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The Influence of Coal Particle Size on a Swirl Burner's Combustion and Slagging Performance

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Coal particle size has a great influence on the flow field and combustion characteristics of a swirl burner, which is widely used in coal-fired boilers. As the combustibility and slagging tendency of a swirl burner has great impacts on the efficiency and safety of a boiler, a full burner complexity was considered in a computational fluid dynamics (CFD) research. As concluded from the reasearch results, the coal particle size affects the particle phase flow field conspicuously through in a complicated way. Not only the continuous phase flow is influenced, but the particle concentration and the temperature distribution are also influenced, which is thought to be important for the slagging tendency and corrosion. Besides, the studied swirl burner is found to have a very strong asymmetrical performance. The increment of coal particle size has a negetive effect on the following-up performance of the particle and the combustion performances of the burner, which declines the overall temperature by around 50 ℃, consequently, the combustion efficiency and flame stability might also be degraded.

1. Introduction

Coal-fired power has always been China’s main power source, and accounts for around 70% of the power generation over the past half century (Wang et al., 2019). Determined by the coal reserves characteristics, there is a lot of low-grade coal in China, characterized in low volatile matter, high fixed carbon content, high coalification degree, high moisture, high ash content and poor reactivity (Wang et al., 2019a). Due to the advantages in combustion stability and low emission, coal-fired boiler equipped with swirl burner is widely used in China (Zhou et al., 2009). As the worldwide most stringent “ultra-low emission” was put forward in China, the concentration of NOx emission is asked to be limited to 50 mg/m^3 on the reference of 6 % oxygen content (National Development and Reform Commission of the People's Republic of China, 2014), most of the swirl burner were further retrofitted to combine the low emission combustion technologies with air staged combustion, so as to reduce the original NOx emission and decrease the operation cost of the SCR (Ma et al., 2018). However, it may also lead to some problems of high-temperature corrosion (Zhang et al., 2019), slagging (Wang et al., 2019), flame instability and low combustion efficiency (Pei et al., 2019), especially for low-volatile coal or anthracite (Pei et al., 2019).
The basic mechanism for the performances of a swirl burner on high-temperature corrosion, slagging, flame stability and combustion efficiency relies largely on the two phase flow characteristics around the burner outlet. Particle trajectory enclosed by the swirling vent air is supposed to be the key factor. Particle size ratios can significantly affect combustion and emissions characteristics, which in turn affects burner performance (Abbs et al., 1993).Through simulating the pulverized coal particle trajectory in the furnace by glass beads, the NOx formation and coal combustion efficiency of a swirl burner was investigated (Wang et al., 2019b). Li et al. (2019) focused on the effect of coal particle size on the flame structure of internal recirculation zone and exhaust pipe vortex and combustion characteristics in a swirl burner. By investigating the coal particle residence time in the

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recirculation zone around a swirl burner, the NOx reduction performance is also predicted. The effect of coal particle sizes on burnout characteristics and NOx emissions in a lab-scale furnace was reported by Sung et al. (2016). They observed that the air staging significantly reduces NO reduction efficiency in the flames with fine pulverized coal particles, while the deteriorating influence of air staging is more obvious in burnout performance with high coal fineness.

From the studies reviewed above, it can be known that considerable research efforts have been devoted to the effect of particle size on flame structure and emissions characteristics, with particular focus on NOx emissions. There are relatively few studies dedicated to the combustibility and slagging tendency of a swirl burner, which are of great importance for the efficiency and safety of a boiler. In order to fill this knowledge gap, the effect of particle size ranges from around 37.5 to around 75 µm on the tow phase flow field and combustion performance was studied comprehensively by a CFD simulation in the swirl burner.

