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Numerical investigation of air-staged combustion emphasizing char gasification and gas temperature deviation in a large-scale, tangentially fired pulverized-coal boiler

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HIGHLIGHTS

- Systematic comparison of various models on simulation under deep air staging.
- Refined char gasification model reasonably predicts the combustion process.
- Significantly higher CO profile in furnace under deep air staging.
- Horse-saddle type distribution of the thermal load for the final super-heater.

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ABSTRACT

A refined char gasification model, successfully validated in a pilot-scale 20 kW down-fired furnace, is now applied to a numerical investigation of the characteristics of the flow, temperature, and species distribution under various air-staged levels of combustion in a 600 MWe tangentially fired (T-fired) pulverized-coal (PC) boiler. The simulation results with char gasification show that the CO concentration profile in both the primary combustion zone and the reduction zone is much higher than the corresponding case without the gasification model for deep (burnout air rate, $f_S = 0.42$), middle ($f_S = 0.30$), and shallow ($f_S = 0.17$) air-staged cases. Moreover, this result is in accordance with the tests from an industrial pulverized-coal-fired furnace. It can be concluded that the char gasification mechanism should be considered in the numerical simulation of large-scale air-staged T-fired PC boilers. On the basis of a reasonable prediction of combustion characteristics, the gas temperature deviation in the crossover pass was also depicted under conditions of various air-staged levels. The result of the thermal load curve of the final super-heater panels clearly presents a saddle-type distribution for the existing two peak values. These inherent deviations originate from the residual swirling flow at the furnace exit. More specifically, parameters of swirling momentum intensity (δ) in the furnace and heat flow intensity (Ψ) at the entry of the final super-heater were employed to identify the temperature deviation in degrees.

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1. Introduction

Tangentially fired pulverized-coal (T-fired PC) boilers are widely employed in the thermal power generation industry. This combustion system can guarantee stable combustion of fuel, wide coal adaptability, and high combustion efficiency. However, some inherent problems related to this combustion mode always exist, especially gas temperature deviation in super-heaters and re-heaters [1–3]. The latest policies on restricting NOx emissions from coal-fired power boilers are stringent. To comply with these policies the overall deep air-staged combustion system (also called a separated over-fire air system) has been adopted for the updating of many old burners in active service. This system was chosen due to its high ability to abate NOx, higher reliability, greater suitability, and lower investment compared to various other low-NOx emission technologies. Previous studies indicated that over-fire air (OFA) operation is an effective way to reduce the NOx emissions of pulverized-coal (PC) fired boilers [4–6]. Zhang et al. [7] developed a numerical model to investigate the influence of horizontal bias combustion (HBC) and air staging combustion (OFA) technologies on NOx emission in a 200 MWe tangentially fired pulverized-coal boiler. Their results showed that the air-staged combustion plays a dominant role in comparison with HBC in terms of NOx

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reduction. Zhang et al. [8] investigated the effect of OFA on NOx emission in a 3 MW pilot-scale T-fired boiler. Simultaneously, the corresponding simulations on the boiler were conducted. The experimental and simulated results were in good agreement and showed that NOx emission decreased as the excess air ratio in the primary combustion zone decreased and residence time in the reduction zone increased, but the carbon content in the fly ash increased at the furnace exit. Recent studies elucidated the chemical reaction mechanisms of coal combustion and nitric oxide formation mechanisms. Specifically, Al-Abbas et al. [9] described the main sources of NOx formation with a model (thermal NO and fuel NO) and performed the experiments in air-firing and oxy-firing conditions on a lab-scale 100 kW Chalmers furnace. Perhaps NOx simulation and measurements under air-staged combustion conditions were not the main concern in the article, and therefore, in the case of air-staged combustion was not arranged to investigate NOx reduction. Hodžić et al. [10] firstly tested the influence on NOx reduction of reburning various fuels in parallel during co-firing of coal with sawdust and natural gas in a 20 kW PC furnace, and in their measurements, NOx reduction efficiency was higher in natural gas reburning.

Though overall air-staged combustion technology has been widely applied in reducing NOx emissions in the last ten years, there is still insufficient theoretical research on this combustion mode. Few studies are focused on the effect of char gasification on the characteristics of the flow, temperature, and species distribution in tangentially fired pulverized-coal boilers under air-staged conditions. These characteristics would exert a significant impact on reduction of NOx [11]. It is widely accepted that char gasification reactions should be considered in oxy-fuel combustion of pulverized fuels [12], but fewer scholars pay major attention to applying gasification reactions in tangentially fired pulverized-coal boilers under air-staged conditions. In conventional simulations of pulverized-coal combustion, the gasification reactions between char and CO_2 or H_2O are not taken into consideration because these reactions are thought to be negligible compared with the primary reaction of char oxidized by O_2. Actually, in the case of air-staged combustion, the partial pressures of CO_2 and H_2O become higher than that of O_2 in the primary combustion zone of the furnace [13]. Especially in the case of deep air-staged combustion, the char gasification reaction with CO_2 or H_2O is more intensive. Taniguchi et al. [14] reported the experimental data and numerical calculations when considering char gasification reactions in a high-temperature tandem-type staged drop-tube where a higher temperature drop occurred in the middle due to its structure. However, CO concentrations were not obtained in their results, which significantly impacted the combustion performance and emission of pollutants.

