

Thermodynamic analysis of CO₂ capture by calcium looping process driven by coal and concentrated solar power



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ABSTRACT

Carbon capture for coal-fired power plant draws an increasing attention, due to CO₂ emissions may have an impact on global climate change. Retrofitting existing power plants with post-combustion CO₂ capture using solvent process is one of the most mature carbon capture technologies. However, a significant thermal efficiency drop was observed when integrating coal-fired power plant with post-combustion carbon capture process. Therefore, in this paper, solar energy was introduced to the CO₂ capture process, in order to recover the energy of the capture system. Coal-fired power plant with solar aided CO₂ capture system ((solar + CC) + PP) and solar aided coal-fired power plant with CO₂ capture system ((solar + PP) + CC) were simulated by EBSILON professional and Aspen Plus. Then, energy input, heat recovery, energy penalty and some important evaluate index of these two systems were calculated and compared. Finally, sensitivity analysis were carried out to find the influence of heat recovery efficiency, solar radiation received, purge percentage and CO₂ capture efficiency. The finding indicate that the thermal performance of (solar + CC) + PP is 31.20%, which means that the overall efficiency penalty is 13.44% percentage points; the thermal performance of (solar + PP) + CC is 31.09%, which means that the overall efficiency penalty is 13.57 percentage points. However, considering technical and environmental aspects, (solar + PP) + CC is better than (solar + CC) + PP. Electricity consumption for CO₂ compression accounts for the biggest proportion, over 70%, and electricity consumption for the air separation unit takes the second position.

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1. Introduction

With the rapid development of the industry, the consumption of fossil fuels such as coal is increasing, and the CO₂ and other greenhouse gases emitted by fossil fuels have serious damage to the ecological environment and human society [1]. To adopt energy-saving and emission-reduction policies are important measures to control and reduce the CO₂ emissions from fossil fuel. What's more, power generation from coal produces more than 40% of the global anthropogenic CO₂ emissions to the atmosphere [2]. Therefore, in order to realize large-scale CO₂ emission reduction targets, coal-fired power plants should be put to an important position.

Carbon capture and storage (CCS) technology, which is considered as a feasible future option that contains CO₂ emissions to the atmosphere, refers to collect and store the CO₂ produced by power plants using a variety of methods in order to avoid its emission into the atmosphere [3]. CCS can be categorized into post-

combustion capture, pre-combustion capture and oxy-fuel capture [4,5]. The post-combustion technology is the most widespread and adopted approach due to it can be easily applied to existing power plants, so a number of researchers have investigated various post-combustion CO₂ capture sorbent in the recent years [3,6–10], such as monoethanolamine, alkanolamine, polyethyleneimine-based solid sorbent, ionic liquid, CaO/CaCO₃. Out of these, monoethanolamine (MEA)-based processes have been proved commercially for post-combustion CO₂ capture systems, but the overall power generation system efficiency decrease is relatively high during plant operation. Numerous scholars focused their study on the CO₂ capture unit itself [11–14], in order to reduce the energy consumption of the CO₂ capture process.

Another emerging method for mid-term applications of post-combustion capture technology is the carbonation-calcination (Ca-looping) process. Ca-looping process [15] is based on sorbent properties of CaO to react with CO₂ at high temperatures (500–650 °C) by forming CaCO₃. Then the CaCO₃ is decomposed back to CaO and CO₂ in a calcination reactor where heat must be provided for the endothermic reaction. The temperature in the calcination reactor is about 850–950 °C. The calcium sorbent then

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regenerates through the cycle and a concentrated CO_2 is ready for sequestration. The main advantage of Ca-looping process over an MEA-based post-combustion capture system is that the high reactor temperature during CO_2 sorption and sorbent regeneration process. Therefore, the heat of the carbonation reaction can be recovered at high temperature by steam evaporation, which has a positive influence on overall plant energy efficiency. In contrast, in MEA-based cycles, CO_2 capture process is nearly at ambient temperatures and heat of the absorption reaction hardly be recovered but it is released into the environment leading to a higher efficiency penalty. What's more, CaCO_3 source are in abundance, which results in lower operational costs.

Along with a number of fundamental studies focused on the properties of Ca-based sorbent, such as reactivation techniques, reaction kinetics. Valverde et al. explored the influence of CO_2 partial pressure on limestone decarbonation near equilibrium in order to explore the fundamental mechanisms governing the reaction at these conditions. The results suggested that at low CO_2 partial pressures, desorption of CO_2 is fast, but high CO_2 partial pressures and high temperatures hindered desorption of CO_2 [16]. Some researchers studied the limestone, a kind of natural Ca-based sorbent, and the finding indicated that the presence of CO_2 at high concentration in the calcination environment produces a significantly marked drop of conversion for CaO derived from limestone precalcined in air [17–19]. Some lab-scale results indicate that a modification on the operating conditions, within the constraints of the Ca-looping process, could lead to a significant improvement of the CO_2 capture capacity. Ortiz et al. proposed a new carbonator model to determine the CO_2 capture efficiency of the carbonator under different operating conditions. One of important conclusion of their work is that the capture efficiency is improved by increasing the residence time in the carbontor [20]. Grasa et al. reported that the calcium-based sorbent could achieve higher carbonation conversions when the carbonation temperature was between $650\text{ }^\circ\text{C}$ and $720\text{ }^\circ\text{C}$ [21].

