Journal of the Energy Institute xxx (2016) 1–18

Contents lists available at ScienceDirect

Journal of the Energy Institute

journal homepage: http://www.journals.elsevier.com/journal-of-the-energy-institute

Effect of outer secondary-air vane angle on the flow and combustion characteristics and NO_x formation of the swirl burner in a 300-MW low-volatile coal-fired boiler with deep air staging

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ARTICLE INFO

Article history:
Received 28 April 2015
Received in revised form
4 January 2016
Accepted 25 January 2016
Available online xxx

Keywords:
Swirl burner
Pulverized coal combustion
NO_x emission
Deep air staging

ABSTRACT

Small-scale laboratory experiments of airflow through a single burner model and industrial-scale experiments on the centrally fuel-rich, low NO_x swirl burner on a 300-MW wall-fired subcritical boiler burning low-volatile coal under deep air staging were performed. The aerodynamic characteristics, flue gas temperature, and gas concentrations were measured for various vane angles of outer secondary air in the burner nozzle region. The results show that a stable, symmetric central reverse-flow zone forms close to the exit of the burner nozzle region under deep air staging. With decreasing vane angle, i) the maximum axial, radial, and tangential velocities and swirl intensity of the airstream increase; ii) the decaying rate of velocity increases between $X/D = 0$ and $X/D = 0.8$; iii) the maximum diameter, length, and the jet divergence angle of the central reverse-flow zone increase; and iv) the relative reverse-flow rate increases. While the primary air concentration decreases slightly, the maximum primary air concentration decreases rapidly with decreasing vane angle. In contrast, the maximum axial relative mixing rate increases in the initial stage along the airstream direction. A decrease in vane angle increases the flue gas temperature, the rate of increase indicating a closer ignition position of the anthracite and lean coal along the airstream direction of the burner. The O_2 consumption rate and NO_x formation rate increase in the initial stage of combustion, whereas in the later stage the CO concentration increases notably and the O_2 concentration remains almost constant below 1%. The CO concentration can exceed 20,000 ppm, which restrains the NO_x formation and reduces the NO_x concentration notably, but beyond $X' = 0.8$ m, the NO_x concentration remains almost constant. The flue gas temperature varies slightly for different vane angles in the side-wall region. The O_2 concentration exceeds 4% near the location of the water-cooled wall. The O_2 concentrations are below 2% and the CO concentrations are above 5000 ppm along the radial direction 1.8375 m $\leq R' \leq$ 2.3375 m from the centerline of the burner in the side-wall region. With decreasing vane angle, the CO concentration increases while the NO_x concentration decreases.

1. Introduction

Various environmental concerns are caused by nitrogen oxide (NO_x) emissions, including degradation in visibility, acid rain formation, forest damage, acidification of aquatic systems, formation of photochemical smog, and hazy weather [1–3]. There is thus an urgent need to reduce NO_x emissions during the operation of coal-fired power plants. In recent years, regulations regarding emissions have become increasingly strict worldwide. The main objective of the CAFENOW project (Cost Abatement for Effective NO_x Reduction in PF Coal-fired Power Plants) is to determine whether primary techniques can be employed to meet the standards of exhaust NO_x emission proposed by the European Parliament. From January 1, 2008, to December 31, 2015, the permissible NO_x emission limit for a utility boiler rated over

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http://dx.doi.org/10.1016/j.joei.2016.01.005

500 MW in the European Union was set at 500 mg/m^3 (6% O_2). As of January 1, 2016, the limit is 200 mg/m^3 (6% O_2) [4]. In China, according to the "Air pollutants Emission standard of the utility boiler", issued by the Ministry of Environmental Protection, from July 1, 2014 the permissible NO_x emission limit for existing power plants was set at 100 mg/m^3 (6% O_2) or 200 mg/m^3 (6% O_2) (for a down-fired boiler only). In 2014, some provinces in China had set emissions limits of 50 mg/m^3 (6% O_2) [5] for July 1, 2017. Technical innovations that will realize low-NO_x combustion by reducing the NO_x emission at the furnace exit are urgently needed for most existing power plants. These renovations will be combined with selective non-catalytic reduction technology to meet emission limits. Many scholars have investigated low-NO_x combustion technology and obtained results that are important to the operating regulations and combustion system retrofits of boilers, as well as the design of new types of boilers [6–8].

