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Numerical investigation of low NO_x combustion strategies in tangentially-fired coal boilers

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HIGHLIGHTS

- The prediction shows a good agreement with the measurement on-site.
- HBC can reduce the NO_x in the primary combustion zone when there is no air staging.
- The predicted results have shown that OFA has a remarkable reduction of NO_x emission.
- Air staging dominates the integral contribution when combined with HBC burner.
- The lower stoichiometry and unburned char in PCZ contribute to the final NO_x reduction.

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ABSTRACT

A numerical model is developed to investigate the effects of horizontal bias combustion (HBC) and air staging combustion (over-fire air, OFA) technologies on the performance of a 200 MWe tangentially-fired pulverized-coal boiler. The devolatilization rate and volatiles amount are determined by a kinetic devolatilization model, which predicts the coal devolatilization prior to the volatile matter and char combustion. The characteristics of the devolatilization, combustion, heat transfer and NO_x emission are studied and compared to achieve a comprehensive understanding of the low NO_x combustion. The prediction shows a good agreement with the on-site measurement results, which confirms that the model is capable of predicting the characteristics of the investigated boiler. The predicted results have shown that the OFA has a remarkable effect on the reduction of NO_x emission. The HBC makes a significant NO_x reduction in the primary combustion zone (PCZ) when there is no air staging. In terms of the NO_x reduction, the air staging plays a dominant role in comparison with HBC burners. The application of OFA tends to lead to slagging in the PCZ, which can be avoided using HBC due to the higher stoichiometry close to the furnace wall. The details of this study improve the understanding of combustion and NO_x emissions in tangentially-fired pulverized-coal boilers with low NO_x combustion technologies, especially for boilers adopting HBC burners and OFA.

1. Introduction

Pulverized coal will still be a main fossil fuel used by power stations to generate electricity and heat in the coming years, though it is difficult to control pollutants emitted from pulverized-coal boilers. Nitrogen oxide (NO_x) is one of the main pollutants formed during the coal combustion process. Selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) have become the principal methods employed in controlling NO_x emissions. Meanwhile, low NO_x combustion technologies play an important role in reducing NO_x emission on account of their lower capital and maintenance costs.

Normally, low NO_x combustion technologies can be classified into three categories: low NO_x burner, air staging, and fuel staging (reburning). The former two technologies are usually used together to reduce the generation of NO_x during the coal combustion process.

Computational Fluid Dynamics (CFD) is a useful tool to optimize the low NO_x technologies. In addition, proven numerical models are regarded as an important way to improve the understanding of coal combustion and boiler operation, which can otherwise only be achieved through expensive experiment.

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In recent decades, numerous simulation studies related to the flow field, coal combustion and pollutant emissions of boilers have been conducted by many researchers. Gómez et al. [1] and Huang et al. [2] investigated the fluid flow and heat transfer in different boilers. Their predictions in both flow field and heat transfer agreed well with experimental results. In terms of mathematical simulation for pulverized-coal-fired boilers, pyrolysis and combustion are the two main investigated processes. Chaos et al. [3] and Papadikis et al. [4] adopted the rapid pyrolysis process to validate the CFD devolatilization model. Backreedy et al. [5] improved a package for co-firing pulverized coal and biomass. A modeling study carried out by Modlinski [6] was applied to investigate a tangentially-fired furnace with swirl burners. Eddings et al. [7] and Chen et al. [8] predicted the mineral matter coalescence and char burnout in boilers with different capacities, respectively.

The reaction rates of NO and N_2 were determined considering HCN and ammonia as intermediates in the fuel NO mechanism [9]. Homogenous reactions related with volatile nitrogen were studied [10]. It is suggested that the volatile nitrogen yield and the NH_3/HCN ratio strongly affected the NO_x formation. A NO_x index to predict NO_x levels was proposed taking into account the effects of function groups related with coal nitrogen and nitrogen-containing species. The heterogeneous reactions between NO and char were studied over the temperature range of 1250–1750 K by Levy et al. [11], who also investigated the effects of H_2O and CO on the NO emission rate.

As an important part of the post-processing of CFD modeling, the NO_x models studied by De Soete [9], Levy et al. [11] and Smoot and Smith [12] were further developed by Leeds University, UK, and were mentioned in the FLUENT 6.3 User's guide. The NO_x models include three principal NO_x mechanisms: thermal, prompt, and fuel NO_x. The NO_x post-processing was used not only for the general combustion prediction but also for the advanced reburning [13] and oxy-fuel combustion [14].

