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Study on a new IGCC (Integrated Gasification Combined Cycle) system with CO_2 capture by integrating MCFC (Molten Carbonate Fuel Cell)

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ABSTRACT

In this paper, a new Integrated Gasification Combined Cycle (IGCC) system with less CO_2 emission by integrating a Molten Carbonate Fuel Cell (MCFC) to capture CO_2 has been proposed. The performance of the new system is compared with other three systems: a conventional IGCC system without CO_2 capture, an IGCC system with pre-combustion capture and an IGCC system with oxy-fuel combustion capture. In addition, the effects of the key parameters of MCFC such as CO_2 utilization factor, fuel utilization factor and the operating temperature of MCFC on the new system performance have been analyzed and compared. The results show that when the CO_2 capture rate is 88%, the efficiency of the new system is about 47.31%, 2.97% higher than that of the IGCC without CO_2 capture, 10.45% higher than the IGCC system with pre-combustion CO_2 capture, and 12.55% higher than the IGCC system with oxy-fuel combustion CO_2 capture. Though the new system has an obvious superiority of thermal performance, its technical economic performance needs be improved with the technical development of MCFC. The research achievements will provide a new way for further study on CO_2 capture from IGCC system with lower energy penalty.

1. Introduction

With the phenomenon of global warming worsening at present, how to reduce the greenhouse gas (especially CO_2 gas) emission has caught an extensive concern of numerous scholars all over the world [1]. The utilization of fossil fuel in conventional power plants is the main reason for a large amount of CO_2 emission. Now, fossil fuels still have a dominant share for the electric power generation, and coal will continue to be the most important fossil fuel in a medium and long term. Hence, improving the energy utilization efficiency of fossil fuel and developing CO_2 capture and storage (CCS) technologies are two major methods to further reduce CO_2 emission [2,3].

It is well known that the Integrated Gasification Combined Cycle (IGCC) is an advanced environmental-friendly coal power generation system. Though it is ever regarded as the cleanest coal-fired power plant, the CO_2 emission cannot be greatly reduced by itself. So how to effectively reduce the CO_2 emission from IGCC system is a main research focus at present [4]. Currently, there are three kinds of typical technological approaches to capture CO_2 from power plants such as pre-combustion CO_2 capture, oxy-fuel combustion CO_2 capture and post-combustion CO_2 capture. Unfortunately, the efficiency drop due to the CO_2 capture is still great and unacceptable. As for the pre-combustion CO_2 capture, as its name suggested, the CO_2 is removed before the fuel combustion. For example, in an IGCC system, after the gasification process, the raw syngas is mainly consisted of H_2 and CO, and the CO can be easily converted to CO_2 through a water-gas shift reaction ($CO + H_2O = CO_2 + H_2$) in a shift reactor. After the reaction, the concentration of CO_2 is remarkably increased (approximately 30%–40%), and the CO_2 with the high concentration can be separated by using a physical or chemical absorption method. Then the rest hydrogen-rich syngas is fed into the combustion chamber. As the shift reactor requires a larger amount of steam, the system net efficiency is reduced by 6–7%. Moreover, both the CO_2 separation and the solvent regeneration process lead to a significant energy loss and the decrease of net system power output [5,6]. The second CO_2 capture method, the oxy-fuel combustion CO_2 capture, avoids the difficulties of CO_2 separation from voluminous flue gas stream by combusting the syngas with the pure oxygen instead of air. The produced flue gas mainly consists of CO_2 and H_2O. At the same time,

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the flue gas is re-circulated to the combustor in order to control the combustion chamber outlet temperature and further increase the CO_2 concentration in the combustion product gas. However, the selection of gas turbine is a key issue, which will make the system investment cost increase greatly. In addition, a large scale production of oxygen will make the economic performance of the system worsen significantly. Compared to the conventional IGCC system without CO_2 capture, the net efficiency of the IGCC system with the oxy-fuel combustion capture method is always reduced about 7–12% [7–9]. The third CO_2 capture option, the post-combustion capture method, can be retrofitted to an existing power plant because it has only a minor impact on the power conversion process. The CO_2 is usually removed by the proven chemical washing processes based on amine solvents. Currently, the chemical absorption technology has already matured in many chemical processes. However, the flue gas is of large volume, low discharge pressure, a large amount of nitrogen content and low CO_2 partial pressure, which leads to a high energy consumption and operating cost. Meanwhile, a lot of steam is required during the solvent regeneration process, which will sharply reduce the power output of the steam system, even result in an efficiency drop of about 10% [10].

