Energy Conversion and Management 79 (2014) 367–376

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Effect of overfire air angle on flow characteristics within a small-scale model for a deep-air-staging down-fired furnace

Min Kuang [a], Zhengqi Li [b], Zhongqian Ling [a,*], Xinjing Jing [b], Qunyi Zhu [b]

[a] Institute of Thermal Engineering, China Jiliang University, Hangzhou 310018, PR China
[b] School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, PR China

ARTICLE INFO

Article history:
Received 22 June 2013
Accepted 5 December 2013
Available online 11 January 2014

Keywords:
Down-fired furnace
Deep-air-staging
Overfire air angle
Flow field
Penetration depth

ABSTRACT

A deep-air-staging combustion technology consisting of special combustion organization and overfire air (OFA) application, has been developed previously for the particularly high NO_x emissions, severely asymmetric combustion, and serious slagging that were found in a 350 MW_e down-fired furnace. To evaluate the flow characteristics with respect to the OFA angle and thus establish an optimal OFA angle for the furnace, cold airflow experiments were conducted by recording flow field data within a 1:15-scaled model of the furnace at different OFA angle settings (i.e., 30°, 35°, 40°, 45°, and 50°, respectively). Various data such as the flow field pattern, velocity distribution in the furnace throat region where OFA flows, and the decay in the OFA jet, were compared among different angle settings. No negative effect on the flow field could be found with increasing the OFA angle except for 50°. As the angle increased, the vertical reach of the OFA flow increased continually, whereas the transverse spread of OFA increased initially but then decreased in the furnace throat region. To establish a symmetric flow field along with an appropriate OFA penetration depth, an optimal setting of 40° was found for the OFA angle. Our published numerical results uncovered that applying the deep-air-staging combustion technology with the optimized OFA angle, well-formed symmetric combustion developed and NO_x emissions could be reduced by 50%, without increasing levels of carbon in fly ash.

1. Introduction

Anthracite and lean coal are widely used in power generators in North America, Western Europe, Australia, and East Asia, although these fuels present difficulty in achieving ignition, maintaining stable combustion and attaining sufficient burnout because of their low proportion of volatile matter and poor reactive activity [1–4]. Down-fired furnaces (also called down-shot fired furnaces, arch-fired furnaces, or W-shaped flame furnaces), which are designed especially for industry firing of anthracite and lean coal are equipped with carefully-designed strategies to attain satisfactory firing of these fuels [5–7]. These strategies are: (1) creating a W-shaped flame to prolong the residence time of pulverized-coal in the furnace so as to achieve good burnout; (2) maintaining high gas temperature levels with lots of refractory coverage on the walls in its lower furnace to advance the coal ignition and raise burnout; (3) forming a recirculation zone below its furnace arch which directs the up-flowing hot gas to provide heat in assisting coal ignition and maintaining flame stability; and (4) admitting secondary air through openings along the vertical wall underneath the furnace arches as the flame develops to achieve flame stability. As a result, down-fired furnaces are thought to be better than tangential-fired and wall-arranged furnaces to burn these fuels [8] and have been well popularized within China in recent years. However, problems such as late coal ignition [5,6], serious slagging [9], poor burnout [6,10], high levels of NO_x emissions [1,10–14], and asymmetric combustion [15–17], are widely present in practical operations of down-fired furnaces. In comparison with other problems, the understanding on asymmetric combustion is relatively less. Asymmetric combustion creates large differences in volumetric heat load distribution in the furnace. Under these circumstances, problems such as fine cracking and tube bursting of water-cooled walls, especially for supercritical down-fired furnaces, caused by large differences in wall temperatures and limits being exceeded, jeopardize boiler safety operations [18].

To improve the down-fired furnace performance, much research dealing with these problems have reported various solutions, such as burning blended coals (i.e., mixtures of anthracite bituminous coal) to advance coal ignition and raise combustion stability [5,19], shutting down burners close to the side walls to alleviate heavy slagging [9], inclining downward the F-layer secondary air to improve burnout [10,20], and parametric tuning of operating conditions [13,14,21] and combustion system retrofits [1,22,23] to reduce NO_x emissions. In addition, Kuang et al. [24] found that the appearance of a deflected flow field was

* Corresponding author. Tel.: +86 571 86914542; fax: +86 571 86835763.
E-mail addresses: kmwust2000@163.com, tgzycjlu@163.com (Z. Ling).

0196-8904/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2013.12.012

the major reason given for the asymmetric combustion in down-fired furnaces and sharply inclining downward the staged-air feed direction could establish a relatively symmetric flow field. However, these investigations focus partly on the above problems and little research has been reported on comprehensive methods that can improve poor burnout, greatly reduce NO_x emissions, minimize slagging, and eliminate asymmetric combustion. In our published work [25,26], we have proposed a comprehensive deep-air-staging combustion technology based on the concept of multiple injection and multiple staging (for brevity, the "MIMSC technology"), specifically for a 350 MW_e down-fired furnace. The MIMSC technology consists of a unique configuration in the combustion system with overfire air (OFA) application. However, establishing deep-air-staging conditions by applying OFA [27–30] usually leads to high levels of carbon in the produced fly ash because of mixing incompletely between OFA with the unburnt particles. This means that, for a better design of OFA for the 350 MW_e down-fired furnace with the MIMSC technology, an essential OFA optimization needs to be conducted.