2. Methodology

2.1 Problem description

The investigated swirl burner in this paper is developed by Ishikawajima-Harima Heavy Industries (IHI), named as IDF burner. The dual register IDF burner can achieve air stage combustion by regulating the volume of inner and outer secondary air, so as to reduce the NOx formation. The inner and outer secondary are regulated by adjusting the inner and outer vanes to achieve a swirling flow in the furnace. A straight flow tertiary air is supplied from the core tube to regulate the flame position. The primary air mixed up with pulverized coal is directed tangentially to an annular volute, and speeded up by a converging taper nozzle. The vorticial movement of the swirling primary air has a strong radial bias effect of inside lean and outside dense for the carried coal particle. In order to reduce the fraction of coal particles escaping from the rotational path, a group of primary air guiding vanes is equipped on the inner sleeve, so as to reducing the slagging tendency. 24 IDF burners are equipped on a IHI-FWSK type opposed wall firing boiler in the second phase 3 × 600 MW units in Zhejiang Beilun power plant. The boiler has a size of 22.2 m (width) × 15.97 m (depth) × 48.5 m (height). After the boiler was put into operation, the combustion stability, low load performance, and flue gas temperature went well. However, the NOx concentration in the flue gas is relatively high, up to 700 ppm in some condition; and the slagging problems emerges frequently, especially in high load condition.

2.2 Simulation approach

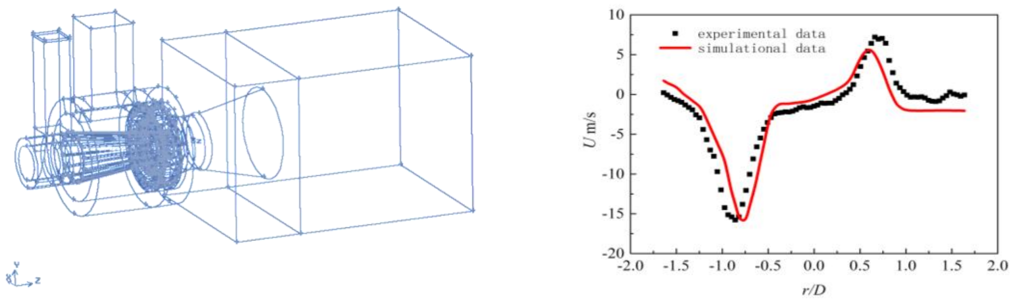
The computational field is shown in Figure 1a, where the full complexity of the IDF burner and its upstream primary and secondary air ducts are all considered, which was developed strictly scaled down from the prototype at the ratio of 1/8. Consequently, the two phase flow field inside and outside the burner could be well developed in the computational field, so as to precisely predict the asymmetry of the two phase flow in the real case. Considering the displacement of the 12 burners in each wall, and the swirl directions, the furnace field was simulated as a cuboid with a size of 3.5 m (height) × 3.591 m (width) × 3 m (depth), where the upper and bottom surfaces were set as periodic property, and the front and back surfaces were set as symmetry. The outlet surface was set as 3 m away from the burner exit, avoiding to affect the main upward flue gas movement in the centre of the furnace.

The flow and combustion process from the burner to the furnace is a very complicated process, where the turbulence flow, radiation and chemical reaction are all coupled with each other (Nemoda et al, 2005). As to the turbulence model, the Reynolds Stress Model (RSM) was chosen based on a better performance on the flow field, calculation cost, and convergence (Cui et al., 2006), against the well recommended Realizable κ-ε model (You et al., 2006). As to the radiation model, the Surface to Surface model was chosen for its high calculation efficiency and suit for the enclosed radiation space. The combustion in the swirl burner furnace is a typical non-premixed combustion process. The primary air carrying the pulverized coal gas flow can be regarded as the fuel flow, and the pure air coming out of the secondary air nozzle can be regarded as the oxidant. The chemical reaction model was set as Probability Density Function, considering the non-premixed combustion studied in this paper (Fluent, 2011).

The inlet of the primary air and second air ducts were defined as velocity inlets. The particle size distribution of the discrete coal was set according to a Rosin-rammer law in accordance with the experiment. The outlet of the computational field was set as pressure outlet, where the temperatures of the inverse flue gas and the radiation were both set as 2,000 K. The walls of the burner, vanes, and other hard surface were all set as adiabatic/elastic wall with no slip conditions. The pressure-velocity coupling SIMPLEC method is used for the pressure-based solver in Fluent. The discretization of the momentum, energy, turbulent kinetic energy and dissipation rate governing equations adopted the second-order upwind differencing scheme. The developed simulation approach has been validated by a previous publication (Cui et al., 2006).

