Numerical Study of the Influence of Secondary Air Uniformity on Jet Penetration and Gas-Solid Diffusion Characteristics in a Large-Scale CFB Boiler

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Abstract: The uniformity of secondary air (SA) in large-scale CFB boilers has an important influence on gas-solid flow and combustion, but was seldom considered in previous studies. Numerical simulation based on the Eulerian–Eulerian and RNG k-ε turbulence models was conducted to explore the influence of SA uniformity and load variation on jet penetration, diffusion characteristics and gas-solid mixing in the first 600 MW supercritical CFB boiler. The results showed that better SA uniformity was conductive to the uniformity of SA penetration and gas-solid mixing along the furnace height, although the penetration depth and diffusion distance showed an opposite trend. In addition, the penetration depth and diffusion distance got enhanced with higher boiler load. The inner and outer SA jets could not cover the furnace width, and the uneven SA uniformity led to a huge deviation of the solid concentration within 10 m of the air distributor. Eventually, a calculation model was successfully established for predicting the penetration depth of inclined thermal SA jets during boiler operation.

Keywords: CFB boiler; secondary air uniformity; gas-solid flow; jet penetration; lateral diffusion

1. Introduction

With the development of circulating fluidized bed (CFB) boilers towards large capacity and high parameters [1–5], boiler dimensions are increasing, resulting in higher requirements for the uniformity of fuel feeding, air distribution, gas-solid mixing, and especially SA uniformity to ensure better air supply in the furnace. Small-scale CFB boilers often adopt annular airducts to realize uniform air distribution, and the air duct does not need to adopt variable cross-section design. Due to layout problem and cost considerations, a single annular air duct is not available in large-scale CFB boilers. Therefore, the updated SA system is generally composed of a linear windbox and curved branch pipes. In this situation, the uniformity of air distribution in branch pipes is more difficult to guarantee, which affects the penetration and diffusion performance of SA jets. The above problem reduces combustion uniformity in the furnace to a great extent, resulting in high carbon content in the fly ash and, obviously, post combustion [6–10].

Scholars have researched the characteristics of the secondary air jet and its influence on gas-solid flow in the furnace. Knoebig et al. [11] studied the gas composition field of large-scale CFB boilers, considering the gas-solid flow and convection/dispersion models with the reaction, and proved that uneven combustion in the boiler is related to the arrangement of the SA port, fuel supply, and returning circulating ash. Zheng et al. [12] conducted a numerical simulation on a 300 MW CFB boiler through the unsteady two fluid model and a RNG k-ε turbulence model, and the results showed that the jet depth of SA was
related to nozzle velocity, jet angle, and the background concentration of materials in the furnace. Wang et al. [13] also studied the SA penetration of a supercritical CFB boiler with different SA rates and background concentration through the two-fluid model and the RNG k-ε turbulence model. They found that the jet depth of SA increased with the increase of background particle concentration, and the jet depth of SA at each level was different. Koksal et al. [14] simulated the fluidized bed with SA injection through Euler–Euler method and found that SA injection led to an increase of material concentration in the dense phase zone below the SA nozzles. No backflow of materials near the wall was observed in the upper area of the SA nozzles. Zhang et al. [15] investigated the influence of the SA ratio on the distribution of gas-solid concentration in the bottom part through a cold-state test, and proposed a method to predict the circulating flow rate based on SA jets.

It is obvious to see from the previous literature that most of the studies focused on the influence of a single SA jet on gas-solid characteristics, without considering the mutual interference between the SA jets or their uneven velocity distribution. In large-scale utility CFB boilers, this effect cannot be ignored. Therefore, based on our previous work related to SA [16,17], this paper took the first 600 MW supercritical CFB boiler as a research object and carried out a numerical simulation based on the actual SA velocity distributions. The influence of SA distribution uniformity, load variation on SA jet penetration and diffusion, and changes of gas-solid flow in the furnace were analyzed in detail. The research results could provide valuable guidance and regulation suggestions for solving various non-uniformity problems in large-scale CFB boilers.

