Applied Thermal Engineering 87 (2015) 316–327

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

A new proposed approach for future large-scale de-carbonization coal-fired power plants

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HIGHLIGHTS

- Problems caused by CO_2 capture in the power plant are deeply analyzed.
- An improved design idea for coal-fired power plants with CO_2 capture is proposed.
- Thermodynamic, exergy and techno-economic analyses are quantitatively conducted.
- Energy-saving effects are found in the proposed coal-fired power plant design idea.

ARTICLE INFO

Article history:
Received 20 November 2014
Accepted 3 May 2015
Available online 19 May 2015

Keywords:
Coal-fired power plants
Post-combustion CO_2 capture
Improved design
Thermodynamic analysis
Techno-economic analysis

ABSTRACT

The post-combustion CO_2 capture technology provides a feasible and promising method for large-scale CO_2 capture in coal-fired power plants. However, the large-scale CO_2 capture in conventionally designed coal-fired power plants is confronted with various problems, such as the selection of the steam extraction point and steam parameter mismatch. To resolve these problems, an improved design idea for the future coal-fired power plant with large-scale de-carbonization is proposed. A main characteristic of the proposed design is the adoption of a back-pressure steam turbine, which extracts the suitable steam for CO_2 capture and ensures the stability of the integrated system. A new let-down steam turbine generator is introduced to retrieve the surplus energy from the exhaust steam of the back-pressure steam turbine when CO_2 capture is cut off. Results show that the net plant efficiency of the improved design is 2.56% points higher than that of the conventional one when CO_2 capture ratio reaches 80%. Meanwhile, the net plant efficiency of the improved design maintains the same level to that of the conventional design when CO_2 capture is cut off. Finally, the match between the extracted steam and the heat demand of the reboiler is significantly increased, which solves the steam parameter mismatch problem. The techno-economic analysis indicates that the proposed design is a cost-effective approach for the large-scale CO_2 capture in coal-fired power plants.

1. Introduction

The effects of climate change on the economy have received considerable attention because fossil fuels are expected to provide a large percentage of the energy requirements for human activities in the next decades. China depends heavily on coal-dominant fossil fuels, the growing energy consumption of which results in a large amount of CO_2 emissions. Statistics show that coal-fired power plants supply 77% of the total electricity generation in China, and the resulting CO_2 emissions account for approximately 40% of the total emissions [1]. Thus, reducing the CO_2 emissions of coal-fired power plants is important for the sustainable development and greenhouse gas control in China.

CO_2 emissions from the coal-fired power plants can be reduced by increasing the energy conversion efficiency or by capturing and storing CO_2. Since the existing coal-fired power plants operate under a sound thermodynamic design, CO_2 emissions in the existing power plants are difficult to reduce by increasing energy conversion efficiency. Recently, CO_2 capture and storage (CCS) technology is considered a feasible method for large-scale CO_2 capture [2]. Among various CCS technologies, CO_2 capture by wet chemical absorption is considered one of the most developed

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http://dx.doi.org/10.1016/j.applthermaleng.2015.05.025
1359-4311/

Nomenclature

CCS	carbon capture and storage
COE	cost of electricity
CRF	capital recovery factor
ESP	electrostatic precipitator
FGD	flue gas desulfurization
HE	heat exchanger
HP	high-pressure
IP	intermediate-pressure
IPCC	intergovernmental panel on climate change
KS-1	hindered amine Kansai-1
LCA	life cycle assessment
LHV	low heating value
LP	low-pressure
LSTG	let-down steam turbine generator
MEA	monoethanolamine
O&M	operation and maintenance
PCC	post-combustion capture
SCR	selective catalytic reduction
SPI	special plant investment
TPI	total plant investment

approaches. Several CO_2 capture projects have been conducted based on the wet chemical absorption technology [3–5]. However, such technology still faces the following difficulties: (1) The large amount of energy consumption caused by CO_2 capture significantly decreases the overall efficiency of the power plant, and considerable energy is wasted by amine degradation [6]; (2) The scale of the existing CO_2 capture projects is insufficient for direct application to the large-scale de-carbonization retrofitting of coal-fired power plants. For example, the CO_2 capture ratio in the existing CO_2 capture projects accounts for only 0.5%–10% [2,5]. Accordingly, the IPCC special report emphasized that CCS is yet to be widely applied to fossil-fuel power plants and large-scale CO_2 capture process must be studied in detail [7].