2.3 Validation of the CFD model

The CFD simulation was validated by a 1/4 larg experimental model. A comparison of the distributions of the radial velocity in the plane 0.5 D to the burner exit are shown in Figure 1b. It can be seen that the prediction results of the model on the radial velocity distribution are good consistent with the experiments.



(a) (b)

Figure 1: (a) The computational field and some basic structures (b) The distributions of radial velocity in the plane about 0.5D to the burner exit ($\bar{d}$ = 44 μm)

3. Results and discussion

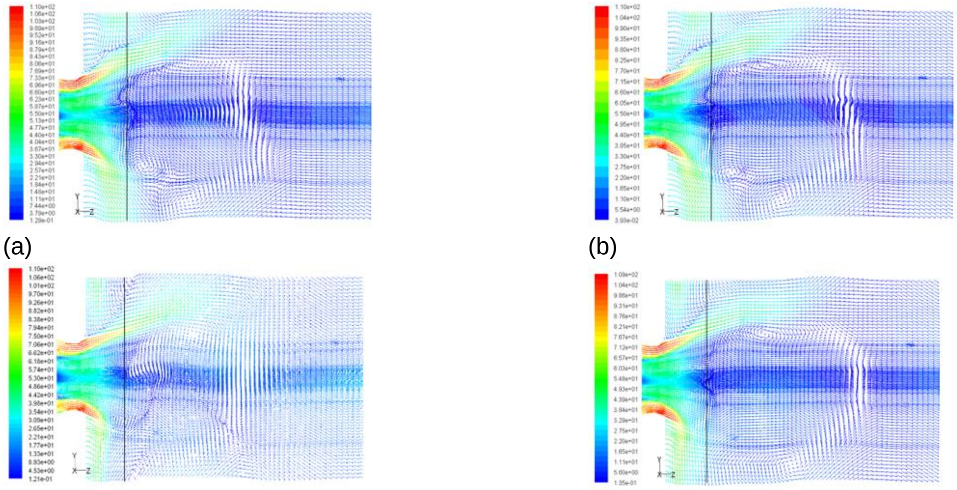
Four average particle sizes of 37.5, 50, 62.5 and 75 μm are selected for the pulverized coal particle considering its general range in industrial operation. The followability of particle phase with gas phase motion can be measured by Stokes number (*Stk*) that calculated through the empirical equation as follows (Soo, 1999).

$$Stk = \rho_P U_g \delta^2 / 18 \mu_g L \quad (1)$$

Where, ρ_p represents the bulk density of the particle phase, Ug is the gas phase velocity, δ is the particle diameter, μ_g is the gas dynamic viscosity, and L is the nozzle diameter of the burner. The *Stk* was calculated as approximately 0.10, 0.18, 0.29 and 0.41 for the pulverized coal particle sizes of 37.5, 50, 62.5 and 75 μm, which implies that most of these coal particles can effectively follow fluid flow and turbulent fluctuations. The flow field, particle concentration and temperature filed on the different particle size cases were calculated under hot state. They are discussed as follows.

3.1 Computational study on the flow field

The hot state continuous phase flow field around the burner under different particle sizes are shown in Figure 2, where the vertical auxiliary lines are set at the same position to help comparing the flow field in different pictures. The hot state continuous phase flow field, are strongly developed in comparison with cold flow field because a combustion reaction of volatile gas and char components in the coal particles actively occurs. As shown by Figure 2, the flow field of continuous phase can also be divided as jet-flow, central recirculation and side recirculation zones. As the diameter of the coal particles increases, the central recirculation zones gradually enlarged, while the side recirculation zones become smaller. It can be seen from Figures 2a to c that, the recirculation zone gradually deflects toward the periphery as the average particle size of pulverized coal particles increases, which is in consistence with the flow field of the particle phase discussed above. However, the asymmetry of the jet-flow of the continuous phase is gradually enlarged as the average particle size increases from 37.5 to 62.5 μm, opposite to the variation trend of particle phase. This might be explained by the combustion effect of particle phase, which will be jointly analyzed with particle concentration and temperature characteristics. When the average particle size is further increased to 70 μm, the variation trends of central recirculation zone position and the asymmetry of the continuous phase flow field are both changed. This will also be further explained in conjunction with the temperature field.