2. Numerical Simulation

2.1. The 600 MW Supercritical CFB Boiler

The secondary air system of the first 600 MW supercritical CFB boiler in the world was involved in the present study. As shown in Figure 1 [18], this boiler consists of a pant-leg furnace, six steam-cooled cyclones and six external fluidized bed heat exchangers (FBHEs). The secondary air coming from the rear wall direction is divided into two paths, one path is used for the outside SA and the other path is used for the inner SA [19]. Figure 2 shows the body structure and the locations of the secondary air ports of the boiler, while the section views A-A and B-B show the symmetrically arranged secondary air system. Figure 2 also gives the dimensions of the furnace. All the outside SA (A1–A8, A1′–A8′) and inner upper SA (B1–B5, B1′–B5′) were about 5.5 m from the air distributors while 2.5 m for the inner down SA (B1–BVIII, B1′–BVIII′). In order to obtain uniform airflow, all the windboxes adopted an isobaric design.

Figure 1. Schematic diagram of the 600 MW CFB boiler (1-slag cooler; 2-material returning device; 3-coal feeding route; 4-coal bunker; 5-storage tank; 6-steam separator; 7-cyclone separator; 8-flue duct; 9,10,11-fluidized bed heat exchangers (FBHEs); 12-secondary air duct; 13-ignition duct; 14-economizer; 15-low temperature reheater; 16-low temperature superheater).
2.2. Computational Mesh and Solution Method

Because of the symmetrical structure of the boiler, only one furnace was simulated. A mixed grid was adopted in this model, where the upper part of the furnace was divided by a hexahedral grid, and the lower part was divided by a tetrahedral unstructured grid, as exhibited in Figure 3.
The Eulerian–Eulerian model and the RNG k-ε turbulence model [20–22] were adopted in this study. The Gidaspow drag model [23] was employed to describe the gas-solid momentum transfer, which is widely used in gas-solid two-phase simulation. The wall function method was used near the walls [24]. The main governing equations are as follows:

Continuity equation:

$$\frac{\partial}{\partial t}(\alpha_i \rho_i) + \nabla \cdot (\alpha_i \rho_i \vec{v}_i) = 0$$

Momentum equation:

$$\frac{\partial}{\partial t}(\alpha_i \rho_i \vec{v}_i) + \nabla \cdot (\alpha_i \rho_i \vec{v}_i \vec{v}_i) = -\frac{\partial}{\partial t}(\alpha_i \rho_i \vec{v}_i) + \nabla \cdot (\alpha_i \rho_i \vec{v}_i) + \beta_{sg}(\vec{v}_j - \vec{v}_i)$$

$$\bar{\tau}_s = \alpha_s \mu_s \left[ \nabla \cdot \vec{v}_s + \left( \nabla \cdot \vec{v}_s \right)^T \right] + \alpha_s(\lambda_s - \frac{2}{3} \mu_s)(\nabla \cdot \vec{v}_s)^T$$

Turbulence equation:

$$\frac{\partial}{\partial t}(\alpha_i \rho_i \vec{v}_i) + \nabla \cdot (\alpha_i \rho_i \vec{v}_i \vec{v}_i) = \nabla \cdot \left( \alpha_i \mu_{eff} \nabla \vec{v}_i \right) + \alpha_i G_{k,i} - \alpha_i \rho_i \vec{e}_i$$

$$\frac{\partial}{\partial t}(\alpha_i \mu_{eff} \vec{v}_i) = \nabla \cdot \left( \alpha_i \mu_{eff} \nabla \vec{v}_i \right) + \beta_{sg}(C_i j k_l - C_j i k_l) - \beta_{sg}\left( \vec{u}_j - \vec{u}_l \right) \cdot \left( \frac{\mu_{eff}}{\alpha_s} \nabla \alpha_s - \frac{\mu_{eff}}{\alpha_g} \nabla \alpha_g \right)$$
Gas-solid drag coefficient (Gidaspow):

\[
\alpha_s > 0.8, \quad \beta_{ss} = \frac{18}{\alpha_s \rho_s \alpha_g Re_s^2} \left[ 1 + \left( \frac{2}{20} \alpha_s \rho_s \alpha_g \frac{\nu}{d_s} \right) \frac{\nu_s - \nu_g}{\nu_g} \right]^{0.687} \alpha_g^{2.65} \tag{10}
\]

\[
\alpha_s < 0.8, \quad \beta_{ss} = 150 \frac{\alpha_s (1 - \alpha_s) \mu_s}{\alpha_g d_s^2} + 1.75 \frac{\alpha_s \rho_s \nu_s - \nu_g}{\nu_g} d_s^{-2.65} \alpha_g
\]

where,

\[
Re_s = \frac{\rho_s d_s \nu_s - \nu_g}{\mu_g}
\tag{11}
\]

