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Study on the performance of coal-fired power plant integrated with Ca-looping CO_2 capture system with recarbonation process

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ABSTRACT

This paper studies the performance of a coal-fired power plant integrated with Ca-looping CO_2 capture system with recarbonation process. The Ca-looping CO_2 capture system with/without the recarbonation process are simulated using the ASPEN PLUS™ software and integrated in a coal-fired power plant with the net system efficiency of 41.57%. Simulation results of the two systems are compared, and a sensitivity analysis of the key parameters is taken. The results show that, when the CO_2 capture rate is 85%, the net system efficiency of the coal-fired power plant integrated with the traditional Ca-looping CO_2 capture system without recarbonation process is 30.66%. The efficiency penalty is 10.91% compared with that of the benchmark coal-fired power plant without CO_2 capture. While the net efficiency of the coal-fired power plant integrated with the Ca-looping CO_2 capture system with recarbonation process is 34.3% and the efficiency penalty is only 7.27%. The analysis results show that reducing the amounts of both calcium sorbents and the fresh sorbent supplement in cycles can further improve the efficiency of the overall system. The achievements from this paper will provide the valuable reference for the CO_2 capture from the coal-fired power plant with lower energy consumption.

1. Introduction

The excessive emission of greenhouse gases (carbon dioxide, methane etc.) has caused a series of influences on the natural ecosystem and human society living environment [1,2]. And the emission of CO_2 accounts for 60% and will increase year by year. The fossil fuel-fired power plant is the main source of CO_2 emission in the industrial production and therefore reducing the carbon emissions from fossil fuel-fired power plants has become the research focus in recent years [3]. The carbon capture and storage technology (CCS) can directly reduce 80%–95% of the CO_2 emissions from the power plants and the theoretical CO_2 reduction potential is very large. At present, there are three main CO_2 capture technologies in fossil fuel power plants: pre-combustion capture, oxy-fuel combustion and post-combustion capture. The post-combustion capture technology is the most suitable for the existing fossil fuel power plants. Due to its simplicity in principle and high CO_2 capture efficiency, it has a wide adaptability in the existing fossil fuel power plants than the first two kinds of CO_2 capture technologies [4–6]. The amine-based CO_2 capture process has been proved to be an efficient method of post-combustion CO_2 capture technology, but the optimization and large scale utilization still need to be further studied [7]. A Ca-looping CO_2 capture system that uses the CaO as the sorbent to capture CO_2 from the flue gases generated in the existing fossil fuel power plants is an emerging post-combustion CO_2 capture method. Its sorbent materials have a wide distribution and low price, which makes it considered one of the most promising methods of decarbonization [8–10]. However, a key problem of the Ca-looping CO_2 capture system is the decay of the activity of the sorbent with the increase of the cycle number [11]. The hydration of the sorbent particles is proved to be an effective method to activate the CaO sorbent, but the mechanical stability of the particles attenuates a lot and the generation of a large amount of steam increases the energy consumption of the overall system [12]. Kierzkowska A.M [13,14]. tried to use the doping method to improve the performance of CaO-based sorbent, but the result was not ideal. Other improvement methods, such as the synthesis-made $CaO/CaZrO_3$ sorbent, are not suitable for the large scale utilization [15].

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In 2014, M. Elena Diego [16] improved the traditional Ca-looping CO_2 capture system on the base of the existing researches of the literature. He added a recarbonator after the carbonator in a traditional Ca-looping CO_2 capture process. Inside the recarbonator, the sorbent particles from the carbonator react with a high concentration CO_2 stream in order to improve the CO_2 carrying capacity of CaO particles. This method acquired a good result. However, in order to improve the activity of CaO sorbent, the reaction conditions of the recarbonator should be at the high temperature (750–800 °C) and high CO_2 concentration (70% vol/vol), thus the energy consumption of the Ca-looping CO_2 capture system will increase and both the carbonator and recarbonator will produce a large amount of waste heat with high grade.

Many current researches on the Ca-looping CO_2 capture system are limited to investigate the different aspects of the Ca-looping process and the sorbent performance, including the decay in the sorbent capture capacity along the cycle numbers, operating conditions, reaction mechanism with CO_2, improvement methods of the sorbent and experimental results comparison [11–15]. Martinez I, Murillo R studied a Ca-looping system without recarbonation integrated with a new supercritical steam cycle; Ströhle J, Lasheras A. applied two different modeling approaches to the carbonator; Lin S, Kiga T analyzed the energy consumption of the $CaCO_3$ calcination with CO_2 capture [29,34,35]. However, few studies focus on the system integrations with recarbonation process, comparisons or the key parameter sensitive analysis, parameter optimization to improve the overall system efficiency. And the effective heat recovery of the hot gas stream after the decarbonization also needs to be further studied.

