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Research Paper

Thermodynamic analysis and economic evaluation of a 1000 MW bituminous coal fired power plant incorporating low-temperature pre-drying (LTPD)

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HIGHLIGHTS

- An improved design of coal pre-drying using flue gas waste heat was proposed.
- 0.4% energy efficiency increase was achieved with the proposed system.
- The additional net economic benefit of the proposed system is $1.91 M per year.
- Proposed concept can be widely applied to improve coal-fired power plant efficiency.

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ABSTRACT

Low-temperature pre-drying (LTPD) of lignite has been identified as an effective approach to improve the efficiency of lignite fired power plants. In this study, an improved concept for the pre-drying of medium moisture bituminous coals using flue gas waste heat was proposed and its feasibility was assessed. In the proposed configuration, the boiler exhaust flue gas is drawn to dryers to heat and pre-dry the raw coal, removing a large proportion of the coal moisture and leading to an improvement in the energy efficiency of the power plant. Thermodynamic analysis and economic evaluation were performed based on a typical 1000 MW bituminous coal fired power plant incorporating the proposed LTPD concept. The results showed that the net power plant efficiency gain is as much as 0.4 percentage point with additional net power output of 9.3 MW as compared to the reference plant without coal pre-drying. This was attributed to the reduction in the moisture content from 10.3 to 2.7 wt%. The additional net economic benefit attained due to the coal pre-drying was estimated to reach $1.91 M per year. This work provides a broadly applicable and economically feasible approach to further improve the energy efficiency of power plants firing coals with medium moisture contents.

1. Introduction

Coal-fired power generation provides over 40% of global electricity supply and is expected to continue to play a key role in the future global energy mix in the foreseeable future [1]. However, the large greenhouse gas (GHG) emissions per unit electric power generated will inevitably weaken the competitiveness of coal-fired power plants as compared to other fuel options, such as natural gas, for power generation [2]. One option to improve the competitiveness of coal-fired power plants is to increase the energy efficiency [3], which could both lessen the impacts on the environment and increase the economic viability, particularly for developing countries where electric power consumption is rapidly rising [4].

Energy efficiency improvements for coal-fired power plants can be reached by using existing equipment refurbishment [1] or incorporating higher steam parameters of 700 °C with double reheat steam cycle [5]. However, these process variants often imply high investment costs due to the revamping and/or reconstruction of the facilities [6] or using nickel-based alloys with extremely high price [7]. Currently, waste heat recovery is considered as another alternative to improve power plant efficiency, and the most widely used is installing a specially design heat exchanger to preheat the condensed water from the steam Rankine cycles, leading to a reduced flow rate of steam bleeds from the low-pressure steam turbine and a corresponding improvement in the overall energy efficiency [8]. However, a large capital equipment expenditure may incur and will largely offset the benefit brought about by the energy efficiency

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enhancement, thus limiting the wide implementation of this technology. Accordingly, it seems to be approaching a bottleneck to further improve the energy efficiency of coal-fired power plants using the current technologies.

Lignite pre-drying technology, which is increasingly incorporated in many newly built lignite-fired power plants to guarantee the milling output as well as to improve the lignite combustion performance by reducing fuel moisture content, has also been demonstrated as an effective technology to improve the plant efficiency [9]. Compared to the commonly used hot flue gas pre-drying at a temperature range of 800–1000 °C, the pre-drying process operating in a low temperature range and generally using low-grade heat as the drying medium is termed as low-temperature pre-drying (LTPD), naturally offering better thermodynamic performance. The concept of the LTPD using waste heat of circulation water has been successfully demonstrated in a 550 MW Coal Creek power plant in the United States with a unit performance improvement of 2.6–2.8% by removing the moisture content from 37.5 to 31.4 wt% [10]. Recently, for LTPD using steam as the heat source, an improved LTPD configuration using waste heat from the air-cooling island was proposed in Ref. 11 and an optimized lignite-fired power generation incorporating a supplementary steam cycle to minimize the exergy destruction of the dryers was proposed in Ref. 12.

It may be noted that bituminous coal, which is more widely and efficiently used for power generation, generally features moderate water content in the range of 8–20 wt% [13]. The moisture content will be even higher when the coal particles are exposed to humid atmosphere or during washing. In power plants using these coals, the pulverizing system is commonly used to grind and dry the coal prior to the furnace. However, the moisture of the coal still exists in the pulverizer exhaust gas and will inevitably enter the furnace via the hot primary combustion air. The moisture within the hot primary combustion air will increase the flue gas flow rate in the boiler, resulting in an increase in the exhaust flue gas heat loss and a detrimental effect on the overall efficiency of the power plant. It follows that if the lignite LTPD technology could be applied to the more widely and energetically used bituminous coal fired power plants, the energy efficiencies of these power plants could be improved and the corresponding carbon dioxide emission per unit electric power generated could be reduced and thus powerfully enhances the competitiveness of coal-fired power generation.