Granular shear viscosity:

\[
\mu_s = \mu_{s, col} + \mu_{s, kin} + \mu_{s, fr}
\tag{12}
\]

where,

\[
\mu_{s, kin} = \frac{d_s \rho_s \sqrt{\Theta_s \pi}}{6 (3 - e_{ss})} \left[ 1 + \frac{2}{5} (1 + e_{ss})(3e_{ss} - 1) \alpha_s \theta_{0, ss} \right]
\tag{13}
\]

\[
\mu_{s, col} = \frac{4}{5} \alpha_s \rho_s d_s \theta_{0, ss} (1 + e_{ss}) \left( \frac{\Theta_s}{\pi} \right)^{1/2}
\tag{14}
\]

\[
\mu_{s, fr} = \frac{P_s \sin \theta}{2 \sqrt{I_2 D}}
\tag{15}
\]

Granular bulk viscosity:

\[
\lambda_s = \frac{4}{3} \alpha_s^2 \rho_s d_s \theta_{0, ss} (1 + e_{ss}) \left( \frac{\Theta_s}{\pi} \right)^{1/2}
\tag{16}
\]

Solid pressure:

\[
P_s = \alpha_s \rho_s \Theta_s + 2 \rho_s (1 + e_{ss}) \alpha_s^2 \theta_{0, ss} \Theta_s
\tag{17}
\]

where,

\[
\theta_{0, ss} \Theta_s = \left[ 1 - \left( \frac{\alpha_s}{\alpha_{s, max}} \right)^{3/5} \right]^{-1}
\tag{18}
\]

Considering the high-temperature gas-solid environment in the real dense phase area, the air density and viscosity at 890 °C were set to improve the simulation accuracy. The inlet velocity boundary was set for every SA port, while the pressure outlet boundary was used at the furnace outlet. The boundary conditions and parameters are shown in Table 1.

**Table 1. Boundary conditions and parameters.**

| Item                  | Value                        |
|-----------------------|------------------------------|
| Gas property          | \( \rho = 0.3032 \text{ kg/m}^3 \), \( \nu = 4.678 \times 10^{-5} \text{ m}^2/\text{s} \) |
| Solid property        | \( \rho = 2600 \text{ kg/m}^3 \), \( \nu = 1.033 \times 10^{-3} \text{ m}^2/\text{s} \) |
| Gravitational acceleration | 9.81 m/s                      |
| Mean particle size    | 0.3 mm                       |
| Particle temperature  | algebraic                    |
| Specular rebound coefficient | 0.01                      |
| Inlet boundary condition | Velocity inlet               |
| Outlet boundary condition | Pressure outlet             |

In addition, external circulation parts such as cyclones were not simulated. However, in order to realize gas-solid recirculation, it was necessary to use the user defined function (UDF) in FLUENT to load the mass flow rates of gas and solid at furnace outlets onto the boundary conditions of the returning ports as inlet parameters. There are three furnace outlets at one side of the 600 MW CFB boiler, and each outlet corresponds to two returning
ports. The flow rate of each circulation loop was determined by our previous experimental and calculated results [17]. Simulations in this study were performed with Ansys FLUENT. Ansys Design Modeler and Ansys Mesh were used to generate the 3D geometries and the grids respectively.

2.3. Calculation Cases

In order to investigate the influence of SA uniformity and load variation, uniform and non-uniform SA case were set. Table 2 shows the PA and SA flow rates for each case, which were obtained from the DCS control system. The uniform SA cases were further divided into three types, i.e., 100%, 80% and 60% BMCR loads, while the PA and SA flow rate at the non-uniform case were the same as that at 100%BMCR. Table 3 exhibits the detailed boundary conditions and parameter settings under uniform SA cases. The same type of SA port has the same velocity inlet. Figure 4 shows the simulated actual SA velocity distribution at the non-uniform SA cases, which were measured with flute type pipes on the authors’ previous cold field test. The measurement of the SA parameters was finished with a KA23 type hot-wire anemometer, of which the accuracy could be 0.1 m/s when measuring air at 0–50 m/s. The uncertainty of data measurement could be calculated as Equation (19). However, because the SA inlet velocity was almost always faster than 15 m/s, the influence of the data measurement uncertainty on the simulation results almost can be ignored.

\[ U_{0.95} = \sqrt{\left(1.96 \times \frac{0.1}{3}\right)^2} = 0.065 \text{m/s} \]  

Table 2. PA and SA flow rate at each case.