Many scholars exerted considerable effort to decrease the energy penalty caused by CO_2 capture. Some researches focused on the CO_2 capture process itself by proposing new absorbents. For instance, Oexmann et al. proposed a CO_2 capture process for the chemical absorption of CO_2 by piperazine-promoted potassium carbonate with the subsequent CO_2-compression train [8]. Korre adopted the life-cycle assessment (LCA) model to investigate the performance of KS-1 in CO_2 capture. A detailed comparison between KS-1 and MEA was elaborated [9]. Other researchers studied the parameter optimization of the CO_2 capture process [10–12]. Meanwhile, some researchers explored the influence of the CO_2 capture process on the thermal performance of coal-fired power plants [13–15]. The integration of the CO_2 capture process into existing coal-fired power plants was also investigated [16].

The abovementioned studies provide valuable ideas for the application of the CO_2 capture process. However, most of these studies were conducted based on the conventional design of coal-fired power plant. The conventional coal-fired power plant is designed without considering large-scale CO_2 capture. Thus, many special problems will be confronted during the large-scale de-carbonization retrofitting of coal-fired power plants. For example, identifying the area from which a huge amount of steam is extracted for the CO_2 capture process is a critical issue. Moreover, the connection of CO_2 capture is bound to have a negative effect on power plant operation because the extracted steam accounts for a large proportion of the steam turbine system.

This paper proposes an improved design idea for the future coal-fired power plant by considering large-scale CO_2 capture in relation to the abovementioned factors. The proposed design can realize the following targets: (1) Efficiently solves the parameter mismatch problem between the extracted steam and the heat demand of the reboiler by adopting a back-pressure steam turbine; (2) The surplus energy from the exhaust steam of the back-pressure steam turbine is recovered by the added let-down steam turbine generator (LSTG) when CO_2 capture is cut off; (3) Can provide a feasible and cost-effective means for the large-scale CO_2 capture in the future coal-fired power plant.

2. Typical power plant with CO_2 capture under the conventional design idea

2.1. Reference power plant without CO_2 capture

A typical coal-fired power plant with ultra-supercritical parameters is selected as the reference system in this paper. The steam–water cycle of the selected power plant has an eight-stage extraction process, including three-stage high-pressure regenerative heaters, four-stage low-pressure regenerative heaters, and one de-aerator. The steam turbines consist of high-pressure (HP), intermediate-pressure (IP), and low-pressure (LP) turbines, which are connected to the generator with a common shaft. The exhaust steam of the HP turbine is returned to the boiler for reheating and then sent to the IP turbine. The exhaust steam from the IP turbine passes through the two-cylinder/four-exhaust LP turbines and flows into the condenser. The condensed water is heated by eight regenerative heaters prior to the boiler for recycling, thermal energy is supplied by the steam extraction from different turbine cylinders. Schematic diagram of the reference system is shown in Fig. 1.

The pressure, temperature, and flow rate of the main steam that enters the HP turbine are 26.25 MPa, 600 °C, and 2707.3 t/h, respectively. Meanwhile, the pressure, temperature, and flow rate of the reheat steam sent to the IP turbine are 5 MPa, 600 °C, and 2290.5 t/h. The exhaust parameters of the condenser are 5.75 kPa and 35.41 °C. The overall performance of the reference power plant and that of the regenerative system are summarized in Tables 1 and 2, respectively. Obviously, the conventional coal-fired power plant is designed with high initial steam parameters and low exhaust parameters, which aim at achieving high thermal efficiency. However, the conventional coal-fired power plant was not designed to be retrofitted with CO_2 post-combustion capture (PCC) and has tended to be disregarded as suitable candidate for large-scale carbon capture [17].

2.2. The integration of the conventional power plant with CO_2 capture

Fig. 2 shows an integrated scheme of the coal-fired power plant with CO_2 capture by using monoethanolamine (MEA). The diagram on the left illustrates the steam–water cycle of the coal-fired power plant. Meanwhile, the right diagram depicts a typical MEA-based CO_2 capture process [18].

For the MEA-based CO_2 capture process, after leaving the desulphurization unit, the flue gas is compressed by a booster fan to the absorber column and reacts with the MEA solution. The treated flue gas released from the absorber is directly vented to the atmosphere. The rich amine solution, chemically combined with CO_2, attained at the bottom of absorber is delivered to the stripper after a lean-rich heat exchanger. The rich amine solution then enters the stripper and is heated to desorb CO_2. The desorbed CO_2 is cooled to remove the moisture in the CO_2 condenser on top of the stripper and is further compressed and cooled to a level that meets the requirements for transport and storage. The lean amine solution