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Exergy analysis of the flue gas pre-dried lignite-fired power system based on the boiler with open pulverizing system

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A B S T R A C T

This paper deals with an exergetic analysis of the flue gas pre-dried lignite-fired power system (FPLPS) based on the boiler with open pulverizing system (OPSB) to explore the energy-saving potential of the FPLPS. A steady-state simulation was performed to obtain thermodynamic properties of process streams in a 600 MW unit. Results indicated that the plant efficiency of the FPLPS was relatively 3.42% higher than that of the conventional lignite-fired power system (CLPS). The improvement benefited from the integration of the flue gas dryer with the OPS, in which the dryer exhaust gas was separated from coal powders and prevented from recycling in the furnace. Consequently, the exergy destruction in the combustion process was reduced by 2.32%-pts for increased flame temperature, and the exergy loss of the boiler exhaust gas was reduced by 0.68%-pts for decreased temperature. Moreover, the dryer exergy efficiency was only 20.20% due to considerable exergy destructions in the moisture evaporation and the mixing of drying agents. The proposed retrofitting option by extracting cold flue gas from the economizer outlet could increase the plant efficiency by 0.33% relatively. Finally, attempts were made to examine the influence of varying pre-drying parameters on system performances.

1. Introduction

Lignite and sub-bituminous coals comprise roughly 1/2 of the world's total coal resources, but their utilization in power generation is limited due to high moisture content, low calorific value, high risk of spontaneous combustion, and high CO_2 emissions. The power generation industry in China, as an example, had the total installed capacity of about 1360.19 GW at the end of year 2014, of which 67.32% (915.69 GW) was supplied by fossil-fired power plants. Lignite accounts for 13% of the total coal resources in China, whereas the capacity provided by large-scale lignite-fired power plants does not exceed 3% (38 GW) of the total installed capacity. Obviously, such a mismatch reflects the plight of lignite utilization. With gradual depletion of high rank coals, the share is expected to rise and a series of low rank coal utilization policies have been promulgated by the Chinese government, which provides most of the impetus to optimize lignite-fired power systems for efficiency enhancement.

The efficient utilization of lignite for power electricity generation sees better prospect due to the concept of lignite pre-drying. Through pre-drying, a portion of moisture in the raw lignite gets removed, and thereby the heating value is elevated. As a matter of fact, many hot streams available in power plants can be utilized as drying heat sources, such as hot flue gas, superheated steam, hot water, and hot air. Accordingly, different drying technologies have been developed to realize the pre-drying of lignite. The recent developments in drying and dewatering techniques for low rank coals were introduced in Ref. [1].

The utilization of low level energy for the pre-drying of lignite realizes the energy cascade utilization in the coal-fired power generation process. So it is an effective method to improve the energy efficiency of lignite power systems. Theoretical studies indicated that PLPSs are characterized by remarkable improvement potential of energy efficiency. The efficiency improvement of the steam pre-dried lignite-fired power systems with and without waste heat recovery was evaluated by Liu et al. [2,3] The comparison between superheated steam fluidized bed drying and air drying was conducted by Hu et al. [4] and Agraniotis et al. [5] Xu et al. proposed a steam lignite pre-drying system with low-level heat integration [6] and an improved configuration of lignite pre-

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drying system using a supplementary steam cycle [7]. Moreover, commercial efforts for pre-drying application in power plants have also been made in many countries which are rich in low-rank-coals to realize the highly-efficient operation and cleaner power generation. The steam rotary drying was applied early in Victoria, Australia. The steam fluidized bed drying (SFBD) underwent extensive testing and development in Australia and Germany between 1990 and 2002. The Loy Yang power plant in Australia applying SFBD with a drying capacity of 55 t h^{-1} was operated for several years [8]. An improvement of the SFBD with internal waste heat utilization (WTA) [9] was achieved by RWE (Rhenish-Westphalian Electric) company in Germany. The application of WTA in the Niederaussem 1000 MW Unit K is a typical case, in which the coal moisture was reduced from 50% to between 10% and 18%, and then the plant thermal efficiency was increased by around 1 percentage point (%-pts) [10]. The WTA technology was also demonstrated at the Hazelwood Power Station in Victoria Australia. A WTA dryer was retrofitted in an existing 200 MW unit to dry 50% of the original feed of high moisture coal to reduce the moisture content from about 60% to 12% [11]. In the USA, the air fluidized bed drying has been tested by GRE (Great River Energy) at the Coal Creek Station's 546 MW unit. The moisture reduction by 8.5% resulted in an average improvement of 0.37%-pts in boiler efficiency (25% fuel being treated) [12]. More recently, pre-drying experimental tests have been carried out in an ultra-supercritical unit of China's Shangdu power plant. Obviously, pre-drying is becoming a sensible choice for efficient utilization of lignite in power plants.