| Item            | Uniform Cases | Non-Uniform Case |
|-----------------|---------------|-----------------|
|                 | 60% BMCR      | 80% BMCR        | 100% BMCR      | 100% BMCR      |
| PA flow rate    | 89.77 kg/s    | 110.60 kg/s     | 117 kg/s       | 117 kg/s       |
| SA flow rate    | 70.74 kg/s    | 103.06 kg/s     | 123.69 kg/s    | 123.69 kg/s    |
| SA ratio        | 44%           | 48%             | 52%            | 52%            |
| Superficial velocity | 2.53 m/s    | 3.36 m/s        | 3.83 m/s       | 3.83 m/s       |

Table 3. Boundary conditions and parameter setting at the uniform SA cases.

| Items            | Boundary Conditions | 60% BMCR | 80% BMCR | 100% BMCR |
|------------------|---------------------|----------|----------|-----------|
| PA               | 2.65 m/s            | 3.26 m/s | 3.45 m/s |
| OUSA             | 37.06 m/s           | 53.99 m/s| 65.84 m/s|
| ILSA             | Velocity inlet      |          |          |           |
| IUSA             | 19.83 m/s           | 28.89 m/s| 35.24 m/s|
| Furnace outlet   | Pressure outlet      | 50 Pa    | 50 Pa    | 50 Pa     |
2.4. Data Analysis

The calculation started from the accumulation of bed materials with a fixed height in the bed until the materials was fully fluidized in the furnace. Thus, the simulation method in this paper could more accurately reflect the actual gas-solid flow situation [25]. Due to the transient simulation, the gas-solid mixing in the furnace was very complex, and a single instantaneous result could not well reflect the actual diffusion characteristics of the secondary air. Therefore, the diffusion characteristics of SA, gas-solid flow and material concentration profiles in this paper were investigated using the method of time average processing of instantaneous results [26,27].

In this paper, the penetration depth of SA was defined as the distance when the axial velocity of SA decreased from the outlet value to 1.2 m/s on the vertical plane where the center point of each nozzle was located, while the lateral diffusion distance was defined as the distance corresponding to the radial velocity of SA.

The correction of the SA port referred to increasing the actual dimensions of the SA port according to the correction modeling method, so as to solve the expansion problem of the SA jet due to the sudden temperature rise [28]. Figure 5a exhibits the diffusion situation of the SA jet with the actual dimensions of SA port, and Figure 5b shows the diffusion characteristics of the SA jet after the correction of the SA port.

![Figure 4. Velocity distributions of SA ports at the non-uniform SA cases.](image)

![Figure 5. Penetration and diffusion characteristics of SA before and after the SA port correction](image)

(a) SA jet with actual dimensions; (b) SA jet after correction.
2.5. Grid Independence

The 100%BMCR uniform case was selected to verify grid independence, and three grids of 1,087,433; 1,311,921; and 1,895,996 were generated based on the same model. As shown in Figure 6, the penetration depth of each SA port calculated with three different meshes were in good agreement, and the standard deviation was within 6%, which verified grid independence. Hence, the simulation was conducted with 1,087,433 grids.

![Figure 6. Penetration depth of SA at 100%BMCR uniform case with various grid quantity.](image)

3. Results and Discussion

3.1. Model Validation

The simulation results of the 100%BMCR non-uniform case, thermal test results, and cold test results were compared to validate the model. As shown in Figure 7, the solid volume fraction distribution along the height of furnace was almost consistent with the thermal test and cold test results, indicating that the model used in this study is effective in simulating gas-solid flow in the furnace. The thermal test results were obtained from the DCS control system, while the cold test results were obtained from the research results by Xu J. et al. [29].

![Figure 7. Solid volume fraction along the height of furnace at various cases.](image)
3.2. Influence of SA Uniformity on Jet Penetration and Diffusion

Figure 8 shows the simulation results of jet penetration under different SA velocity distributions at 100% BMCR load, and Table 4 shows the corresponding standard deviations of air velocity distributions. It can be seen clearly that the penetration depths of various types of SA were 0.8–1.2 m, 1–1.8 m, and 1.6–3.2 m, respectively, of which the OUSA ports had the largest penetration depth. There was no significant difference in penetration depth between the two different SA distribution conditions, and the standard deviation of ILSA penetration depth was smaller under the uneven SA condition. This was mainly because the velocity of the #8 ILSA port was obviously higher under uneven SA conditions, and the #8 nozzle was just located near the rear wall of the furnace. The uneven SA distribution could solve the problem that the penetration depth was short due to the high solid concentration at the rear wall, so the uniformity of the overall penetration depth was improved to a certain extent. In the boundary conditions, the velocities of the #4 and #8 OUSA ports were larger, and the penetration depths of the two corresponding nozzles in Figure 8 are also larger, which were consistent with the SA distributions. Therefore, it is considered that the uneven SA distribution could reduce the uniformity of the jet penetration in the furnace. In particular, the standard deviation of penetration depth of OUSA was more than three times of that under the uniform SA condition.