Against this backdrop, in the present work, a broadly applicable, effective and economically feasible concept of LTPD of medium moisture coals for power plant efficiency improvement has been proposed. In this concept, a part of the low-grade flue gas waste heat is effectively recovered and beneficially utilized to pre-dry the coal prior to the pulverizing system, leading to a reduced moisture content of the fired coal and a corresponding better thermodynamic and economic performance of the power plant. A case analysis was performed based on a 1000 MW ultra-supercritical power plant firing a bituminous coal to achieve the following objectives: (1) to determine the improvement in energy efficiency of the coal-fired power plant with the proposed LTPD; and (2) to assess the economic performance of the power plant using the proposed design, as compared to a reference power plant of the same raw coal feed rate but without LTPD.

It should be noted that the proposed concept in this study differs from the systems proposed in Refs. 11 and 12. The most two significant differences are: (1) Refs. 11 and 12 focused on the system integration in high moisture lignite pre-drying power plants; however, this study proposed an improved coal pre-drying system for medium moisture coal (represented by bituminous coal) fired power plants; and (2) the heat source for pre-drying bituminous coals came from the exhaust flue gas, while in the systems presented in Refs. 11 and 12, the heat source for drying the lignite came from the steam from the turbines.

2. Design of LTPD for bituminous coal using flue gas waste heat

2.1. Consideration of LTPD for bituminous coals

LTPD has proven to be a thermodynamically effective approach to reduce the moisture content of lignite with high moisture content (25–65 wt%) [14] and thus increase the total boiler heat rate under the constant raw coal feed rate and the overall power plant efficiency [13]. However, some technical and scientific issues should be considered when transplanting the LTPD from lignite to bituminous coal fired power plants.

As for the water type in lignite, the literature [15] showed that approximately 60–70 wt% of water in lignite is free water, which is admixed with the coal and contained in macro pores and interstices, as a result of the porous structure of the lignite. The rest water is classified as the inherent water, which is due to the chemical changes taking place during the maturation of the coal and coalification process. Generally speaking, the ratio of the inherent water to total water decreases as the coal rank increases up to the bituminous coal rank [16], and as such, the ratio of the bulk water to the total water of the bituminous coal may be even higher than that of the lignite. It may be noted that the bulk water and a portion of capillary water of the lignite could be removed easily and rapidly using LTPD at nearly constant drying rate due to the weak adsorption functions between water and coal structures. It is therefore possible to remove a large part of the moisture (all the bulk water and part of the capillary water) of bituminous coals using LTPD with suitable drying facilities.

2.2. Conceptualization

It is well known that coal drying is a highly energy intensive process, requiring a large amount of energy to heat and evaporate the moisture. It is therefore beneficial to dry the coal on-site using waste heat available within the power plants. The LTPD drying concept discussed in Ref. 10 makes use of hot circulation water at ~49 °C leaving from the condenser to dry the coal. During this LTPD process, the final moisture of the lignite could be reduced from 37.5 to 20 wt% by warm air passing through the dryer and a flow of hot circulation water passing through a heat exchanger embedded in the dryer.

In addition to the heat discharged in the condenser, the second large amount of power plant waste heat comes from the exhaust flue gas, accounting for 3–8% of the plant total energy input [17]. Commonly, the exhaust flue gas temperature ranges from 120 to 140 °C and could be reduced from 105 to 95 °C by waste heat recovering. The minimum exhaust flue gas temperature is restricted by the dew point of SO_x to prevent heat exchanger fouling and corrosion [18]. As for the bituminous coal, the moisture content of 8–20 wt% is much less than that of the lignite, and thus, it may be feasible to utilize part of flue gas waste heat to dry the bituminous coal to a relatively low moisture content. Moreover, flue gas with low oxygen content can also reduce the chance of spontaneous combustion and its higher temperature features a greater drying rate than using circulation water from the condenser. Within this coal pre-drying process, the flue gas cools from 120–140 °C to 105–95 °C in the dryer to remove part of the moisture from the raw coal, and thus, a considerable portion of the low-grade energy available in the system can be recovered and utilized. As a result, the boiler available heat input increases under constant raw coal feed rate, leading to an improvement in electric power output and power plant efficiency.