Currently, both cold-modeling experiments (such as the published work [6,15,24,31–33]) following certain similarities in modeling criteria and numerical simulations (such as the published work [13,20,25,26,34–36]) are widely used to investigate flow characteristics in coal-fired furnaces. To obtain an appropriate OFA angle for the 350 MW_e down-fired furnace with the new technology, cold airflow experiments within a small-scale model of the furnace were conducted to evaluate field characteristics with respect to the OFA angle. The results of these experiments will be of benefit in aiding deep-air-staging modifications of down-fired furnaces in service and new designs.

In should be noted that our published work [15,24–26] have reported in detail on the flow, combustion, and NO_x emission characteristics within down-fired furnaces but with different combustion technology as compared with the present one. To highlight the main points of the present contribution as compared to our previous work [15,24–26], Table 1 is provided listing major differences between them.

2. Experimental methods

The aforementioned 350 MW_e down-fired furnace was used in this work and the schematics of the furnace configuration and combustion system are presented in Fig. 1. The furnace 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). A total of 16 cyclone concentrators symmetrically arranged on the arches divide the primary air/fuel mixture into fuel-rich and fuel-lean coal/air flows needed to regulate fuel rich/lean combustion. There are 8 burners symmetrically lining the front and rear arches and uniformly positioned along the furnace breadth, with each burner corresponding to a pair of concentrators. The combustion configuration with the 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 45°) 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 (with a declination angle of 40°) 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.

The combustion system configuration applying the MIMSC technology is therefore composed of multiple airflow injections and comprehensive deep-staged combustion. Aside form the injection mechanism derived from the Bernoulli's principle for prolonging the coal/air flow penetration depth in the lower furnace [25], technical principles of the MIMSC technology also consist of details about how the technology regulates an excellent combustion status to achieve four aspects, i.e., timely ignition and stable combustion, high burnout, low NO_x emissions, and weak slagging tendency. Considering that the attention in this work is focused on evaluating the OFA angle effect on flow characteristics and establishing an optimal OFA angle for the technology application, the detailed material in the four aspects of the MIMSC technology is not repeated here and the interested reader can find it in the literature [37].

Fig. 2 shows the experimental system with the MIMSC technology, where θ denotes the OFA angle. In the small-scale model in Fig. 2, the origin of the coordinate system is set at the intersection of the furnace centerline and the line through the OFA port outlet along the measured cross section; d is the equivalent diameter of the slit OFA port, and X_0 is the width of the upper furnace. The horizontal distance between two opposed OFA port outlet centerlines is equivalent to $1.3X_0$.

All airflow rates into the small-scale model were measured by Venturi tube flowmeters with measurement errors being less than 10%. With all venture tubes' reading fluctuating within their measured errors, the flow-field pattern varied little. This reveals that the measured errors of flow rate by venture tube influence little the flow field and these errors are acceptable. An IFA300 constant-temperature anemometer system equipped a 1240-type two-dimensional probe with two hot-film sensors was used to measure the air velocity at various locations within the furnace, giving a measurement error of less than 5%. A detailed description of methods in quantifying the measurement errors relates to Venturi tube flowmeters and the two-dimensional probe, the velocity measurement principle of the anemometer, reasons for employing a two-dimensional probe, and uncertainties in the airflow velocity measurement can be found elsewhere [33].

The similarity criteria for the experiments are as follows: (i) geometric similarity. The ratio of the small-scale model to the full-scale furnace is 1:15; (ii) euler rule for self-similar flow. The limited Reynolds numbers of the primary and secondary airflows through direct-flow split pulverized-coal burner nozzles are 1.48×10^5 and 0.75×10^5, respectively. However, the flow behavior of the jets after leaving their respective nozzle outlets and the mixture characteristics between airflows do not change when the Reynolds number is higher than 1×10^4. The limited Reynolds number for the airflow through the model is 3×10^4. In these experiments, the Reynolds numbers for the airflows through burner nozzles and the model are 1.5×10^4 and 5×10^4, respectively. Thus, given these comparative values, the airflows through the model burner nozzle and in the model were thought to be self-modeling; (iii) the same ratios of momentum flux rate. The ratios of momentum flux rate among the airflows of the small-scale model are consistent with the full-scale furnace.

To evaluate the OFA angle effect on flow characteristics within the furnace and then establish an appropriate angle for the OFA port arrangement, cold airflow experiments were conducted whereby the OFA angle was adjusted in turn to 30°, 35°, 40°, 45°, and 50°. Simultaneously, the air mass flow rate for each airflow into the model is kept constant as adjusting the OFA angle. Velocity parameters for the boiler design and cold airflow experiments are listed in Table 2. Considering that the pulverized-coal combustion