![Figure 8](image)

Figure 8. Penetration depths under uniform/non-uniform SA distributions at 100% BMCR load.

Table 4. Standard deviations of penetration depth of various SA at 100% BMCR load (unit: m).

| Working Conditions | IUSA | ILSA | OUSA |
|--------------------|------|------|------|
| Non-uniform SA     | 0.04 | 0.26 | 0.55 |
| Uniform SA         | 0.09 | 0.28 | 0.18 |

Figure 9 and Table 5, respectively, show the simulation results and standard deviations of the lateral diffusion distances of SA under uniform/non-uniform SA conditions at 100% BMCR load. It can be seen that the lateral diffusion distances of various types of SA
were 0.8–1.5, 0.4–1.7, and 1.3–1.9 m, so the diffusion distance of the SA port with larger penetration depth was also larger. However, some differences in the distribution of jet penetration and lateral diffusion still existed in each SA nozzle, and the standard deviation of the SA lateral diffusion distance was more obvious under non-uniform SA conditions. In particular, the standard deviations of the lateral diffusion distance of the IUSA and ILSA increased nearly three times under the non-uniform SA condition. The reason is that the solid concentration on the inclined wall of the pent-leg furnace is higher than that on the outer wall [17], so changes of SA velocity distribution have a greater impact on the gas lateral diffusion.

![Graph showing lateral diffusion distance under (non-)uniform SA distributions at 100% BMCR load.](image)

**Figure 9.** Lateral diffusion distance under (non-)uniform SA distributions at 100% BMCR load.

| Working Conditions | IUSA | ILSA | OUSA |
|--------------------|------|------|------|
| Non-uniform SA     | 0.23 | 0.24 | 0.27 |
| Uniform SA         | 0.06 | 0.06 | 0.17 |

**Table 5.** Standard deviations of lateral diffusion distance of various SA at 100% BMCR load (unit: m).

3.3. Influence of SA Uniformity on Gas-Solid Mixing in the Furnace

Figure 10 shows the profiles of solid concentration along furnace height (Y-axis). It can be seen from the contours that the solid concentration gradually decreased along the height of the furnace, the value was relatively high near the side walls but low at the center region of the furnace cross-section. At Y = 30 m, gas-solid mixing in the furnace was more uniform. The faster the gas-solid mixing is realized in the furnace, the better the fuel combustion situation will be in the upper dilute phase zone of the furnace.
Figure 10. Material concentration distribution along the furnace height direction.

Figure 11 shows the contours of gas velocity along the height of the furnace. As can be seen in the figure, the core region of the gas flow was partial to the outside of the furnace as a whole. The main reasons are as follows: first, the pent-leg design was adopted in the lower part of the furnace, which caused the bed materials to move towards the inner wall of each furnace leg with the effect of PA, so that the gas flowed upwards towards the outer wall in the upper part; second, the velocities of OUSA on the outer wall of the furnace were much higher than those of the IUSA and ILSA, creating the internal circulation of particles from the outer wall to the inner wall; and third, the furnace outlets were arranged on the outer wall of the furnace, so it was reasonable that the gas flow inclined to the furnace outlet on the outer wall. With the increase of the furnace height, the core area of the gas flow first moved to the middle of the furnace, while the superficial velocity of the gas in the middle was higher, which corresponded to the core-annulus structure of the gas-solid flow. When it reached a certain height, the core area of the gas flow moved towards the outer wall and eventually escaped from the furnace outlets. At this time, three regions with higher gas velocity appeared in the furnace, which were located in the front, middle and rear parts along the furnace depth direction, respectively. The three regions also corresponded to the three furnace outlets at one side.
The gas-solid mixing in the furnace was closely related to the furnace structure, the positions of furnace outlets and ash returning ports, and the arrangement of SA. In order to investigate the influence of PA distributions on gas-solid flow in the furnace, the furnace was divided into three zones equidistant along the width direction. The deviation of solid concentration in each of the three zones could reflect the diffusion uniformity of gas-solid mixing in the furnace, as shown in Figure 12. It is not difficult to observe that the deviations of some local solid concentrations were large under the condition of non-uniform SA distribution, especially in the area below the 10 m height of the furnace. This indicated that the uniformity of SA velocity distribution has a great influence on the diffusion uniformity and mixing of SA in the furnace, and the uniformity of gas-solid mixing in the furnace under the uniform SA distribution condition (100% BMCR load) was better than that under the non-uniform SA distribution condition. Therefore, it is of great significance to improve the SA diffusion and gas-solid mixing uniformity by optimizing the SA supply system, especially the air velocity uniformity of each SA nozzle.

