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Effect of char gasification on NOx formation process in the deep air-staged combustion in a 20 kW down flame furnace

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HIGHLIGHTS

- Char gasification model is refined to modeling deep staging combustion.
- Simulated CO profile agrees well with experiment data in various conditions.
- NOx reduction by CO in reducing zone is underestimated by NOx model.
- In the reducing zone, several undetected nitrogenous species coexist with rich CO concentration.
- Rapid oxidization of nitrogenous species determines the final NOx emission.

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ABSTRACT

Deep air-staged combustion tests of Datong (DT) bituminous coal were carried out in a 20 kW down flame furnace (DFF) with the burner stoichiometric ratio (SR) ranging from 1.200 (unstaged) to as low as 0.696 (deep staged). The experimental results shown that the concentration of CO reach as high as 120,000 ppm (12 vol.%) and the NOx decrease to nearly zero in the reducing zone under deep staging conditions of SR = 0.696, which was never observed before. Thus, the extent of CO formation (i.e. char gasification) and the NOx reaction mechanism under deep staging condition were studied in order to understand the combustion process of coal. This paper presents a refined numerical simulation for reproducing the profiles of CO and NOx along the DFF under deep staging condition. The comparison between simulation and experimental results prove the reasonability of refined kinetic parameters of char gasification. The enhancement of char gasification by CO_2 is proposed and validated. With the simulated CO profile in the DFF confirmed by experiment, the NOx profile could be further analyzed. The discrepancy of simulated NOx profile in the reducing zone (i.e. fuel-rich zone) indicates that there are some undetected nitrogenous species and undiscovered NOx transfer mechanism regardless of the consistence of final NOx emission between simulation and experiment. It is supposed by us that a majority of NOx immersing in high level of CO in the reducing zone is mainly transferred into undetected nitrogenous species (excluding HCN and NH_3) which is then rapidly oxidized into NOx once the remaining oxygen is injected into the DFF.

1. Introduction

In order to resolve the rising problems such as global warming, air pollution, acid rain and heavy mist, more stringent policies have been published to restrict the emission from pulverized coal power plant. The concept of staging combustion technology is a widely used strategy in NOx control. In staging combustion technology, power plant is operated in this way that a fraction of air required for fuel combustion, named as over fire air (OFA) or staged air or burnout stream (adopted behind), is injected into the furnace downstream from the burner or primary combustion zone. Because of the insufficient air in burner or primary combustion zone, a reductive zone caused by incomplete combustion is formed before the injection of remaining air to reduce the pollutants, such as NOx and SOx.

Previously, many researchers have conducted a lot of experiments on staging combustion technology in terms of several parameters, such as burner stoichiometric ratio (SR), the position of burnout stream injection, CO profile, temperature profile, and NOx reduction mechanism, [1,2]. Among the parameters, the SR of the burner and the injection position of burnout stream are critical for the application of staging combustion technology. Costa

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and Azevedo [1] measured the operating parameters on an industrial pulverized coal fired furnace under the staging condition with the SR of 0.85. In their measurements, the highest concentration of CO is around 6 vol.% near the furnace back wall at the highest elevation of burners as a consequence of low SR in the primary combustion zone. The NOx emission is lower because of elevated CO concentration at lower SR. Ribeirete and Costa [2] also carried out air staging combustion experiment with SR of 0.95 in the Instituto Superior Técnico (IST) large-scale laboratory furnace and the similar conclusions were found.

As introduced in the last paragraph, the value of SR in the most related articles was mostly around 0.9, which could be reckoned as shallow staging. Urged by the more stringent regulations on pollutants emission, air staging combustion that has a SR of burner or primary zone less than 0.85 (defined as deep staging combustion) was developed and adopted by some industrial power plants for a stronger effect on reducing pollutants. As the SR decreases to such a low level less than 0.85, there is a new problem concerning enhanced gasification of coal which causes elevated CO concentration and changed NOx reduction mechanism. As a consequence, there is a big blank in understanding what would happen to coal combustion process (the degree of char gasification, NOx transformation) at high temperature in a furnace when the SR is decreased to such a low level. Hence, a series of experiments with stoichiometric ratio of air in burner or primary combustion zone ranging from 1.200 to 0.696 are described in this paper, which could expand the knowledge on deep staging combustion, determine the degree of char gasification, and support more experimental data for the evolvement of NOx formation and reduction models.