As everyone knows, the fuel cell is an electrochemical energy conversion device which can directly convert the chemical energy of fuel into the electricity energy [11–13]. The power generation efficiency of fuel cell is not limited by the Carnot theorem and mainly depends on the change of Gibbs free energy and reaction heat of the chemical reaction [14]. Hence compared with the traditional power generation system, the fuel cell power system has higher power generation efficiency. In addition, the high operating temperature of high temperature fuel cell (HTFC) can further improve the overall system efficiency by the waste heat utilization by a heat recovery steam generator (HRSG). Currently, the HTFC integrated with the traditional power generation system, such as Molten Carbonate Fuel Cell (MCFC), can make the CO_2 gas concentrate during the electrochemical process. And Solid Oxide Fuel Cell (SOFC) can be arranged in hybrid systems with CO_2 capture, because the characteristic of SOFC that fuel is not mixed with air in the SOFC stack leads to the higher CO_2 concentration in the anode outlet gas [15]. Especially the CO_2 gas is required as the reaction gas in the cathode side of MCFC. Therefore, the traditional power generation system with CO_2 capture based on the electrochemical method has become a promising way of CO_2 capture with low energy consumption [16].

Duan et al. proposed three different SOFC hybrid power systems with zero-CO_2 emission (steam injection, CO_2 gas injection and heat exchange layout), and analyzed the performances of each system. Moreover, with the exergy analysis method, the exergy loss distributions of every unit of SOFC hybrid systems with CO_2 capture were studied and the variation rules of exergy loss distributions were revealed. The effects of the main operating parameters on the overall performances of SOFC hybrid systems with CO_2 capture were also investigated. The results show that the zero CO_2 emission SOFC hybrid systems still have higher efficiencies, which only decrease about 3–4% compared with that of the benchmark SOFC hybrid system without CO_2 capture [17]. Jansen et al. studied coal gasification power plants integrated with gas turbines or MCFC without and with CO_2-removal. The energy balances of various system configurations clearly indicate that integrated coal gasification MCFC power plants (IGMCFC) with CO_2-removal have high efficiencies (42–47% LHV (lower heating value)) compared to IGCC power plants with CO_2-removal (33–38% LHV) and that the CO_2-removal is simplified due to the specific properties of the MCFC [18]. Lusardi et al. studied the feasibility of segregating CO_2 from the exhaust of a gas turbine using an MCFC system. With regard to the unreacted gas at the anodic exit, two plants were simulated with the Aspen Plus software: the first one where they were separated from the CO_2-rich stream resulting from the anodic exhaust by a conventional stage of CO_2 separation; and the second one where they were burnt in O_2 to product the additional CO_2 and H_2O. Moreover, these solutions were studied when the MCFC operated at ambient pressure as well as under high pressure. The results show that the suitability of MCFC/GT integration to reduce CO_2 emissions has been demonstrated in any case [19]. Campanari et al. investigated an innovative cycle with the limited CO_2 emission based on the post-combustion capture in a natural gas fired combined cycle power plant, integrated with an MCFC. In the proposed plant, the natural gas combined cycle (NGCC) exhaust gases are sent to an MCFC using gas turbine exhaust gases as the cathode input, and the anode outlet stream is burned in a catalytic combustor with the pure oxygen. The proposed plant can achieve a carbon capture ratio up to 80%. Compared to an NGCC integrated with MCFC plant without CO_2 capture, the efficiency penalty is about 2%, which is about one quarter of the conventional post-combustion capture strategy [20]. Greppi et al. studied the feasibility of operating an MCFC system on an externally-produced syngas. Two configurations are proposed and they share several common traits, but differ in size of micro-turbine, water management, cogeneration and heat recovery arrangement. As a result, the electrical yield is increased from 32% to 43% thanks to an optimally sized micro-turbine, and the thermal and electrical yield are increased from 65% to 88% thanks to the water condensation and recovery [21].

For the IGMCFC power plant proposed in the literature [18], in fact, the gas turbine unit is replaced by MCFC stacks. Two proposed MCFC-GT configurations in the literature [21] are similar to the IGMCFC in the literature [18] in essence, but with different integration methods. Both in the literatures [19] and [20], the MCFC is used to capture CO_2 from the exhaust of gas turbine. In the literature [19], two different methods to segregate CO_2 by using an MCFC system are discussed, and the focus of the simulation is MCFC stack itself. While the integration of NGCC and MCFC is mainly studied in the literature [20], it can be seen that the study on the post-combustion CO_2 capture by integrating MCFC in IGCC is still few. Based on the above researches, a new IGCC system with CO_2 capture by integrating the atmospheric MCFC is proposed in this paper after taking full account of the advantages of both IGCC and MCFC.

2. System descriptions

2.1. The traditional IGCC system without CO_2 capture

The flowchart of the traditional IGCC system without CO_2 capture is shown in Fig. 1. The coal is firstly gasified to the raw syngas in the gasifier using the pure O_2 which is provided by a cryogenic air separation unit (ASU), while the separated nitrogen from ASU enters into the gas turbine combustion chamber after a compression process. The raw syngas is cooled in a raw syngas cooler and removed of the ash of the coal as the slag in a scrubber unit, and then removed of sulfur species in the acid gas removal unit and finally becomes the clean syngas. Then, the clean syngas, which contains mostly of hydrogen and carbon monoxide, is fed to the combustion chamber and combusted in the atmosphere of air. The produced flue gas with high temperature and high pressure expands in a gas turbine and the waste heat from the turbine exhaust gas is recovered in an HRSG to produce the additional power. In addition, the high pressure feed water from the HRSG changes into the saturated steam by the heat released from the raw syngas in the raw syngas cooler.