Figure 12. Influence of secondary air uniformity on the deviation of solid concentration along furnace height in Section 1, 2 and 3 ((a)—Section 1 (b)—Section 2; (c)—Section 3).
3.4. Influence of Boiler Load on Jet Penetration and Diffusion Characteristics of SA

Figure 13 shows the simulation results of the SA penetration depth at different boiler loads. It can be seen that the OUSA and IUSA all showed more uniform distributions with changes of load, while the ILSA located on the inner wall of the pent-leg furnace had obviously uneven distribution. That is, the uniformity of penetration depth of the ILSA was reasonable from the #2 through #7 nozzles. The average penetration depth decreased from 1.5 m to 1 m when boiler load decreased from 100% to 60% BMCR. However, the penetration performance of the ILSA located on the rear and front walls was poor, with a maximum jet depth of less than 0.8 m, which affected the overall jet distribution uniformity. There are two key reasons why this happened. One is that the front and rear wall were equipped with material returning ports. The distance between the ILSA nozzles and the returning ports was close and at the same height, which led to higher solid concentration at the nozzles, thus affecting the penetration depth. The other is that the distance between the #1 and #2 as well as the #7 and #8 ILSA nozzles was relatively close, and the direction of SA jets intersected. Therefore, the penetration depths of the #1 and #8 ILSA nozzles were obviously smaller.

Figure 13. Cont.
Combined with the layout characteristics of the SA nozzles, it was also found that although the SA nozzles on the same level were arranged in a staggered and opposed manner, the lateral diffusion distance of the SA jet was less than the distance between two SA nozzles, and the penetration depth was not enough to cover the width of the furnace, resulting in low-velocity regions existing between adjacent SA nozzles. Therefore, there may be reducing zones at the height of SA nozzles for the actual operation of large-scale CFB boilers. In the design principle of large-scale CFB boilers, the number and location of SA nozzles should be reasonably arranged.

Figure 14 shows the simulation results of SA penetration depths and lateral diffusion distances under the 60% BMCR load. It can be found from the figure that they have opposite trends, i.e., the lateral diffusion distance of the SA with large penetration depth was smaller, and the lateral diffusion distance of the SA with small penetration depth was larger. According to the law of mass conservation, the influence area of the SA jet and diffusion is fixed when the inlet air volume is given, so the penetration depth of SA jet is opposite to the lateral diffusion distance. The diffusion curves of the SA jet in this figure well reflect the relationship between them.

Figure 14. Simulation results of SA penetration depth and lateral diffusion distance under 60% BMCR load.
Regardless of the influence of the penetration depth and the lateral diffusion distance of the SA nozzles at the front and rear walls on the overall uniformity, the standard deviations of the penetration depth and lateral diffusion distance of the SA under different loads were obtained, as shown in Table 6. Overall, the standard deviations of SA penetration depth and lateral diffusion distance were small under different loads, but a comprehensive comparison showed that the diffusion uniformity of SA was better at the 80% BMCR load. The main reason is that the volume flow rate of the SA and the solid concentration in the dense phase zone were different under various loads, which led to the difference in the obstruction effect of the SA at the nozzles. At 60% BMCR load, the penetration depth was short, but the lateral diffusion distance was relatively large, resulting in poor lateral diffusion uniformity of the SA. At 100% BMCR load, the penetration depth was large and the lateral diffusion distance was relatively small, which also led to poor jet penetration uniformity. At 80% BMCR load, the SA jet penetration and lateral diffusion were hindered equally, and the jet deflection and mutual interference were small. Therefore, the load changes had a certain impact on the gas-solid flow and mixing in the furnace. Operators need to adjust the SA flow rate reasonably according to load changes, so as to achieve better gas-solid mixing performance and improve combustion uniformity in the furnace.