In order to investigate the exact behavior of coal combustion process under staging combustion condition, laboratory scale furnace which bridges the gap between the theory and industry is a very important kind of equipment to support such a research [2–10]. Take Instituto Superior Técnico (IST) large-scale laboratory furnace for example, detail measurements inside the furnace space were taken to figure out the O_2, CO and CO_2 profiles [2]. But the furnace was operated with blended natural gas for stabilization of the pulverized coal combustion and the temperature in primary combustion zone is comparatively lower than that in industrial conditions. Another laboratory scale furnace adopted by Mackrory and Tree has the same condition that natural gas was blended to facilitate the stabilization [3]. The blending natural gas has sure influence on the measured species data. Apart from these fuel-heating furnaces, there are other tiny drop tube furnaces featuring electrical temperature control method. Fan et al. laid the emphasis on the final emission of NOx with low SR in an electrical drop tube furnace (DTF). However, in their works the basic reaction mechanism of combustion process cannot be studied due to the lack of species profiles along the furnace [11]. Taniguchi designed an electrical high-temperature tandem-type staged DTF which shows a step temperature profile with a significant temperature drop in the middle caused by the furnace structure [4]. In a word, temperature and species profiles inside the furnaces mentioned above are not maintained by the combustion of coal itself, but by the aiding of electrical heaters and natural gas, which probably have a certain influence on the intrinsic reaction mechanism and the profiles of CO and NOx [9,12]. That is to say, the self-sustained coal combustion in pilot scale furnace, which has a comparable temperature profile to industrial furnace, is an important premise.

It is well known that among the factors influencing the NOx transformation, the profile of CO and temperature in the furnace are critical [13–15]. Without a clear and accurate CO concentration profile, the related reactions involving CO, such as NOx reduction by CO, are hard to discuss [5]. What's more, the CO concentration profile along with other species is strongly dependent on the temperature profile [16].

In order to eliminate the influence of natural gas and to get rid of the limitation of the controlled temperature, a totally self-sustained laboratory scale down flame furnace (DFF) is designed and constructed by the authors [6]. With the temperature profile close to industrial furnace, the discussion of char gasification and NOx transformation under deep staging condition are then enabled by measuring the species concentration along the furnace [17,18]. Furthermore, numerical modeling aiming to reproduce the profiles of experimental results is done to validate the established models. Based on the CO profile along the DFF, the char gasification model is refined in terms of species rate exponent which is rarely discussed specifically in previous similar numerical modeling works [19–22]. With the success in predicting CO profile by the refined gasification model, the NOx profile predicted by the current NOx model is then compared with the measured data. It is firstly found that there are two issues within the current NOx model on prediction of the NOx profile along the furnace, which could guide the improvement for NOx model in the next step.

2. Experimental instruments and methods

2.1. Pilot-scale down flame furnace (DFF)

As shown in Fig. 1, the pilot scale furnace is designed as follows: the burner is installed at the top of the furnace; 6 temperature thermal couples are distributed along the furnace height; 11 injection ports and 11 flue gas sampling orifices are set along the furnace with 250 mm interval; the inner diameter of the upper furnace and the lower furnace is 200 mm and 150 mm respectively, its effective length is 3000 mm from the burner mouth to the end; the furnace wall is refractory lined. Downstream the furnace, the flue gas cooling exchanger and the dust collector are installed. The whole system is operating between a compressed air capacitor and an induced fan. The gauge pressure in the middle furnace is maintained around −40 Pa. The other related parameters are listed in Table 1. The power of the DFF is designed as 20 kW. The electrical heating unit in the top part of the furnace is for temperatures below 1373 K in order to preheat of the furnace and ignite the natural gas which is injected only for acceleration of preheat process. The natural gas is turned off once the pulverized coal is injected into the furnace and it is not used for flame stabilization. Finally, the furnace enters into normal experiment condition once the temperature profile is stable.

The measurement of species in flue gas is carried out by switching the ball valves of the measurement tube network. Once the selected flue gas is extracted from the furnace, the reaction in the flue gas sample is frozen due to the rapid drop of temperature. Hence the chemical species in the flue gas sample can closely represent the instantaneous condition at the sampling position. The selected flue gas (around 1 L/min) is then inhaled by the flue gas analyzer (MRU VARIO PLUS, with high measurable range of CO). By this method, the gas species concentration along the furnace height is recorded in sequence. With the success of the DFF, lots of data is measured when the high repeatability and reliability of data are confirmed during the commissioning. Compared to other pilot scale furnaces, the DFF features self-sustainability (no natural gas blending), high temperature range (above 1800 K for the peak temperature in primary combustion zone, no electrical heating), and one dimensional characteristic of all operating parameters.

According to previous works on staging air combustion technology by Coda et al. [5], Fan et al. [11], and Mackrory and Tree [3], it's believed that the optimal staging position is located around 1300 mm downstream from the burner for the DFF in this article. Thus, the experimental results used in this paper are the cases that burnout stream is injected at the optimal position. In order to make the numerical simulation more efficient through the introduction