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Effects of momentum ratio and velocity difference on combustion performance in lignite-fired pulverized boiler

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ABSTRACT

To study the effects of momentum ratio and velocity difference between primary and secondary air flow on boiler performance, simulation work was conducted on a lignite-fired boiler within a three dimension computational fluid dynamics model. Within the model, 8 cases were simulated where momentum ratio and velocity difference vary among cases. The distributions of combustion temperature, radiative heat flux, gas species concentration and residual particles' concentration were analyzed. Results show that momentum ratio of primary and secondary air flow significantly determines coal combustion behavior and boiler performance, and a reasonably small momentum ratio is beneficial for boiler performance. The velocity difference between primary and secondary air also affects coal combustion performance, and a relatively large velocity difference is favorable in boiler operation. These findings reveal the effects of momentum ratio and velocity difference on boiler performance, and can be helpful in guiding the actual operation of lignite-fired boiler to avoid the unfavorable boiler performance degradation.

1. Introduction

During the past decades, energy consumption has increased dramatically as a result of the rapid population growth and the process of industrialization, urbanization and modernization [1,2]. In 1984, the global primary energy consumption was only 6992.5 million ton oil equivalents (MTOEs) [3], but it is almost doubled in the past few decades and reaches to 13105 MTOEs in 2015 [4]. Furthermore, the global primary energy consumption is predicted to be 17157 MTOEs in 2035 [5]. Among the primary energy sources, fossil fuels have been extensively used and have become a powerful engine for the rapid economic growth and social development of all countries and regions, especially the developing countries. Although the share of renewable energy is estimated to increase from 3.2% to 8.3%, fossil fuels will still be the main provider of global primary energy consumption, about 77.2% in 2035 [4,5]. To further accelerate the worldwide electrification progress, an increasing amount of energy source is needed in our modern society, especially the electric power. In 2016, global electricity production has reached 24816.4 TW h [4], and it is expected to continuously increase significantly in the next few years [1,6]. As the most abundant fossil fuel in the world [7], coal is widely used in electricity generation and coal-fired power stations accounts for about 40% of the total electricity production on a global scale [8,9]. Despite the rich global reserve of coal resource, a concern of energy depletion is raised in recent years [10,11] and the utilization of low rank coal, in particular lignite, has attracted significant interests all around the world [12]. In China, lignite has a reservation over 130 billion tons, about 13% of China's total coal reserves [13], and 3/4 of the lignite coal is located in Northeast Inner Mongolia [14]. Compared with high rank coal, lignite has the advantages of low mining cost, high reactivity, high volatile matters and low pollution formation impurities [15,16]. However, lignite is naturally characterized by high moisture content, which can be up to 30%–60% on a wet basis [17,18]. Therefore, the widespread application of lignite in power plants is hindered because of the adverse consequence of the high moisture content, like lower energy density, lower calorific value and the consequent lower power plant efficiency [19,20].

In order to improve the availability and energy efficiency of lignite coal, a large number of researches have been focused on pre-drying technologies to upgrade high moisture lignite in recent years [18,21,22]. It was estimated that with an optimized pre-drying process in the future operation, the efficiency of lignite-fired power plant may be improved by 4%–6% [23]. However, this

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beneficial technology cannot be used in those lignite-fired boiler that are not equipped with pre-drying facilities. For these boilers, high moisture lignite is directly fed into the coal grinding device, in which coal particles undergo a simultaneous pulverization and drying process [24]. When moisture content is too high, the energy provided by primary air is not enough to dry the lignite particles to a desirable level, and leads to a drying capacity deficiency in the coal mills system. Under this condition, the dense wet particles cannot be lifted away by primary air and then results in a blockage in the powder feeding system [25]. In order to avoid this, primary air ratio is usually increased in boiler operation to increase the total energy input of primary air, so that the drying capacity of coal mill system can be maintained. However, this forced increase of primary air ratio alters the air distribution and air flow velocity and then damages the original aerodynamic field in the furnace, which will unavoidably affect the combustion process of coal particles and the overall boiler performance [8].

