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Evaluation of staged air and overfire air in regulating air-staging conditions within a large-scale down-fired furnace

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HIGHLIGHTS

- A deep-air-staging combustion technology consisting of staged air and overfire air.
- Evaluating effects of staged air and overfire air in deepening air-staging conditions.
- Staged air actually acting as the combustion air in the primary combustion zone.
- Deep-air-staging conditions for great NO_x reduction relying on opening OFA.

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ABSTRACT

To understand the deep-air-staging combustion performance and evaluate effects of staged air and overfire air (OFA) in regulating deep-air-staging conditions within a 600-MW_e down-fired supercritical boiler, industrial-size measurements were performed in turn at three settings (i.e., damper opening partners of 30%:15%, 50%:15%, and 30%:40% for staged air and OFA, respectively). It was found that the staged-air effect on combustion and NO_x emissions was opposite to that of OFA. At a shallow OFA opening of 15%, the furnace attained low carbon in fly ash of 4.47–5.24% and high NO_x emissions of 1234–1360 mg/m^3 at 6% O_2. Under these circumstances, deepening air-staging conditions by increasing the staged-air damper opening from 30% to 50% essentially favored the NO_x formation and improved burnout rate. With the staged-air opening fixed at 30%, opening OFA from 15% to 40%, on the contrary, acted as a positive role in strengthening air-staging conditions, i.e., reducing NO_x emissions to levels of about 1000 mg/m^3 at 6% O_2 and raising combustible loss. The results suggested in the down-fired furnace, regulating deep-air-staging conditions to sharply reduce NO_x emissions relied on opening OFA rather than staged air.

1. Introduction

Anthracite and lean coal, characterized by low volatile matter and poor reactive activity, present difficulties in achieving ignition, maintaining stable combustion, and completing burnout when industrially fired in furnaces [1–3]. Consequently, effective ignition conditions, high gas temperature levels, and long resistance times for coal particles in the high-temperature furnace zone must be established if good burnout needs to be achieved in industrial firing of these fuels [4–6]. Down-fired furnaces (also called down-shot fired boilers, arch-fired boilers, or W-shaped flame boilers) [7–9], designed especially for industry firing anthracite and lean coal, attempt various carefully-designed strategies to attain satisfactory firing of these fuels, such as creating a W-shaped flame to prolong pulverized-coal residence times in the furnace, positioning large refractory coverage on furnace walls to attain high gas temperature levels in the fuel-burning zone, and supplying air in various staging patterns so as to inhibit NO_x production. However, the actual combustion performance essentially deviates from the designed combustion concept and some problems such as late coal ignition [10,11], poor burnout [12,13], heavy slagging [14,15], and particularly high NO_x emissions (reaching levels of 1600 mg/m^3 at 6% O_2 for large quantities of down-fired furnaces at normal full-load operations) [4,12,16,17] have been widely reported in these furnace operations. Accordingly, various solutions have been reported on dealing with these problems, such as burning blended fuels [16,18] and retrofitting combustion configurations [19,20] to improve

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burnout, shutting down burners close to the side walls and reducing boiler load to alleviate the serious slagging phenomenon [14], and regulating low-NO_x operating conditions to restrict the initial stoichiometry in the burner zone by adjusting the arch- and wall-air distribution (reducing NO_x emissions by about 20% when using this method without combustion configuration modifications, in addition to an unavoidable increase in combustible loss) [8,12,21–23].

However, the still high NO_x emissions (reaching up to 1200 mg/m^3 at 6% O_2 after restricting the initial stoichiometry in the burner zone) hinder the further application of down-fired furnaces in most of developed countries [24–27], despite lots of down-fired furnaces appearing in these regions in 1960–1980s [6,17,18,23]. As a country possessing the largest reserves and consumption of anthracite and lean coal in the world and producing about 30% of its generated electricity by burning these fuels, China has allowed down-fired furnaces to popularize well in the past 25 years [2,17,19]. However, to comply with the increasingly strict NO_x emission standards (i.e., 200 mg/m^3 at 6% O_2 as of July 1, 2014), sharply reducing the particularly high NO_x emissions to acceptable levels is urgent for boiler managers and manufacturers to maintain commercial operations and further popularization in the country. Currently, comprehensive combustion retrofits in down-fired furnaces in service and carefully-designed combustion configuration in new designs to establish deep-air-staging conditions are preferred in China in the next several years [10,28].

