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Establishing an overall symmetrical combustion setup for a 600 MW_e supercritical down-fired boiler: A numerical and cold-modeling experimental verification

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ABSTRACT

The aim in this work is to establish an overall symmetrical combustion setup for a 600 MW_e supercritical down-fired boiler via evaluating effects of various factors (related with the upper furnace parameters and combustion system) on asymmetric combustion. Firstly, based on comparing the flow-field symmetry and performance parameters at the furnace outlet, effects of various factors (such as the dimensionless upper furnace height C_{H2}, boiler nose depth C_L, upper/lower furnace depth ratio C_W, furnace arch's burner location C_D, burner span C_S, and staged-air angle θ) were numerically determined under coal-combustion conditions. Secondly, three combined setups that considering all these factors were numerically compared. With C_W and C_D fixed at the boiler's design levels, applying an integrated solution consisting of lengthening upper furnace to $C_{H2} = 1.125$, shortening burner span to $C_S = 0.387$, and performing a sharp staged-air declination, developed symmetrical combustion plus apparent improvements in burnout and NO_x emissions. Under these circumstances, maintaining C_L at its original value of 0.298 and meanwhile setting θ at 45°, which corresponded to the combined setup 2 in this work, attained the best performance parameters at the furnace outlet. In view of the cold-modeling experiment also confirming the symmetrical gas/particle flow-field formation, the combined setup 2 was finally recommended as an overall symmetrical combustion setup for the down-fired boiler.

1. Introduction

Down-fired boilers, which are designed especially for firing low-volatile, hard-to-burn fuels (such as anthracite and lean coals) [1,2] with the application of various combustion-strengthened strategies [3–5], currently suffer from various problems such as late ignition and poor combustion stability [6,7], heavy slagging [8,9], poor burnout [10–12], particularly high NO_x emissions [4,13–15], and asymmetric combustion [9,16–18]. In detail, the combustion-strengthened strategies [3–5] in down-fired boiler's design concepts include: (i) maintaining high-temperature levels with lots of refractory coverage on the lower furnace walls to advance coal combustion; (ii) creating a W-shaped flame to prolong coal in-furnace residence times so as to achieve burnout; (iii) regulating fuel rich/lean combustion and entraining the high-temperature recirculating gas below furnace arches to assist coal ignition and maintain flame stability. Heavy slagging [8,9] always occurs on the wing and side walls surrounding the primary combustion zone in the lower furnace, where the refractory coverage is positioned for maintaining high temperature levels and no cold air is supplied. The typical level ranges reflect the poor burnout and particularly high NO_x emissions are carbon in fly ash of 7–15% [10–12] and 1100–2100 mg/m^3 at 6% O_2 [4,13–15], respectively. Asymmetric combustion [9,16–18] reported in down-fired boilers is usually characterized as the combustion status in the furnace depth direction being apparently better in one half side than in the opposite half side.

Up to now, various solutions were developed for these problems, such as burning blended fuels to improve ignition [19,20], positioning fuel-lean coal/airflow nozzle far from the furnace

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central part [9] or shutting down near-wall burners [21] to weaken slagging, inclining downward wall-air jets below furnace arches to improve burnout [22,23], and performing comprehensive combustion retrofits that consist of improving burners and regulating deep-air-staging conditions to sharply reduce NO_x emissions [4,24–26]. In a conventional large-scale combustion facility where the facility configuration is symmetrical and a multiburner system with each of the burners intentionally behaving in a uniform manner, the asymmetric combustion appearance is usually attributed to the air/fuel supplying difference among different burners. In this aspect, Choi et al. [27,28] focused on effects of axi-asymmetric combustion air supply in horizontally oil-fired burner and furnace and found that the asymmetric combustion characteristics in a furnace were significantly affected by axi-asymmetrically supplied combustion air. While in the asymmetric combustion issue restricted in down-fired, pulverized-coal boilers, only Kuang and Li's group published a series of investigations and the major findings include the following aspects: (i) reporting that the occurrence of a deflected in-furnace flow field results in asymmetric combustion [9,11,16]; (ii) initially giving out a conjectural explanation (i.e., the combination of the asymmetric upper furnace configuration effect and unreasonable combustion system designs) [11,16] of the deflected flow-field formation and then confirming it by comparing three down-fired boilers' asymmetric combustion performance [9]; (iii) trialing various primary measures (such as decreasing the staged-air ratio [11,18,29], lowering boiler load [16], inclining downward staged-air [30], and constructing asymmetric air distribution model [31]) to improve the flow-field deflection problem. However, under the circumstances without improvements in the asymmetric upper furnace configuration and unreasonable combustion system designs, these primary measures still show limitations when applied into different boilers. For example, the effective solutions of deceasing staged-air and inclining downward staged-air in 300 and 350 MW_e sub-critical down-fired boilers [11,18,32] were confirmed to be unavailable in a 600 MW_e supercritical down-fired [29,30] with a clearly shorter upper furnace and larger burner span along the furnace depth [9]. Meanwhile, no published work is focused on improving the aforementioned asymmetric upper furnace configuration effect and unreasonable combustion system designs, so as to fully eliminate the flow-field deflection problem from its potential source.

