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Study on a novel pressurized MCFC hybrid system with CO_2 capture

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ABSTRACT

Based on the benchmark pressurized molten carbonate fuel cell hybrid system without CO_2 capture, this paper proposes a novel pressurized molten carbonate fuel cell hybrid system with CO_2 capture. Firstly, the benchmark system is optimized to obtain the optimum fuel cell operating pressure, under the same pressure the performance of the new system is investigated and compared with that of the benchmark system. In addition, the sensitivity and economic performance analyses of the new system are made. Results show the benchmark system can achieve the highest efficiency of 69.34% when the molten carbonate fuel cell operates at 0.6 MPa, under the same operating pressure, the efficiency of the new system is only 0.91% lower than that of the benchmark system when capturing 90% of the emitted CO_2. When the natural gas price is 6.7 $/GJ and the cost of molten carbonate fuel cell is 2700 $/kW, the cost of electricity for the proposed new system is 16.43 cents/kWh. The specific capital cost is still too high, the cost of the molten carbonate fuel cell needs to be further reduced. Achievements from this paper will provide valuable references for capturing CO_2 from molten carbonate fuel cell power system with lower energy consumption.

1. Introduction

Excessive greenhouse gas emissions have caused the serious issue of global warming. The literature [1,2] estimate that by the end of this century the global average temperature will rise by 1.5 °C–4 °C, depending on what measures for controlling the greenhouse gas emission are taken. Because CO_2 is one of the main greenhouse gases, controlling the emission of CO_2 is very significant for alleviating the global warming and maintaining the sustainable development of our society.

Among all the anthropogenic sources of CO_2 emissions, the power generation system that utilizes the fossil fuel occupies a major part. Currently the potential technologies to reduce CO_2 emission are the CO_2 capture and storage (CCS) technologies, of which the CO_2 capture technologies can be divided into three kinds of methods: pre-combustion, oxy-fuel combustion and post-combustion. However, all the three CO_2 capture methods will cause a great decrease of system efficiency. Therefore, many scholars have started to seek a new method for CO_2 capture with the low energy consumption.

As we know, the MCFC (molten carbonate fuel cell) is a very promising power generation technology. Compared with the traditional power generation system, the efficiency of MCFC is far higher as it is not limited by the Carnot cycle and the waste heat from the high temperature exhaust gas can be recovered. In addition, the CO_2 gas is required in the MCFC cathode electrochemical reaction and many traditional power plants will emit the CO_2 gas, therefore the integration of MCFC with the traditional power generation system will provide a new way for CO_2 capture.

Currently, most of the researches on the MCFC focuses on how to use the MCFC as a CO_2 concentrator in flue gases exhausted from different power plants, the unique electrochemical reaction mechanism enables the MCFC to transfer the low concentration CO_2 in the flue gas into the high concentration CO_2, which is beneficial to reduce the energy consumption of CO_2 capture. P. Chiesa [3] investigates an advanced cycle with limited CO_2 emissions based on the integration of MCFC in a natural gas fired combined cycle power plant in order to capture CO_2 from the exhaust gas of the gas turbine. The gas turbine flue gases are used as the cathode feeding gas for an MCFC, where CO_2 is transferred from the cathode to the anode side, concentrating the CO_2 in the anode exhaust, then the stream is cooled in the heat recovery steam generator (HRSG) and

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sent to a cryogenic CO_2 removal section, results show the final electric efficiency is about the same as that of the original combined cycle system (58.7% LHV) when achieving a CO_2 capture ratio of 80%, and the power output increases by about 22%. J. Milewski [4] presents an experimental investigation of using a MCFC to reduce the CO_2 emission from the flue gas of a lignite-fired boiler, in the research the MCFC is placed in the flue gas stream and separates the CO_2 from the cathode side to the anode side, as a result the high-purity CO_2 can be obtained through the condensation of water, the results show that the use of an MCFC can reduce CO_2 emissions by 90% with the 15% additional power. Desideri [5] presents a study of using the MCFC to separate the CO_2 from the cogeneration plant exhaust gas and introduces the cathode recirculation to optimize the performance of the MCFC, results show that in this system the previously set target of 60% CO_2 removal efficiency is achieved and the total cogeneration efficiency is higher than 85%. Spallina [6] studies a possibility of integrating the MCFC with an integrated gasification combined cycle (IGCC) system to capture the CO_2, the syngas produced in a high efficiency Shell gasifier is cleaned and mainly burned in a combustion turbine. The turbine flue gas, rich with O_2 and CO_2, is then used as the oxidant stream for the fuel cell at the cathode side, while the remaining clean syngas is oxidized at the anode side. The results show that the proposed system efficiency is about 46.0–47.1%, 0.1–1.25% less than that of the reference IGCC system, while achieving 58–91% lower specific CO_2 emissions. S. Campanari [7] proposes to place a MCFC system downstream a conventional power plant, feeding the cathode with its exhaust gas with the aim of concentrating and then separating a fraction of the CO_2 otherwise vented, results show the overall net system efficiency including the MCFC output power and gas treatment consumption slightly increases from the original 45% of the simple stream plant to 45.8% of the new plant when achieving a global CO_2 separation efficiency of 77%. The author has also carried out some researches in this field, for example, the literature [8] studies a gas-steam combined cycle system with CO_2 capture by integrating the MCFC, using the MCFC to capture the CO_2 in the gas turbine exhaust gas, in order to further reduce the efficiency penalty of CO_2 capture, the oxygen ion transfer membrane (ITM) is used to provide the required pure O_2 for the afterburner combustion, results show that when the carbon capture ratio reaches to 85%, the efficiency of the new system is about 54.96%, only 0.67% lower than that of the original gas-steam combined cycle system. The literature [9] studies a new IGCC system with CO_2 capture by integrating an atmospheric pressure MCFC, which is based on the use of MCFC for the post-combustion CO_2 capture. The research results show that the new system efficiency is 2.97% higher than that of the IGCC system without CO_2 capture when the CO_2 capture ratio is 88%.