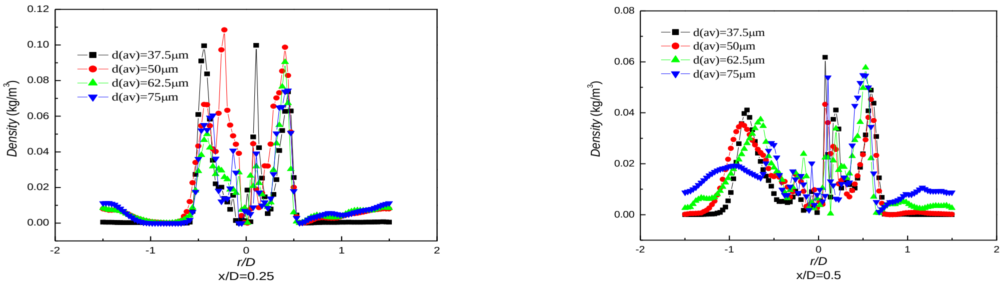


(a) (b) (c) (d)

Figure 2: The continuous phase velocity fields on different particle sizes (unit: m/s) (a) $\bar{d}$ = 37.5 μm (b) $\bar{d}$ = 50 μm (c) $\bar{d}$ = 62.5 μm (d) $\bar{d}$ = 75 μm

3.2 Computational study on the particle concentration

The particle concentration in different particle size cases are compared on two locations around the burner exit, as shown in Figure 3 . As can be seen from Figure 3a and b that, there is almost no particle exist outside the main stream when the average pulverized coal particle size is 37.5 μm. That means all of the coal particles are either enclosed by the swirling jet-flow, or burnt out before they escape to the side recirculation zone. As the particle size increases, the particle concentration in the side recirculation zone is gradually increased, as illustrated in Figure 3a and b. However, as the particle size increases, the particle concentration is seen to be reduced either in the jet-flow zone or the central recirculation zone in the near-burner area, as shown in Figure 3a. One reason for this phenomenon can be referred to high Stokes number of the large coal particles as analyzed in 3.1 section. The other reason is that, the large coal particles are hard to be burnt out, then their remaining time in the flow field would be extended, and so forth the chance to be recirculated to the side zone would be increased.



(a) (b)

Figure 3: A comparison of the particle concentrations in different particle sizes cases (a) x/D = 0.25 (b) x/D = 0.5

Besides, the asymmetry of particle concentration in the jet-flow is enlarged by the increasing of the coal particle size in Figure 3a, and it is further enlarged as the flow move further to the furnace as shown in Figure 3b. These results are consistent to the continuous flow field variation as shown in Figure 2, while opposite to the results of cold test. They will also be explained coupled with the temperature field in the following paragraphs.

3.3 Computational study on the temperature distribution

The contour of the temperature field around the burner exit in different particle size cases are shown in Figure 4, where the contours are illustrated on different calibrations. It can be seen from Figure 4 that the recirculation area is the area with the highest temperature, responsible for ignite the coal particle and sustain the flame stability. The temperature situations between the cases on particle sizes of 37.5 and 50 μm are very close; while as the particle size further increases to 62.5 and 70 μm, the overall temperature declines obviously. Generally speaking, the overall temperature situation has a negative correlation with the average coal particle size. This can be explained by the relationship between the combustibility and the coal particle size. When the average particle size is below 50 μm, the coal particle has a very good combustibility, which may assure a good combustion efficiency of the whole coal particles. The overall temperature situations between the particle size cases of 37.5 and 50 μm are close. As the average coal particle sizes further increase, the combustion efficiency of the coal particles declines conspicuously. Consequently, the temperature situation declines by around 50 °C accordingly.