Currently, it is common practice to use flue gas as the drying medium, and the dryer exhaust gas is fed into the boilers directly. Improved mill drying system has been applied in the Megalopoli power plant in Greece and the Elbistan power plant in Turkey, in which part of the evaporated moisture is separated before the fuel is introduced to the furnace [13]. It is of great significance for arid geological areas such as Northwest China since the shortage of water stands in the way of using steam-based or water-based drying and dewatering techniques [1]. So the hot gas-based or air-based drying methods are better options. Ma et al. [14,15] discussed the design parameters of the FPLPS and identified its energy-saving and water-saving potentials. Our previous works [16,17] focused on the thermodynamic characteristics of the FPLPS at design and off-design conditions. The analyses were conducted on the basis of the First Law of Thermodynamics. To the best of author's knowledge, limited information is available in the open literature about the exergy analysis of the FPLPS.

Apart from energy, exergy is also an essential factor to evaluate the potential efficiency of a process. Exergy is defined as the maximum amount of work which can be produced by a stream of matter, heat or work as it comes to equilibrium (thermal, mechanical, and chemical) with a specified reference environment through reversible processes [18]. The exergetic performance analysis based on the Second Law of Thermodynamics has been proved to be an effective and efficient tool in system design and performance optimization in recent decades [19]. The energetic and exergetic performances of coal-fired [20–23] and gas-fired thermal power plants [24–27] have been analyzed by a lot of researchers. According to these studies, the main exergy destructions in coal-fired and gas-fired plants occurred in the boiler and the combustion chamber, respectively. Besides, exergy analysis has been widely used in performance evaluation of advanced power systems, such as CCPP (combined cycle power plant) [28–30], CHP (combined heat and power) [31,32], CCHP (combined cooling, heating and power) [33], ORC (organic Rankine cycle) [34], SOFC (solid oxide fuel cell) [35]. By means of exergy analysis, the location, the magnitude and the sources of thermodynamic inefficiencies in a thermal system could be identified, and thus information for improving the overall efficiency of a system or for comparing the performance of various systems could be provided.

Therefore, the focus of this context lies on the exergy analysis of the FPLPS to explore the energy-saving potential and mechanism of the FPLPS from the perspective of the Second Law of Thermodynamics. To achieve this goal, the exergy analysis model of the FPLPS was developed to calculate the exergy destruction distributions and component exergy efficiencies. Based on the simulation results, the improvement in the plant efficiency of the FPLPS compared with that of the CLPS was identified at the system level. Then the exergy destructions in the subsystems of the FPLPS and the CLPS were compared. Furthermore, optimization proposals were put forward after the determination of the exergy destruction sources in the flue gas dryer. Accordingly, simulations for the retrofitting case were performed to examine the efficiency improvement potential. Finally, a comprehensive performance assessment of the FPLPS was conducted through parametric analysis to investigate the influence of drying parameters on the system performances.

2. Thermodynamic cycle of the FPLPS

Fig. 1 illustrates schematically the layout of the FPLPS, consisting of boiler subsystem, turbine subsystem, and an electrical generator, which is consistent with the system previously investigated in Ref. [16]. The boiler subsystem is characterized by the integration of the OPSB with the flue gas dryer. The dryer exhaust gas, containing a large amount of water vapor, is not recycled to the furnace but led to the heat recovery system, in which the waste heat is utilized to pre-heat the air supply of the OPSB. Apart from the original system configuration (base case), a retrofit configuration is proposed in the present work, in which the cold flue gas extraction point changes from the boiler exhaust to the economizer outlet (retrofitting case).

3. Models and methodology

3.1. Simulation modeling approach

A commercial simulator – GSE software was used to perform steady-state simulations of the FPLPS and obtain thermodynamic properties of the streams in power generation process based on mass and energy balances. The simulation details and model validations have been discussed previously [16].

3.2. Exergetic analysis approach

Exergy is a measure of the potential of a stream to cause change, as a consequence of not being completely stable relative to the reference environment [18]. It is composed of four parts: physical exergy ($\dot{E}_{PH}$), kinetic exergy ($\dot{E}_{KN}$), potential exergy ($\dot{E}_{PT}$), and chemical exergy ($\dot{E}_{CH}$). In the exergy analysis of thermodynamic systems, especially coal-fired power plants, the $\dot{E}_{KN}$ and $\dot{E}_{PT}$, which are related to velocity and elevation, respectively, are often not considered for the negligible changes in the velocity and elevation [36].

The specific physical exergy of the working fluid is generally defined as: (kJ kg^{-1})

$$e_x = (h - h_0) - T_0(s - s_0) \tag{1}$$

where subscript "0" denotes the reference state. In the calculation, the atmospheric pressure and reference state temperature are taken respectively as:

$$p_0 = 101.325 \text{ kpa (1 atm)}, \quad T_0 = 298.15 \text{ K} \tag{2}$$