Table 6. Standard deviations of penetration depth and lateral diffusion distance of SA under various boiler loads (unit: m).

| Item    | SA Port | 60% BMCR | 80% BMCR | 100% BMCR |
|---------|---------|----------|----------|-----------|
| Penetration | OUSA    | 0.131    | 0.043    | 0.147     |
|          | IUSA    | 0.085    | 0.091    | 0.089     |
|          | ILFA    | 0.046    | 0.041    | 0.111     |
| Dispersion | OUSA    | 0.163    | 0.110    | 0.070     |
|          | IUSA    | 0.217    | 0.065    | 0.150     |
|          | ILFA    | 0.174    | 0.123    | 0.082     |

3.5. Prediction of the Thermal SA Penetration Depth

The ideal situation is to get the distribution of gas concentration along the cross-section of furnace, and the best way to do so is to establish a comprehensive model of fuel dispersion and chemical reaction, considering the influence of the SA jet and fuel distribution on profiles of gas composition. Yang et al. [30] proposed a penetration depth model of the SA jet without considering the jet angle, and the penetration depth calculated was 0.869 m, which is different from the actual test and simulation results. This paper made a prediction of the SA penetration depth based on the simulation results of non-uniform SA distribution and previous measured values [16]. In order to avoid the influence of SA lateral diffusion, only the results under the 60% BMCR load were modeled. The main solution is as follows: (1) the background concentration of each SA nozzle was characterized by the solid concentration in each area of the cross-section of the furnace; (2) the air velocity was converted according to the SA velocity distribution and the DCS data during thermal operation of the boiler; (3) the classical calculation model of SA penetration depth was modified, considering the inclined jet and the expansion process of SA. In the SA jet of gas-solid flow, the momentum model of the cross jet has been widely adopted, as described by Equation (20):

\[
\frac{x}{d_0} = K \left( \frac{\rho_s u_{SA}^2}{\rho_g u_{PA}^2 + C u_P^2} \right)^{0.5}
\]

where \(x\) is the penetration depth of SA, \(d_0\) is the diameter of the SA nozzles, \(\rho_s\) and \(\rho_g\) are the densities of the solid and gas, respectively, \(u_{SA}\), \(u_{PA}\), and \(u_P\) are the velocities of secondary air, primary air and solid particles, respectively. \(K\) and \(C\) are undetermined coefficients, and the value of \(K\) depends on the nozzle shape and spray angle, which is generally an empirical value. As mentioned above, the 30-degree jet and the expansion of SA should be considered in the case. For the jet angle, the blocking effect of upwards flow...
was replaced by the longitudinal component of SA. For the temperature rise and volume expansion, our previous studies showed that the SA was heated up to the corresponding furnace temperature within 0.5 m from the side wall, and the solid volume fraction at the height of the upper SA reached 0.99 [16], so the momentum consumption caused by the entrainment in a short distance and a short time could be ignored. Therefore, the position of 0.5 m away from the side wall was regarded as the starting point of the jet flow, and the parameters of the SA jets were subject to the temperature of the main flow. Equation (20) is thus rewritten as:

$$x - l = Kd_0 \left( \frac{\rho_s' (u_{SA}' \cos \alpha_b)^2}{\rho_s ' u_{SA}^2 + C u_p^2} \right)^{0.5}$$

(21)

where the value of \(l\) is obtained by measuring the temperature profile along the jet direction of SA, which was tentatively determined to be 0.5 m in this paper. \(\alpha_b\) is the angle between the SA jet and the horizontal direction. After a fitting calculation, the values of \(K\) and \(C\) were determined to be 1.52 and 0.76, respectively. The penetration depth of actual thermal SA jets under more conditions were predicted using the modified model and the model proposed by Yang et al. [30], which are exhibited in Figure 15. The modified model shows that the results calculated by Yang are all smaller than the numerical results, while the results calculated by Equation (21) match well with the numerical and experimental values at 60% BMCR load. This might be explained if the model proposed by Yang et al. were summarized according to the test results on a bench-scale facility with horizontal SA injection, and there are certain limitations when applying Yang’s model on a large-scale CFB boiler. Additionally, it was found that the penetration depth in each level was significantly larger than the corresponding simulated results or measured values at 100% BMCR load. This was mainly because the solid concentration in the SA region was higher under high boiler load, and a single SA jet could be affected by the lateral diffusion and mixing of adjacent SA jets. Thus, this calculation model is more suitable for the prediction of SA penetration depth at low boiler load.