As the capacity of the T-fired PC boiler increases, the problem of the gas temperature deviation in the crossover pass tends to be more serious. This can result in tube explosions in super-heaters and re-heaters. Many researchers generally agree that the velocity deviation at the exit of furnace plays a dominant role on temperature deviation in the crossover pass where super-heaters and re-heaters are arranged. Xu et al. [15] reported, by simulations and experiments in two utility boilers, that gas temperature deviation originates from the after-twirl and the platen SH, and it could be decreased by decreasing the tangential circle diameter of the secondary air if the flow field was not disturbed. Moreover, other effective ways to alleviate deviation in a horizontal pass for large-scale T-fired boilers were proposed by Yin et al. [16], such as a deeper, higher furnace arch and different arrangements of division platen SH.

This paper presents a numerical study of the importance of a refined char gasification model on combustion characteristics in a 600 MWe tangentially fired pulverized-coal boiler under different degrees of air staging. The numerical models used have been validated against experimental data from a pilot-scale 20 kW down-fired furnace. Meanwhile, the conditions without the gasification model were also compared to present the impact of considering gasification on the accuracy of the prediction of combustion characteristics. Major attention is paid to the CO concentration profile due to a more important role of CO in the combustion reaction and NOx reduction, which significantly impacts the prediction of NOx formation. On the basis of a reasonable prediction of combustion characteristics in the furnace, the gas temperature deviation of the final super-heaters in the horizontal flue was analyzed.

2. Design and operating conditions of the boiler

2.1. Boiler specifications

The boiler considered in this study is a tangentially fired furnace, ultra-supercritical, once-through, single reheat, 600 MWe boiler and is shown schematically in Fig. 1. The height to the furnace exit is approximately 57.5 m, and the horizontal cross section of the furnace has a width of 18.816 m and depth of 18.144 m. The utility boiler has six layers of low NOx concentric firing system (LNCFS) burners with two layers of close-coupled over-fire air (CCOFA) and five layers of separate over-fire air (SOFA) to provide burnout air. The primary air and secondary air from the nozzles installed at the four corners are injected into the furnace center to form two imaginary circles in the furnace center which rotate clockwise. Moreover, as shown in Fig. 2, Concentric Firing Secondary (CFS) air nozzles are biased 22° with respect to the jet direction of the primary air, which generates a stronger oxidizing atmosphere in the area close to the furnace wall and consequently reduces the risk of slagging. Yaw angles of the SOFA and CCOFA can be horizontally varied in the range of ±15°, the function of which is to alleviate the residual swirling flow at the furnace exit. In this paper, the yaw angle is fixed at 0°.

Although twenty-four pulverized-coal burners are installed at the four corners ranging from the lower layer A to the upper layer F, only twenty burners from the upper five layers are on duty under a full-load condition. The idle burners still need to be protected by passing a little cooling air through them. That is to say, this boiler is operated with twenty low-NOx burners working during normal operations. The arrangement of the burners explained above is shown in Fig. 1; CCOFA and SOFA ports are installed above the burners. In the crossover pass of the boiler, there are division super-heaters (SH), platen SH, final SH and two re-heaters (RH) along the gas flow direction. The furnace walls from the hopper inlet to the furnace exit comprise spiral water walls, which minimize the number of tubes as well as ensuring a higher mass flux in the water-wall tubes. The other walls above the furnace are of the vertical water wall type.

2.2. Operating conditions of the boiler

This boiler is designed to use Huainan (HN) bituminous coal. Its basic properties are listed in Table 1. The present calculations are carried out under the practical operating conditions with a boiler load of 100% MCR. The total mass flow rate of coal fired is 267,610 kg/h, and the total air mass flow rate is 2,345,940 kg/h at 617 K with equal flow rates distributed among all burners. In all, 17%, 30%, and 42% of the total air mass are assigned to the OFA ports, respectively. These just represent three cases of different air-staged levels. In each case the CCOFA makes up 10% of the total amount of OFA. The primary air ratio (marked by f_M) means the ratio of all air injected into the primary combustion zone except CCOFA and the total air amount injected into the fur-

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