unit itself is an integration of topping gas turbine and bottoming steam turbine sections with a complex heat exchanger network used for electricity and heat generation. The HRSG (heat recovery stream generation) section is a heat exchanger package which is integrated with steam turbines in order to generate HP, IP and LP pressure steam which in turn generates electricity.

2.2. Integration of IGCC with the reforming process (Case 2)

Case 2 presents a process design where an IGCC power plant is integrated with the steam reforming unit to increase the overall power output. In this case, a reforming unit is placed after the gasification unit which is fed with natural gas compressed to the