Anthracite is a type of coal with the volatile content of dry ash-free basis (V_{daf}) less than 10%, while lean coal has V_{daf} between 10% and 20%. Anthracite and lean coal are generally characterized by low content of volatile matter, high content of ash, high coalification degree, but weak combustion reactivity. These fuels are difficult to use in terms of timely ignition, combustion stability, and burnout sufficiency. Additionally, the high temperature needed in the furnace for ignition and burnout of anthracite and lean coal results in high NO_x emissions from the power plant; NO_x emissions are usually higher than 1000 mg/m^3 (6% O_2) and as much as 1700 mg/m^3 (6% O_2) [9]. At present, many wall-fired utility boilers with swirl burners use anthracite and lean coal as fuel. Huang et al. conducted a numerical simulation to study the effects of various parameters and layout of over-fire air (OFA) on the aerodynamic characteristics of a 200-MW wall-fired boiler burning lean coal, and used optimized OFA parameters and arrangements to simulate the reacting flow. Their optimization reduced NO_x emissions from the furnace with OFA by 11% [10]. Backreedy described a CFD model, which incorporates a detailed coal combustion model allowing predictions of NO_x and unburned carbon to be made from coal properties. The model has been validated with experimental data and the effects of leakage air should be taken into account for accurate predictions [11]. Xue et al. performed experiments on a 1-MW coal-fired pilot-scale test furnace installed with a new type of swirl burner. They determined the impact of various parameters such as primary air (PA) ratio, OFA ratio, relative location of the OFA nozzle and inner secondary air (ISA)/outer secondary air (OSA) ratio, and swirling intensity on coal combustion and NO_x formation, when burning three typical Chinese coals, namely meager coal, low-rank bituminous, and high-rank bituminous [12]. Jones discussed the role of char gasification reactions within a tangential fired boiler under staged combustion, and also considered the wall fired case. Predictions for unburned carbon and NO_x in the furnaces were made with/without gasification equations and are compared with test data. Results indicate that the char gasification reactions play a small role only for the larger unburned coal particles [13]. Zhang et al. performed a stable combustion test for burning anthracite coal and pure petroleum coke with a special burner and conducted a series of experiments to investigate the performance of the burner in a 12-MW pilot-scale test facility located at the IHI Research Department (Ishikawajima-Harima Heavy Industries, Aioi, Japan). Compared with results obtained for a conventional low NO_x burner on the same facility, when anthracite was burned, NO_x emissions were 50% less at the outlet of the furnace but were at the same level when petroleum coke was burned [14]. However, all the above works are confined to the laboratory, numerical research, and research on bituminous-fired boilers. Additional studies are needed on innovative low-NO_x combustion technology that can achieve important NO_x reductions when applied to full-scale wall-fired utility boilers burning anthracite and lean coal.

With an OFA ratio generally greater than 25%, deep-air-staging combustion technology is one of the more attractive and efficient combustion technologies for reducing NO_x emissions [15]. With regard to wall-fired utility boilers, compared with non-deep air staging, the secondary air (SA) flow is reduced by about 30% under deep air staging. However, for a swirl burner, the formation of the central reverse-flow zone (CRFZ) relies on the rotation of SA, which can entrain the downstream high-temperature flue gas upward to ignite the primary fuel/air flows in time. If SA is reduced, forming the CRFZ will be a huge challenge. Deep-air-staging combustion technology that can be applied to full-scale wall-fired utility boilers burning anthracite and lean coal requires further research.

Different aerodynamic characteristics lead to a variation of operating conditions during the process of the coal combustion. By conducting experiments with small-scale burner models and full-scale burners, many scholars have analyzed the aerodynamic characteristics of the swirl burner to investigate its effect on pulverized-coal combustion. Mahmud studied the cold aerodynamic characteristics of a 1:9-scale burner model [16], revealing the effect of momentum flux ratio and swirl level. The experiment results showed that a stable, symmetric reverse-flow zone can be produced for a range of flow conditions. With increasing momentum flux ratio, the degree of penetration into the reverse-flow zone increased, and under a high momentum flux ratio, there was complete penetration. Li et al. studied the cold airflow characteristics of two types of swirl burners burning low-grade coal in a 300-MW utility boiler [17]. In practical operating conditions, the ratios of the maximum length and diameter of the CRFZ to the largest diameter of the OSA nozzle of the centrally fuel-rich (CFR) burner were 1.89 and 1.40, respectively, whereas the enhanced-ignition dual-register (EI-DR) burner had no CRFZ. Fan et al. performed experiments on mixing characteristics using a quarter-scale burner model [18]. As vane angles increased, the rate of decay in the maximum value of the PA concentration increased in the region $x/d < 1.5$ and decreased thereafter. The diffusion velocity of PA increased with increasing vane angle. Vu made detailed time-averaged and instantaneous flow measurements in a model combustor under co-swirl and counter-swirl conditions with a directional pitot probe and hot-wire anemometer, and investigated flow characteristics [19]. Lilley has systematically studied the application of swirl to injected air and fuel in combustion systems aimed at understanding and characterizing the observed phenomena. Advances in experimental study, modeling, and prediction of combustor swirl flows were reviewed [20]. Syred described the progress in understanding and using swirling flows. The main effects of swirl were to improve flame stability by forming a recirculation zone and to reduce combustion lengths by producing high rates of entrainment of the ambient fluid and fast mixing, particularly near the boundaries of recirculation zones [21]. Pröbstle presented an experimental study of flow properties in a swirl-driven combustion chamber for pulverized anthracite using a laser-Doppler anemometer. Axial and tangential particle velocity components under isothermal and non-reacting conditions are compared with those in high-temperature reacting flows [22].

In the present study, small-scale airflow experiments were performed in the laboratory with a swirl burner model. For various vane angles of OSA, the aerodynamic characteristics of the CFR burner jet flow were studied as well as mixing characteristics. To investigate the effects of vane angle on NO_x formation characteristics of an industrial-scale CFR swirl burner burning anthracite and lean coal, industrial experiments were performed on a 300-MW wall-fired subcritical utility boiler. For the CFR low-NO_x swirl burner and deep air staging combustion technology, which can achieve remarkable NO_x reductions when applied to a full-scale wall-fired utility boiler with the swirl burner burning anthracite and lean coal, was investigated in detail. The results obtained from these experiments are important in terms of operating regulations and combustion system retrofits of this type of wall-fired utility boiler burning anthracite and lean coal, as well as the

Please cite this article in press as: S. Li, et al., Effect of outer secondary-air vane angle on the flow and combustion characteristics and NO_x formation of the swirl burner in a 300-MW low-volatile coal-fired boiler with deep air staging, Journal of the Energy Institute (2016), http://dx.doi.org/10.1016/j.joei.2016.01.005