Deep-air-staging combustion technology used in large-scale pulverized-coal furnaces is generally characterized as sub-stoichiometric air conditions formed both at the coal ignited stage and in the primary combustion zone [2,27–31]. In consequence, air is supplied into furnaces in several stages as coal combustion proceeds. By carefully regulating deep-air-staging combustion in tangential-fired and wall-arranged furnaces that burn coals of relatively high volatile matter (i.e., bituminous coal and lignite), ultra-low NO_x emissions and relatively high burnout have been reported in various pilot- and full-scale furnace applications [27,31–33]. However, within down-fired furnaces designed specially for firing anthracite and lean coal, few deep-air-staging combustion applications have been reported except those from Li et al. [28], Garcia-Mallol et al. [34], and Leisse et al. [35] developed for Foster Wheeler (FW) and Babcock & Wilcox (B&W) down-fired boilers. Li et al. [28] retrofitted a 300-MW_e FW down-fired furnace with a so-called combined high efficiency and low-NO_x technology and found that NO_x emissions could be lowered by as much as 50% (i.e., from 2101 to 1057 mg/m^3 at 6% O_2), with carbon in fly ash maintaining the original levels of 7–8%. By applying fuel preheated nozzles and supplying vent air through the equipped overfire air (OFA) ports, Garcia-Mallol et al. [34] achieved low-NO_x levels below 510 mg/m^3 at 6% O_2 (equaling to a sharp NO_x reduction by over 50%) within several FW down-fired furnaces in the capacity range of 50–350 MW_e. By retrofitting swirl burners and applying OFA within a 350-MW_e B&W down-fired furnace, Leisse et al. [35] achieved a sharp NO_x reduction from 1700 to 1060 mg/m^3 at 6% O_2, accompanied by carbon in fly increasing from 3.5% to 5.7%.

Generally, several stages of air-staging combustion need to be established to form deep-air-staging conditions in large-scale down-fired furnaces. Accordingly, there will be one dominating air-staging stage that greatly affects NO_x emissions and coal burnout. However, the aforementioned investigations [28,34,35] suggest that up to now, deep-air-staging applications are only for FW and B&W down-fired furnaces and none for other new types. Again, no investigation has been reported on (i) the respective effect of each air-staging stage on coal combustion and NO_x emissions and (ii) which air-staging stage can be dominating as coal combustion proceeds. To address these research vacancies and provide useful information for perfecting deep-air-staging combustion technologies for down-fired furnaces, this paper presents an experimental evaluation of combustion characteristics and NO_x emissions under various air-staging conditions within a newly-operated down-fired 600-MW_e supercritical furnace. With a multiple-injection and multiple-staging combustion technology (i.e., the MIMSC technology in the literature [36]) equipped, the 600-MW_e down-fired furnace actually belongs to a new type rather than the aforementioned FW and B&W down-fired furnaces. The deep-air-staging combustion configuration in the 600-MW_e down-fired furnace consists of fuel rich/lean combustion and two layers of secondary air supplying in the burner zone, staged-air supplying in the middle period of coal combustion, and OFA supplying in the burnout zone. Considering that changing the staged-air and OFA damper openings is usually the preferred method for boiler managers to adjust air-staging conditions and combustion status within the furnace, the attention in this work is thus focused on (i) uncovering effects of staged air and OFA on coal combustion and NO_x emissions and (ii) evaluating their validities in regulating deep-air-staging conditions to reduce NO_x emissions.

2. Experimental section

2.1. Utility boiler

Fig. 1 presents the vertical and transverse cross-sections through the furnace, air distribution model along the furnace height, concentrator and burner layout patterns on furnace arches, and groups of staged-air slots on the front and real walls in the lower furnace. The furnace configuration suggests that the arches divide the furnace into two sections: the octagonal lower furnace (i.e., the fuel-burning zone) with four wing walls and the rectangular upper furnace (i.e., the fuel-burnout zone). As shown in Fig. 1b, a total of 24 louver concentrators, symmetrically arranged on the two arches to connect with six millers labeled as A–F, divide the primary air/fuel mixture into fuel-rich and fuel-lean coal/air flows needed to regulate fuel rich/lean combustion. 12 burner groups are symmetrically lining the front and rear arches and uniformly positioned along the furnace breadth, with each burner group corresponding to two concentrators and a group of OFA ports (Fig. 1c) on arches and a staged-air slot group (Fig. 1d) below arches. The combustion configuration with the deep-air-staging MIMSC technology consists of four sections: (1) Regulating fuel rich/lean combustion in the burner zone to enrich the pulverized-coal concentration, lower the coal/air flow velocity and establish a relatively oxygen-lean atmosphere before coal ignition; (2) Supplying secondary air through arches in a two-stage manner (i.e., the high-speed inner and outer secondary-air jets parallel to the fuel-rich coal/air flow) to postpone the mixing of secondary air and the ignited coal/air flow, thereby forming the first combustion stage in the zone below arches; (3) Feeding the high-speed staged air (with a declination angle of 20°) into the lower furnace through the lower part of the front and rear walls to establish a second combustion stage along the flame travel; (4) Positioning OFA ports (also with a declination angle of 20°) on the front and near arches but close to the furnace center, thereby supplying OFA into the furnace throat zone to develop a third combustion stage.

In combination with the combustion configuration listed in Fig. 1e, the combustion-zone partitioning associated with the combustion air supply is given as follows: (i) In the region below the arches but not far from the burner outlets, the pulverized-coal is ignited and the two-stage secondary air (i.e., inner and outer secondary air) guides the relatively low-temperature, fuel-rich, and oxygen-deficient chemical atmosphere downstream into the lower furnace. This combustion zone is hereafter referred to as the