Studies on plant modeling and simulation enable researchers to estimate the performance of complete power plants. Vorrias et al. investigated the CO_2 capture process of a 300 MW lignite fired power plant by two software, i.e. Aspen Plus and IPSE Pro, and compared the Ca-looping CO_2 capture process with MEA-based and oxyfuel combustion CO_2 capture methods. Their finding indicated that overall net electrical efficiency of Ca-looping process is 34.09%, while for MEA-based and oxyfuel combustion methods, the number are 31.25% and 33.20%, respectively. What's more, energy penalty of Ca-looping process is 4.96%, which is lower than MEA-based and oxyfuel combustion methods [22]. Hanak et al. compared the performance of the Ca-looping plant against another two technologies – the MEA-based and the chilled ammonia chemical scrubbing processes – using the same reference power plant. The results of the process analysis revealed that the efficiency penalty imposed in the Ca-looping plant retrofit scenario was 6.7–7.9%. Such performance compares favorably to the MEA-based and chilled ammonia scrubbing retrofit scenarios, which have efficiency penalties of 9.5% and 9.0%, respectively [10]. Zhao et al. compared and contrasted Ca-looping against another three promising technologies, which are chilled ammonia, alkali-metal carbonates and membranes, for the post-combustion capture of CO_2 that can be retrofitted to a coal-fired power plant. Ca-looping technology results in the lowest efficiency penalty (4.6%-points) and cost of post-combustion capture (36.3% increase in levelised cost of electricity) [23]. These works confirm the inherent thermodynamic advantages of the Ca-looping concept.

However, from previous studies, it can be concluded that energy penalty and high investment cost are still obstacles to the development of Ca-looping CO_2 capture process. One way to solve this problem is to recover the energy of the capture system by inte-

grating the existing power plant with additional power. Solar energy, a kind of clean energy, can be used to supply the energy for the CO_2 capture process. On the one hand, it can reduce the consumption of fossil fuel. On the other hand, it can reduce the amount of flue gas, so the flow of CaO/CaCO_3 and the energy consumption of CO_2 compress process can be reduced. In this paper, two Ca-looping CO_2 capture system driven by coal and concentrated solar power (CSP) system are investigated, i.e. coal-fired power plant with solar aided CO_2 capture system ((solar + CC) + PP) and solar aided coal-fired power plant with CO_2 capture system ((solar + PP) + CC). This paper aims to analyze and compare the performance of these two complex systems, in order to provide a new way for the realization of low energy consumption of CO_2 capture. Servicing this aim, the contents of this paper are: (1) EBSILON professional and Aspen Plus were used to simulate these two systems. (2) Energy input, heat recovery, energy penalty and some important evaluate index of these two systems were calculated and compared. (3) Sensitivity analysis were carried out to find the influence of heat recovery efficiency, solar radiation received, purge percentage and CO_2 capture efficiency on the system.

2. System descriptions

The basic layout of the Ca-looping CO_2 capture process, coal-fired power plant with solar aided CO_2 capture system and solar aided coal-fired power plant with CO_2 capture system are described in detail in this section.

2.1. Ca-looping CO_2 capture process

The scheme of the process for CO_2 capture using the carbonation-calcination loop of CaO is demonstrated in Fig. 1. The system is mainly composed by carbonator and calciner [24].

The main reaction equations in two containers are as follow:



In the carbonator, CO_2 -rich flue gas reacts with CaO to form CaCO_3 and CO_2 -lean flue gas is discharged from the carbonator after reaction. CaCO_3 coming from the reaction in carbonation and fresh CaCO_3 are carried into calciner to heating together, in order to forming CaO and high concentration of CO_2 . After the heat

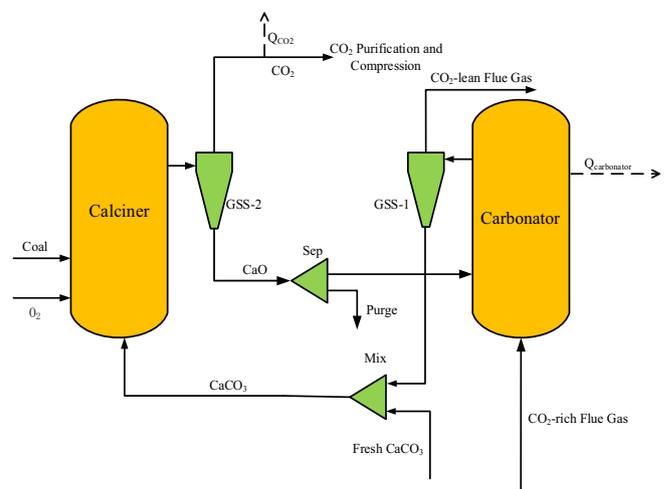


Fig. 1. Scheme of Ca-looping CO_2 capture process.

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