This paper makes a comparison study of the Ca-looping CO_2 capture system without recarbonation process and with recarbonation process. With the ASPEN PLUS™ software, the models of the decarbonization system, heat recovery steam generator (HRSG) system and CO_2 compression system are built. The Ca-looping CO_2 capture system with recarbonation process is optimized in order to avoid the additional fuel consumption of the recarbonator. A 600 MW conventional supercritical coal-fired power plant with the net system efficiency of 41.57% is used to integrate with these two kinds of Ca-looping CO_2 capture systems. Two integration systems of the coal-fired power plant with Ca-looping CO_2 capture system with/without recarbonation process are deeply investigated and compared. The effects of the key parameters on the thermal performance of the proposed systems with/without recarbonation process are revealed.

2. Process descriptions

2.1. Process description of the traditional Ca-looping CO_2 capture system (without recarbonation process)

The Ca-looping CO_2 capture system was put forward by Shimizu [17] in 1999. The Ca-looping process relies on the use of lime as a regenerated CO_2 sorbent, which undergoes the consecutive carbonation/calcination process in two fluidized beds (carbonator and calciner). The flowchart of the traditional Ca-looping CO_2 capture system is showed in Fig. 1. The fresh sorbent, including the active CaO, goes into the carbonator to react with the CO_2 gas of the flue gas exhausted from the coal-fired power plant, and forms the $CaCO_3$ with a large amount of reaction heat releasing. The carbonator operates at a temperature around 650 °C. After the carbonation reaction, both the lean CO_2 flue gas and the partially carbonated stream of sorbent particles are transported to a cyclone to separate. The solid matter goes into the calciner to regenerate CaO and be purified. The operating temperature of the calciner is in the range of 880–950 °C, and the calcination reaction is endothermic with the heat provided by the oxy-fuel combustion of coal. Both the $CaCO_3$ from the carbonator and a stream of fresh limestone are calcinated there. A stream of fresh limestone is added into the calciner in order to compensate for the decay of the activity of lime with the increased cycle number of the carbonation/calcination. The reaction equations of both the carbonation and calcination processes are as follows:

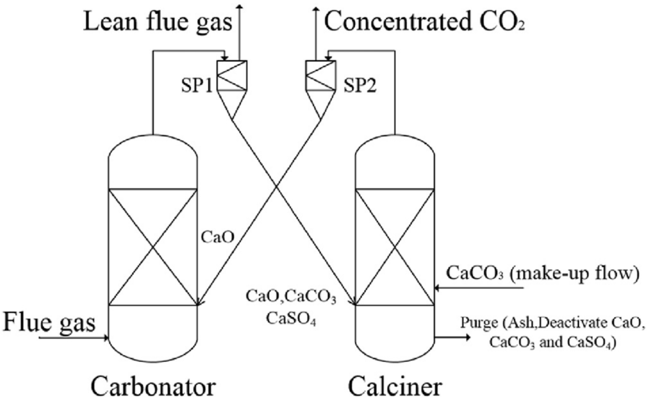

Fig. 1. Flowchart of the traditional Ca-looping CO_2 capture system.

$$CaO + CO_2 \rightarrow CaCO_3 \quad \Delta H = -179.2kJ/mol$$

$$CaCO_3 \rightarrow CaO + CO_2 \quad \Delta H = +179.2kJ/mol$$

2.2. Process description of Ca-looping CO_2 capture system with recarbonation process

M. Elena Diego improved the traditional Ca-looping CO_2 capture system by adding a recarbonator after the original carbonator on the base of the existing research [30–32]. The flowchart of a Ca-looping CO_2 capture system with recarbonation process is showed in Fig. 2. Inside the recarbonator, the sorbent particles from the original carbonator react with a high concentration CO_2 gas stream in order to improve the CO_2 carrying capacity of CaO particles. The recarbonator operates at a temperature around 750–800 °C. The results show that the residual activity of the CaO sorbent among all the cycles increases from 0.07 to 0.16, about twice the original residual activity of the CaO sorbent particles in the traditional Ca-looping CO_2 capture system [16,18–22].

J.M. Valverde et al. [11,23–25] further improved the Ca-looping CO_2 capture system with the recarbonation process. The fresh limestone is firstly pre-calcinated for a long time under the high temperature and a long time (950 °C, 12 h) before entering into the Ca-looping CO_2 capture system (with the recarbonation process). The results showed that this improvement method can lead to an increase of the residual activity of CaO sorbent from 0.12 to 0.37, and the activity still remains in this variation range after hundreds of carbonation/calcination cycle numbers.

3. System modeling

With the ASPEN PLUS™ software, the models of a Ca-looping CO_2 capture system with and without recarbonation process, a heat recovery steam generator system (HRSG) and a CO_2 compression system are built. In order to facilitate the analysis of the system during the simulation, the following assumptions are made: