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Research Paper

CFD investigation on combustion and NO_x emission characteristics in a 600 MW wall-fired boiler under high temperature and strong reducing atmosphere

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HIGHLIGHTS

- High temperature and strong reducing combustion was realized in unity boiler.
- Deep air stage and mixing O_2 to secondary were used in combination.
- NO_x was reduced by about 60% via the proposed method.
- Simulation results agrees well to the industrial test.

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ABSTRACT

In this paper, a modified air staging technology for pulverized coal boilers was proposed, to notably reduce NO_x emission by creating a zone with high temperature and strong reducing atmosphere (HT&SRA) in furnace. Here, the conventional air staging technology was employed in combination with increasing O_2 fraction of feeding gas in primary zone ($O_{2,p}$). The new technology was numerically verified in a 600 MW wall-fired boiler and the temperature distribution, the char burnout and the effectiveness in NO_x reduction were mainly examined. The results indicate that a sufficiently low stoichiometric O_2 ratio in primary zone (SR_p) is essential to reduce NO_x emission by increasing $O_{2,p}$. The effectiveness in NO_x reduction by increasing $O_{2,p}$ also depends greatly on the injection position of over fire air (OFA). Under the condition of 0.7 SR_p and a relatively high OFA position, the NO_x emission could be reduced by 27.6% when $O_{2,p}$ is increased from 21% to 33%, while the incomplete combustion heat loss only shows a slight rise. In addition, the NO_x reduction ratio could reach to >60% through the proposed low-NO_x combustion technology compared with the current operation condition.

1. Introduction

In China, the NO_x emission from coal-fired power plants have resulted in many serious environmental problems and worsened human health over past few years [1]. As a response to these urgent issues, the regulation against NO_x emission from thermal power plants was revised to be more strict in 2014. According to the latest regulation, the limitation of NO_x emission from pulverized coal boilers is 100 mg/Nm^3 (at 6% O_2) [2–4]. To meet such a strict emission standard, the lower-NO_x combustion technology and the selective catalytic reduction (SCR) technology are usually employed in combination.

Although SCR technology is considered as the most effective approach for NO_x reduction in power plants [5], there still exists a series of unresolved issues involved in operation of SCR. The cost of catalysts and reductants is quite high. The working lifetime of catalysts is short and it could cause secondary pollution to discard the deactivated catalysts [6]. Furthermore, the operation of SCR could accelerate the formation of ammonium bisulfate, which may result in the blocking of air preheater [7]. In addition, the gas temperature in SCR equipment is influenced by the load variation of boiler and it is quite possible that the catalyst works outside of the optimum condition [8,9]. As explained above, SCR technology is not a reliable long-term strategy for NO_x emission control.

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Hence, it is preferred to develop low-NO_x combustion technology to further reduce the initial production of NO_x within furnace. If the production of NO_x within furnace is low enough, the SCR could be disused or replaced by selective non-catalytic reduction, or at least a layer of catalyst can be saved in SCR system. These improvements are all favorable in terms of cost saving and environmental conservation.

The combustion technology of air staging along furnace height is the most widely used method to reduce NO_x production because of the simple structure and facile air distribution system [1,8,9], and it has also been extensively studied both experimentally and numerically during the past few decades. Currently, the air staging technology mainly includes over fire air (OFA) system [10–12], separate over fire air (SOFA) system [13–15], close coupled over fire air (CCOFA) and SOFA system [1] and multi-group SOFA system [2,16], while the former three technologies have been widely used in practice. The previous studies are mainly focused on the influence of OFA ratios, OFA positions and OFA injection angles on NO_x reduction within furnace. Generally, the initial NO_x production can be reduced by 40–65% through air staging for bituminous coal fired boilers, and the final NO_x concentration at furnace outlet is usually 180–300 mg/Nm^3 [10,14,17]. However, the reduction effect of ordinary air staging technology on lean coal and anthracite combustion is much weaker, and the NO_x outlet concentration is usually >400 mg/Nm^3 [1,2,11]. Overall, the regulation of NO_x emission cannot be achieved only by the existing air staging combustion but has to rely on SCR. In addition, the emission standard of NO_x may be tightened to 50 mg/Nm^3 in the next few years. Therefore, it is significant and inevitable to further develop low-NO_x combustion technology.

During the combustion of pulverized coal, it has been proved very beneficial for NO_x reduction to increase temperature in fuel-rich zone [18–20]. On this basis, the method of high temperature and strong reducing atmosphere (HT&SRA) combustion was put forward to further reduce NO_x production in our previous work [21]. It is suggested that raising combustion temperature can lead to a substantial reduction of NO_x while the air stoichiometric ratio of reducing zone is $\leq$0.7 [21]. However, the previous study was conducted just on a lab-scale furnace, and HT&SRA combustion can be realized by controlling temperature with electric heater [18,19,21]. Obviously, it is very difficult to raise the combustion temperature under such a lower air stoichiometric ratio for pulverized coal boilers in power plants, and report on the application of HT&SRA combustion is still vacant. Hence, investigation on converting the HT&SRA combustion technology to practical use is very necessary and of great value, which makes this clean coal technology with more realistic significance and development prospect.

In this paper, a new air distribution mode which aims to build a HT&SRA in pulverized coal boiler was proposed. The new combustion technology is implemented in pulverized coal boilers by adopting deep air staging combustion, increasing the O_2 fraction of feeding gas in the primary zone ($O_{2,p}$, for short) by mixing some pure O_2 into the air, and optimizing SOFA arrangement. The deep air staging can keep the primary zone under a strong reducing atmosphere, and increasing $O_{2,p}$ can accelerate the combustion of pulverized coal, to effectively raise combustion temperature in primary zone even O_2 is insufficient. The employment of SOFA means that OFA is kept quite far from the coal injector, which can ensure the NO_x generated in burner zone to be reduced adequately by providing a longer residence time in the reducing zone. The proposed combustion method was investigated by the cost-effective computational fluid dynamics (CFD) to study the feasibility on utility boiler. The effects of increasing $O_{2,p}$ on NO_x reduction and char burnout were inspected under various conditions with different OFA positions and OFA ratios. This work can offer guidance for the development of the low-NO_x combustion technology, which is crucial to decrease the NO_x emission and lessen many troubles involved in the denitration process for power plant.

2. Modelling methodology

2.1. Physical model

The simulations were performed based on a 600 MW wall-fired boiler, with the configuration and size parameters illustrated in Fig. 1. The details of the arrangement, internal structure and air distribution of each burners and OFA nozzles are available in our previous work [1,2].

2.2. Numerical analysis

The turbulent flow, combustion, heat transfer, particles motion, and NO_x formation in the furnace were numerically simulated by commercial CFD software FLUENT (ANSYS, Inc., USA). The grid independence was firstly tested, and the total grid number of 1,467,228, and 1,904,070 was employed in the primary calculation. As shown in Fig. 2, the gas temperature distribution along furnace height computed based on these two number of cells are almost the same, thus the mesh system of 1,467,228 cells was employed in this following study.

The SIMPLE algorithm was adopted to formulate the time averaged conservation equation for mass, momentum and energy. The standard k-ε model was used to describe the turbulent flow. The P-1 model was chosen to model the radiation heat transfer, and the number of bands was set to zero, indicating only gray radiation was modeled [22]. The absorption coefficient was calculated by the wsggm-domain-based approach. The particle emissivity was assumed to be 0.9 and the scattering factor was 0.6. The two-competing-reactions model and kinetics/diffusion-limited model were used to respectively calculate the devolatilization rate and char oxidation rate, with the detailed parameters shown in Table 1. The O_2 concentrations of feeding gas injected from different nozzles were different, and then the species transport model was adopted to make the boundary condition setting convenient, with turbulence-chemistry interaction described by the finite-rate/eddy-dissipation model. The gas phase combustion of volatiles was simulated by a 4-step global reaction mechanism with the following 4 reactions included [23].

$$CH_yO_x + (0.5 + 0.25y - 0.5x)O_2 \rightarrow CO + 0.5yH_2O \quad (R1)$$

$$CO + 0.5O_2 \leftrightarrow CO_2 \quad (R2)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (R3)$$

$$H_2 + 0.5O_2 \leftrightarrow H_2O \quad (R4)$$

As the presence of NO_x makes negligible influence to the calculation of combustion solution, NO_x calculation was executed as a post-processing procedure based on the results of flow, temperature field, and species distributions. The prompt-NO formation was not taken into account since its contribution is limited in coal-fired systems [23,24]. Hence, the NO_x formation was calculated based on the thermal-NO [25] and fuel-NO mechanisms [26]. In this study, the fraction of fuel-N in volatile and in char were determined to be 40% and 60%, respectively, based on the volatile content of the coal adopted here [27]. For lean coal, it is assumed that 90% of the volatile-N converts to HCN while the rest directly forms NO with consideration of the temperature and O_2 concentration near the coal inlet [27–29]. Regarding the char-N, the conversion rate was set to 90% to reflect the incomplete combustion of char [30]. Then, among the released char-N, it is assumed that 30% of that directly conveys to NO, and the rest forms HCN [30,31].