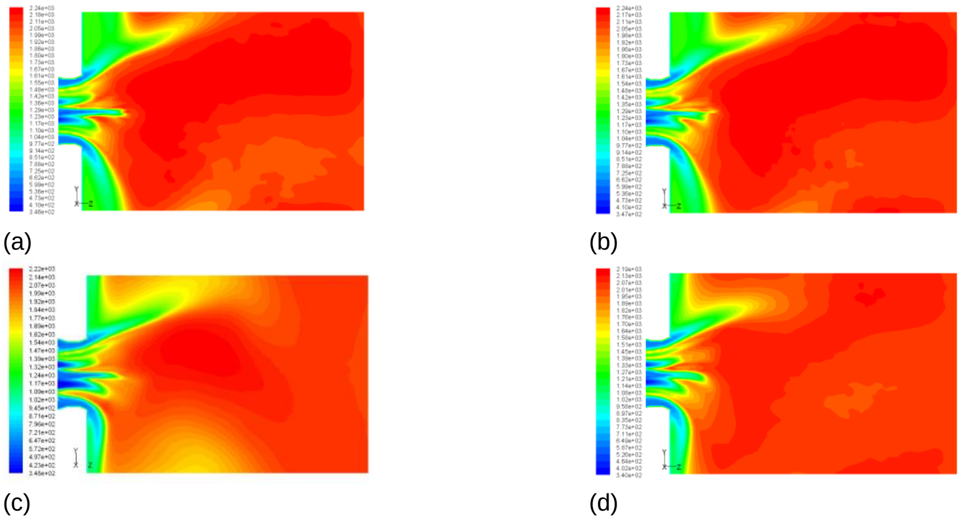


Figure 4: The temperature fields on different particle sizes (unit: K) (a) $\bar{d}$ = 37.5 μm (b) $\bar{d}$ = 50 μm (c) $\bar{d}$ = 62.5 μm (d) $\bar{d}$ = 75 μm

Combined with 3.2.1 and 3.2.2 sections, it can be further indicated that, as the particle size increases, the increasing hot flue gas is entrained into the burner outlet zones and the pulverized coal particles are more concentratedly distributed along the burner axis, which lead to the recirculation zone with more intense burning and more heat release. In fine coal particle conditions like 37.5 and 50 μm, the coal particles are quickly burned by the recirculated hot flue gas, resulting in a reduction in coal particle density and large amounts of devolatilization. Then the volume flowrate of the flame is greatly increased, and the main flame is dominated by the primary air jet-flow, leading a light asymmetry of the continuous flow field. As the average coal particle size increases to 62.5 μm, the combustibility of the coal particles declines. As a result, many unburnt coal particles are recirculated by the secondary air flow-jet and re-burned, which increases the asymmetrical impact of the secondary air jet-flow. While as the average coal particle size further increases to 75 μm, the combustibility of the coal particles declines greatly. The high temperature zone of the burner outlet is pushed outward, and side recirculation zones is not sufficiently heated. The positive effect of particle size increment on reducing the flow field asymmetry is magnified, then the variation trends of continuous flow field is changed.

4. Conclusions

The particle phase flow field, continuous phase flow field, particle concentration, as well as the temperature distribution are discussed under different average particle size cases by a CFD simulation, where the influences of average coal particle size is found to be very conspicuous and complicated impact on those aspects. It is found that the investigated swirl burner has a very obvious asymmetrical characteristic in the above investigated aspects, and the asymmetrical extent of the secondary air is worse than the primary air. The central recirculation zone with high temperature flue gas is supposed to ignite the coal particles carried by the primary air. As the coal particle size increase, its combustibility declines, and the overall temperature situation declines by around 50 ℃, which is not good for flame stability and combustion efficiency. The particle concentration and temperature situation increase in the side recirculation area, which is likely to increase the tendency of slagging and high temperature corrosion. Besides, the flame asymmetry also increases as the particle size increases.

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