![Figure 15](image-url)  
*Figure 15. Prediction of SA penetration depth under 60% and 100% BMCR loads with actual SA velocity distributions.*

4. Conclusions

In this paper, the Eulerian–Eulerian model was used to simulate the gas-solid flow in the first 600 MW supercritical CFB boiler to discuss the influence of SA distribution...
uniformity. The characteristics of jet penetration and the lateral diffusion of the SA system under different SA velocity distributions and boiler loads were investigated, and the changes to the gas-solid mixing characteristics along furnace height were analyzed in detail. Eventually, a calculation model to predict the penetration depth of the thermal SA jet was successfully proposed. The key results are as follows:

1. The distribution uniformity of SA had a great influence on the penetration and lateral diffusion distance of the SA jet. Non-uniform SA led to the deviation of kinetic energy at the inlet of each SA nozzle, especially the SA ports on the front and rear walls.
2. Under the condition of uneven SA distribution, the deviation of solid concentration was greater than that when under uniform SA distribution, especially in these areas below 10 m from the air distributor with a doubled deviation.
3. With the increase of load, the penetration depth and lateral diffusion distance of SA jets increased, while the uniformity of SA diffusion was best at the 80% BMCR load, indicating that it was not linear with the increase of load.
4. Jet angle and volume expansion were taken into consideration in the proposed calculation model of SA penetration depth, and the predicted value was more accurate at 60% BMCR load. Due to the influence of adjacent SA diffusion, the deviation of predicted value at high load could exceed 20%.

Author Contributions: Conceptualization, J.Y. and X.L.; investigation, J.Y., X.Z.; methodology, J.Y. and J.W.; writing—original draft preparation, J.Y.; writing—review and editing, X.Z. and J.W.; validation, J.Y. and J.W.; All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the Scientific Research Start-up Foundation funding of High-level Introduction Talents of Nanjing Institute of Technology (Grants No. YKJ201962) and the Prospective Project of Industry and University of Nanjing Institute of Technology (Grants No. CXY202006).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: Authors are thankful to the stuff from Baima Power Plant for valuable support during the research.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

- $t$: time, s
- $v$: velocity, m/s
- $P$: pressure, Pa
- $P_s$: particle phase pressure, Pa
- $g$: gravitational acceleration, m$^2$/s$^2$
- $\beta_{gs}, \beta_{sg}$: interphase exchange coefficient of momentum, kg/(m$^3$.s)
- $k$: Turbulence kinetic energy, m$^2$/s$^2$
- $U$: phase weighed velocity, m/s
- $C_k$: generation of turbulence kinetic energy due to mean velocity
- $C_{1k}, C_{2k}, C_{3k}, C_{ij}, C_{ji}$: constant in turbulence model
- $Re$: Reynolds number
- $d_s$: particle diameter, mm
- $g_{0,ss}$: radial distribution function
- $e_{ss}$: particle-particle restitution coefficient
- $I_{2D}$: the second invariant of the deviator stress tensor
- $x$: penetration depth of SA
- $d_0$: diameter of the SA nozzle, m
- $l$: core jet length, m
CFB circulating fluidized bed
ILSA inner lower SA
IUSA inner upper SA
OUSA outer upper SA
PA primary air
SA secondary air
$\alpha_b$ angle between the SA jet and the horizontal direction
$K$ constant
$C$ constant

Greek letters
$\alpha$ volume fraction
$\mu$ dynamic viscosity, Pa·s
$\mu_t$ turbulence viscosity, Pa·s
$\mu_{eff}$ effective viscosity, Pa·s
$\mu_s$ solid shear viscosity, Pa·s
$\mu_{s,\text{col}}$ solid collision viscosity, Pa·s
$\mu_{s,\text{kin}}$ solid kinetic viscosity, Pa·s
$\mu_{s,\text{fr}}$ solid frictional viscosity, Pa·s
$\rho$ density, kg/m$^3$
$\tau$ shear stress, N/m$^2$
$I$ identity matrix
$\varepsilon$ turbulence dissipation rate
$\sigma$ turbulent Prandtl numbers
$\Theta_s$ granular temperature, m$^2$/s$^2$
$\theta$ angle of internal friction
$\lambda_s$ granular bulk viscosity, Pa·s

Subscripts
i, j gas or solid phase, i and j are different
g gas
s solid
max maximum
SA secondary air
PA primary air
p solid particles

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