Based on the validated sub-models, combustion process in a series of boilers has been simulated to predict and optimize the boiler operation and NO_x emission characteristics [15–21]. Choi and Kim [20] and Park et al. [21] investigated the combustion and the NO_x emission performance of a tangential-fired (T-fired) boiler. More studies have been focused on the effect of the wall-fired burner [22–24] rather than the T-fired burner on the reduction of NO_x emissions. A numerical investigation on HBC burners, however, is still lacking. In this paper, T-fired HBC burners, a type of fuel-staging technology, were studied using mathematical modeling. The T-fired HBC burner was originally developed for the anthracite-fired boiler in the late 1980s in China [25], and has been successfully applied to a wide range of boilers with varying boiler capacities and coal characteristics. The aims of this study were to achieve a deeper understanding of combustion and NO_x emissions in T-fired pulverized-coal boilers with low NO_x combustion technologies, and furthermore, to evaluate the performance of different low NO_x control technologies on the reduction of NO_x emissions.

2. Boiler specification

The considered supercritical T-fired boiler with steam conditions of 16.8 MPa/540 °C/540 °C possesses a 670 t/h unit, single reheat steam power cycle and balanced draft. In order to reduce the NO_x emission at the exit, the HBC combustor system in the primary combustion zone (PCZ) consisted of 20 HBC burners in five rows. Only 12 burners in the bottom three rows were taken into service and the cooling air was injected to protect idle burners. The application of the HBC divided the horizontal primary air/coal stream into two substreams with a large difference in the fuel concentration. The two substreams were injected into the furnace from the same elevation with an angle (typically between 0° and 15°) between their axes. The fuel-rich substream formed a higher temperature flame core in the central zone of the furnace, which improved the ignition stability, while the fuel-lean substream generated an outer layer of a more oxidizing atmosphere, blanketing the high temperature flame core, which consequently reduced the risk of slagging in the area close to the furnace wall. The air staging technology was also employed to control the NO_x concentration at a lower level. Partial combustion air was injected through eight OFA nozzles in two rows above the PCZ. Fig. 1 shows the 3-D structure of the simulated boiler. The proximate and ultimate analyses of the used coal are shown in Table 1. According to the Chinese Standard, GB/T 212–2008, the coal sample was heated to 900 °C ± 10 °C for 7 min to test the volatile yield.

3. Numerical analysis procedures

3.1. Domain and mesh system

The calculation domain is considered to be from the hopper to the reheater, including all the primary air and secondary air nozzles. With structured mesh approaches the calculation domain is made of around 5 million hexahedron cells. Three million cells are generated in the hopper and primary combustion zones. The OFA zone contains around 1 million cells. The upper furnace zone, which includes a platen superheater, superheater, and two reheaters, has around 1 million cells.

3.2. Numerical models

3.2.1. Turbulent, radiation and DPM models

The numerical investigation is supported by a commercial computational fluid dynamics code (Ansys FLUENT 6.3.26). The mathematical modeling has been carried out using different Ansys FLUENT versions (e.g. v14), and the modeling results are identical. Therefore, it is reasonable to use FLUENT 6.3.26 in this study. The species transport model is selected to solve the continuous phase equations. The standard k–ε two-equation model is employed for the turbulent modeling and the Discrete Ordinates (DO) model is selected for the radiation modeling. The DO model first developed by Truelove [16] can solve problems ranging from the surface-to-surface radiation to the participating radiation in combustion problems. It is more suitable for calculating the radiation of the boiler furnace wall and the coal particle surface. Hence, the combination of k–ε two-equation model and DO model is capable of simulating the turbulent flow and heat transfer in the industrial flow.

Additionally, the Lagrangian discrete phase model is used to consider the pulverized-coal injection and the mass, momentum, and heat exchange between the discrete and continuous phases. The incompressible ideal gas, mass-weighted mixing law, and weighted-sum-of-gray-gases models are chosen to define the density, viscosity, and absorption coefficient of the gas phase mixture.

The particle size distribution is simulated using the Rosin–Rammler equation. Table 2 lists the key parameters of the Rosin–Rammler function. The mean diameter and spread parameter are decided by testing the coal samples, which gave 82% passing and 98% passing on 75 μm and 150 μm sieves, respectively.

3.2.2. Devolatilization kinetic model

The single-rate and kinetics/diffusion-limited models are selected to predict the devolatilization and combustion processes. In terms of the coal devolatilization and combustion, the proper volatile and fixed char fractions at the high heating rate (approximate 10^4 K/s) play an important role in the prediction of the temperature and flue gas components. The FG-DVC model is employed