In the above researches, many scholars have discussed about using the MCFC to capture the CO_2 gas in the conventional coal fired power plant exhaust gas [4,7], the NGCC exhaust gas [3,8], the IGCC exhaust gas [6,9] and the cogeneration power plant exhaust gas [5]. However, few scholars have noticed that MCFC power plant itself will also emit the CO_2 gas since it also utilizes the fossil fuels such as the natural gas, moreover, the MCFC generating capacity will increase with the development of the MCFC commercialization, which means the CO_2 emission issue from the MCFC power system will worsen in the future. Hence, it is significant to do some researches on the CO_2 capture of MCFC hybrid system. Since we have studied the CO_2 capture from an atmospheric pressure MCFC hybrid system [10], this paper will focus on the research of a pressurized MCFC hybrid system with CO_2 capture. A pressurized MCFC hybrid system without CO_2 capture is chosen as the benchmark system, by changing the MCFC operating pressure this paper firstly optimizes the thermal performance of the benchmark system and obtains the optimum MCFC operating pressure. Under the optimum MCFC operating pressure, a pressurized MCFC hybrid new system with CO_2 capture is proposed. Different from the system proposed in the references [5,10] which operates at the atmospheric pressure, the new system in this paper that operates at a high pressure puts a ASU and oxyfuel combustor system at the cell anode outlet, the oxyfuel combustion products are mixture gases of CO_2 and H_2O, part of which recycles to the cathode inlet to provide the CO_2 needed for the cathode reaction, the other part is removed of H_2O after the heat recovery, then part of the pure CO_2 recycles to the afterburner to control the oxy-combustion temperature, the rest CO_2 is compressed and liquefied for storage. In addition, the cathode recycle can provide part of the CO_2 needed for the cathode reaction and improve the system CO_2 capture ratio. Finally, the CO_2 recycle can reduce the oxy-fuel combustion temperature as well as improving the system efficiency. The performances of the new system are compared with that of the benchmark system and other different systems with CO_2 capture, in addition, the sensitivity and preliminary economic analyses are also made to further evaluate the performance of the new system.

The originality of this paper lies in the following several aspects:

(1) In the previous papers, most of the MCFC stacks operate under the ambient pressure. This paper investigates and optimized the performance of the pressurized MCFC hybrid power system with CO_2 capture.
(2) Part of the cathode outlet gas is introduced to the afterburner and heated in a special heat exchanger in which the gas has no contact with the fuel and O_2, which avoids the dilution of CO_2 gas.
(3) The combustion gas outlet temperature of the afterburner is kept in a reasonable value by the recycling the part CO_2 gas to the afterburner and heating part of the cathode outlet gas.
(4) The effects of the key parameters on the thermal and economic performances of the proposed system in this paper are revealed.

2. Systems descriptions

2.1. Pressurized MCFC hybrid system without CO_2 capture (benchmark system)

The flowchart of the pressurized MCFC hybrid system without CO_2 capture is shown in Fig. 1. The fuel flows through the compressor1 and then mixes with part of the circulated MCFC anode exhaust gas in the mixer1, then the mixed gases enter into the pre-reformer for reforming, in the pre-reformer the fuel which consists of CH_4, C_2H_6, C_3H_8 and C_4H_{10} reacts with the steam H_2O to produce CO and H_2, part of the CO gas will react with the steam H_2O and the final production gases are CO_2 and H_2, as shown in Eqs. (1) and (2), then the reformed gases (mainly H_2) react with the carbonate ions (CO_3^{2-}) for the electrochemical reaction. The air flows through the compressor2 and then mixes with part of the afterburner exhaust gas in the mixer2, and then the mixed gases enter into the MCFC cathode. The electrochemical reaction takes place in the MCFC stack and the electricity is generated and output through the DC/AC converter. The anode exhaust gas is split into two parts by the spliter1: one part circulates to the mixer1 to preheat the fuel and adjust the steam/carbon ratio, the other part is sent to the afterburner for combustion together with the cathode exhaust gas. The afterburner exhaust gas is split into two parts: one part circulates to the mixer2 to preheat the air and provide the needed CO_2 for cathode reaction, the other part expands in the turbine1 and then enters into the heat recovery steam generator (HRSG) to recover the waste heat and produce the steam for steam turbine,