A large number of researches have been carried out to investigate the effects of air distribution and airflow velocity on coal combustion behavior and boiler performance. Through experiments on a start-up ignition burner, Liu et al. found that a low primary air velocity was beneficial for the ignition and combustion behavior of bituminous coal [26]. Huang et al. [27] investigated the influence of fuel injection velocity in an axially staged MILD combustor, and found that an increased fuel injection velocity was advantageous for the mixing process of fuel and oxidizer. A similar conclusion was also reported by Mao et al. [28], and it was explained that the rapid species and heat mixing process were due to the enhanced internal recirculation under large fuel injection velocity. For the arch-fired pulverized boilers, Liu et al. [29] studied the effects of air distribution on aerodynamic field and coal combustion behavior, while the influence of arc-supplied over fire air ratio on the flow and combustion characteristics was reported by Liu et al. [30]. Liang et al. [31] investigated the effects of momentum ratio of arch air to secondary air in a down-fired pulverized coal boiler. It was revealed that the penetration depth of arch air was remarkably deepened with the increase of momentum ratio, but a non-uniform velocity distribution in the lower furnace was also found when the momentum ratio is increased. Jing et al. [8] reported that with the decrease of primary air ratio in swirl burners, gas temperature, temperature gradient and CO concentration increased in the burners' zone, while O_2 and NOx concentration decreased. Sun et al. [32] investigated the effects of secondary air on flow and combustion characteristics of a novel swirl burner, results indicated that the existence of an outer secondary air prevents the slagging in the adiabatic chamber. Besides, with the introduction of an outer secondary air, the formation of NOx was suppressed due to the enhanced effects of air-staged combustion. Guo et al. [33,34] numerically studied the air distribution strategy in a 200 MW tangentially fixed oxy-fuel combustion boiler, and found that CO concentration increased in the ash hopper zone when bottom secondary air momentum is decreased. In addition, with the increase of bottom secondary air momentum, the heat transfer increased on the membrane walls, while decreased on the upper convective superheaters.

Although there have been lots of studies on the influence of air distribution ratio and airflow velocity, the previous researches mainly focused on the flow and combustion characteristics of down-fired pulverized boiler [29–31], oxy-fuel combustion [33,34], or tangentially fired pulverized boilers with swirl burner [8,32]. For the direct-flow pulverized boiler, emphasis was on the effects of air staging or over fire air ratio [35–37], while the influence of momentum ratio and velocity difference between primary air and secondary air flow was rarely studied. Considering the increasing use of high moisture lignite, the forced rise of primary air ratio is sometimes inevitable, which then alters the velocity and flow momentum of primary and secondary air flow. As can be seen from the above literature review, air distribution and air velocity have great impact on the aerodynamic field and coal combustion process inside the furnace. Therefore, it is quite necessary to investigate the effects of momentum ratio of primary and secondary air flow (MRPSA) and velocity difference between primary and secondary air flow (VDPSA) on coal combustion behavior and boiler performance, especially in large-scale lignite-fired boilers.

In this paper, effects of MRPSA and VDPSA on coal combustion behavior and boiler performance were investigated. For this purpose, a three dimensional computational fluid dynamics (CFD) model was developed based on a 660 MW wall-tangentially fired lignite boiler. After model validation, the model was utilized to simulate 8 operation cases, of which MRPSA and VDPSA vary between cases. In order to compare coal combustion behavior and boiler performance under different operating conditions, the distributions of combustion temperature, radiative heat flux intensity, O_2 and CO mass fraction, and the mass concentration of residual particles (RPs) were discussed in detail. Results show that both MRPSA and VDPSA affect coal combustion behavior and boiler performance. The difference is that MRPSA significantly determines coal combustion quality and boiler performance to a large extent, while VDPSA only affects the combustion process in a small range. The mechanisms of how MRPSA and VDPSA affect coal combustion behavior and boiler performance are presented in this work, and suggestions on actual boiler operation are also given to avoid boiler performance degradation. The findings of this study reveal the influence of MRPSA and VDPSA on coal combustion behavior, and thus deepen the understanding of boiler performance variation under different operating conditions. In view of the increasing use of lignite, especially high moisture lignite in power plants, air distribution ratio is usually adjusted to maintain the drying capacity of mill system, and thus may adversely affect coal combustion performance. The suggestion of maintaining a reasonably small MRPSA and large VDPSA in practical boiler operation can effectively prevent the possible degradation of boiler performance, and thus improves power plant efficiency and reduces power generation costs.

2. Boiler description and operating scenarios

2.1. Boiler geometry and burner configuration

The boiler studied in this paper is a 660 MW wall-tangentially fired lignite boiler with a single furnace system, which is schematically shown in Fig. 1. Along the furnace height, there are ash hopper zone, main burner's zone, separated over fire air (SOFA) zone, rear heating surfaces zone and furnace exit. The height of furnace from the bottom of ash hopper zone to the furnace top is 68.5 m, and the furnace cross-section is a rectangle with a width of 20.0 m and a depth of 20.3 m, respectively. In main burners region, 6 sets of main burners (MBs) and 9 sets of secondary air nozzles (SANs) are installed on four side furnace walls (FWs), with an offset distance of 5.05 m from the centerline of each furnace wall. In each burners group, MBs and SANs are alternatively arranged to enhance the mixing process of pulverized coal particles and the supplementary secondary air. In SOFA zone, 4 sets of SOFA nozzles are mounted at the four corners, with an inclination angle of 42° between the nozzle centerline and the furnace wall. In order to keep a better agreement with the actual situation, the platen-super-heater (PSH) and rear-super-heater (RSH) in the rear heating surface zone are also taken into consideration. However, due to the huge computational cost, it is not possible to consider the actual tube