In the aforementioned 600 MW_e supercritical down-fired boiler [29,30] (as shown in Fig. 1 in this work), the potential factors affecting the asymmetric upper furnace configuration effect may refer to the dimensionless upper furnace height C_{H2} (C_{H2}=H_2/W_2), boiler nose depth C_L ($C_L = L/W_2$), and upper/lower furnace depth ratio C_W ($C_W = W_2/W_1$, signifying the furnace throat shrink extent), while those related with the unreasonable combustion system designs may contain the dimensionless burner location C_D ($C_D = D/R$), burner span C_S ($C_S = S/R$) along the furnace depth, and staged-air angle θ. The definition of various aforementioned symbols (i.e., L, W_1, W_2, H_1, H_2, R, D, S, C_{H2}, C_L, C_W, C_D, C_S and θ) is listed in the Nomenclature section. A systematic evaluation about effects of these potential factors on the flow-field deflection and asymmetric combustion must be performed so as to determine which are the major factors and then establish an overall symmetrical combustion setup for the boiler. In China, to obtain a furnace parameter assemble with high reliability, boiler manufacturers and managers prefer to a comprehensive design parameter optimization for all major factors that can affect the in-furnace coal combustion. Under these circumstances, the work in this study is divided into two parts. Firstly, a series of numerical simulations under coal-combustion conditions that comparing the flow-field symmetry and performance parameters at the furnace outlet are carried out for uncovering effects of various single factors (such as C_{H2}, C_L, C_W, C_D, C_S, and θ) and then fixing an optimal setting range for each factor. Secondly, several combined setups that considering all these optimal setting ranges are numerically compared to determine an overall symmetrical combustion setup. Thereafter, cold-modeling gas/particle flow experiments at the recommended setup are used to confirming the symmetrical flow-field formation. Findings in this work are helpful to establish a symmetrical W-shaped flame for new down-fired boiler designs.

2. Methodology

2.1. Utility boiler and industrial-size measurements that used for numerical simulation validation

Fig. 1 shows the furnace configuration and combustion system of the 600 MW_e down-fired boiler. The boiler furnace is divided into upper and lower furnace parts by two arches. The joint of the upper and lower furnaces is called furnace throat. In its pyknic furnace pattern, a short upper furnace ($C_{H2} = 0.864$) is equipped with a large boiler nose ($C_L = 0.298$), corresponding to a relatively large upper/lower furnace depth ratio ($C_W = 0.529$). A uniform burner layout pattern along the furnace breadth, with burners positioned at $C_D = 0.396$ and a large burner span of $C_S = 0.441$ (corresponding to the design secondary-air velocity of about 36 m/s at full load) on furnace arches, is used for a relatively uniform heat load distribution in terms of the working medium's supercritical parameters. Staged-air is horizontally fed through the lower part of the front and rear walls (i.e., $\theta = 0°$). More detailed introductory material about the furnace configuration, combustion zone division, combustion system, air-distribution pattern can be found elsewhere [29,30].

In the real furnace with the above design setup, industrial-size measurements were performed at normal full load with measurements taken of local gas temperatures and species concentrations, carbon in fly ash, and NO_x emissions. In major operational parameters listed in Table 1, the real-furnace airflow velocities were calculated according to the airflow flux, temperature, and nozzle/port area. Carbon in fly ash and NO_x emissions were acquired by sampling fly ash and flue gas at the air preheater exit. In the near-wall region surrounding ports 1–4 (Fig. 1), a thermocouple device consisting of (i) a 16-mm-diameter and 3.5-m-length heat-resistant steel tube and (ii) a 0.3-mm-diameter and 4-m-length platinum/platinum fine wire thermocouple (located in a 4-mm-diameter twin-bore stainless steel sheath), was used to acquire local gas temperatures. Meanwhile, a 3-m-long water-cooled stainless steel probe (for sucking high-temperature gas samples and then cooling them quickly) plus a Testo 350 M gas analyzer (with measurement errors of 1% for O_2, 5% for CO, and 50 ppm for NO_x) was used to obtain local gas species concentrations. Errors for the thermocouple's measurement (i.e., the extent of the measured values deviating from the "true" temperatures) are below 8% [22,33,34]. More detailed introductory material about the industrial-size measurement methods, measurement errors and uncertainties analysis, and configuration parameters of the water-cooled stainless steel probe, can be found in the literature [9,16,35].

2.2. Numerical simulations

Fluent 6.3.26 was used to perform numerical simulations on gas/particle flow, coal combustion, and NO_x formation in the down-fired furnace at each setting. The gas turbulence was specifically taken into account using the realizable $k-\varepsilon$ model [36], which performs well in the simulation of non-swirl flames. The Lagrangian stochastic tracking model was used to analyze the pulverized-coal/air mixture, and gas/particle coupling was