



Article Computational Particle Fluid Dynamics Simulation on Combustion Characteristics of Blended Fuels of Coal, Biomass, and Oil Sludge in a 130 t h⁻¹ Circulating Fluidized Bed Boiler

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Abstract: In this study, the co-combustion of coal and biomass, and the tri-combustion of coal, biomass, and oil sludge in a 130 t h⁻¹ circulating fluidized bed (CFB) boiler are investigated via the computational particle fluid dynamics (CPFD) approach. Furthermore, the effect of biomass feeding position is also comprehensively evaluated. The results show that for the co-combustion of coal and biomass, the O₂ mole fraction at the furnace outlet rises from 0.0541 to 0.0640 as the biomass blending ratio enhances from 40% to 100%, while the CO₂ mole fraction reduces from 0.1357 to 0.1267. The mole fraction of NO_x and SO₂ at the furnace outlet decreases from 4.5867 × 10⁻⁵ to 3.9096 × 10⁻⁵ and 2.8253 × 10⁻⁴ to 4.6635 × 10⁻⁵, respectively. For the tri-combustion of three fuels, the average NO_x mole fraction initially grows quickly and then declines gradually, ranging from 4.1173 × 10⁻⁵ to 4.2556 × 10⁻⁵. The mole fraction of SO₂ at the furnace outlet increases from 3.5176 × 10⁻⁴ to 4.7043 × 10⁻⁴ when the ratio of oil sludge rises from 10% to 20%. The uniformity of temperature and gas components distribution is "new inlet > secondary air inlet > feed inlet". As for the three inlet positions, the mole fractions of NO_x at the furnace outlet are between 3.9096 × 10⁻⁵ and 5.1537 × 10⁻⁵, while those for SO₂ are between 2.5978 × 10⁻⁴ and 2.5278 × 10⁻⁴.

Keywords: tri-combustion; CPFD; CFB boiler; combustion characteristics; NO_x emission

1. Introduction

The consumption of fossil energy continues to increase with the sustained economic growth and increased industrial demand [1,2]. The extensive utilization of fossil energy leads to problems such as environmental pollution and the greenhouse effect, which have become key issues that need to be solved urgently [3,4]. China is a large coal-consuming country. To reduce the impact of excessive coal utilization on the environment and alleviate the pressure brought on by the energy crisis, utilizing renewable energy to partially replace coal has become an important direction of current research [5]. Among the many renewable energy sources, biomass, as environmentally friendly, renewable, and widely sourced, has received widespread attention in recent years [6,7].

Currently, the predominant method of utilizing biomass is thermochemical conversion (including pyrolysis, gasification, and combustion), in which direct combustion accounts for 97% of the total biomass energy generation [8–10]. However, the direct combustion of biomass results in many problems such as ash deposition, slagging, and rusting, which



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). could be effectively alleviated by the co-combustion of biomass and coal [11]. Many researchers [12–14] have carried out investigation on the co-combustion characteristics of coal and biomass. Yang et al. [13] discussed the combustion and NO_x emission characteristics during the co-combustion of biomass and coal. The results showed that co-combustion coal with biomass could effectively reduce pollutant emissions, but it also caused a decrement in the temperature in the furnace. Zhou et al. [12] applied the double Euler method to conduct a numerical simulation on a circulating fluidized bed (CFB) boiler, and verified the accuracy of the selected model. According to numerous research findings [15,16], they found that the co-combustion of coal and biomass could reduce the emissions of gas phase pollutants like NO_x from the fluidized bed. The existing research mainly focuses on power plant boilers. However, the effect of blending biomass on the combustion characteristics of CFB boiler remains to be further discussed.

In the production process of oil fields, it is inevitable to produce oil sludge, which consists of water, oil, and sediment, among other constituents [17]. Oil sludge is rich in petroleum hydrocarbons, which will cause serious pollution to the environment and even endanger human health. In addition, oilfield sludge has been identified as hazardous waste by most countries and must be disposed of [18]. Among various disposal technologies for oil sludge, incineration has received extensive attention because it could achieve harmless disposal and utilize the heat energy in sludge [19]. However, oil sludge has a high water content and is difficult to ignite. Therefore, oil sludge is usually blended with other fuels for incineration [18]. To fully utilize the oil sludge resource, some coal could be partially substituted by CFB boilers to co-dispose oil sludge. In addition, the cost of treating oil sludge could be avoided and the secondary pollution brought on by its disposal could be properly and effectively disposed of, and biomass resources might be fully utilized via the tri-combustion of coal, biomass, and oil sludge in a CFB boiler.

The Euler–Euler approach, as a continuum model for the interaction force of a fluid and a solid, was adopted in the majority of earlier investigations [20,21]. However, it is unable to account for movement process such as particle collisions and the impact of particle size distribution, which are fundamentally distinct from the process itself. As a way to solve this problem, the computational particle fluid dynamics (CPFD) method is gradually becoming the center of attention of researchers [22]. Compared with traditional computational fluid dynamics (CFD), the CPFD method could model particles with diverse particle size distributions as well as the background of a massive number of particles in the engineering industry, which provides an efficient technological method for simulating CFB boilers employed in industrial settings [23]. Recently, some researchers [24–28] have applied the CPFD method to conduct various numerical simulations. Their main focus was on the simulation of the reaction process in coal gasification, combustion process, and other related concerns. Unfortunately, few studies have been performed on numerical simulations of coal and biomass co-combustion using the CPFD method. In addition, to our knowledge, no research has employed the CPFD method to study the tri-combustion characteristics of coal, biomass, and oil sludge. Given that the CFB boiler is key equipment in the oil field production process, it faces tremendous pressure to reduce CO₂ emissions and protect the environment. Furthermore, the traditional CFD method has great limitations in simulating the combustion characteristics in the CFB boiler. Therefore, the study on applying the CPFD method to simulate the combustion characteristics of blended fuels of coal, biomass, and oil sludge in CFB boilers is an urgent need.

To evaluate the combustion characteristics of blended fuels of coal, biomass, and oil sludge in a 130 t h^{-1} CFB boiler, the CPFD numerical simulation approach is employed in this work. The co-combustion of coal and biomass, tri-combustion of coal, biomass, and oil sludge, and the effect of biomass feeding position are explored in depth. This study could serve as guidance for the combustion of blended fuels of coal, biomass, and oil sludge in CFB boilers.

2. CPFD Methods

In this study, the combustion of blended fuels of coal, biomass, and oil sludge in a CFB boiler is simulated utilizing Barracuda 17.4, employing the CPFD approach, which applies the multiphase particle in-cell (MP-PIC) method to calculate the coupling of continuous fluid and high-density particles in three-dimensional space.

2.1. Mathematical Models

2.1.1. Governing Equations

The gas phase is processed via the Eulerian method. Based on the Navier–Stokes equation, the turbulence adopts the large eddy simulation (LES) method [29]. For the particle phase, the Lagrangian method is employed to describe it. During simulation calculations, the solid and the gas phases are coupled. The main governing equations are listed in Table 1 [30–33].

Table 1. Main governing equations of gas and particle phase.

Items	Equations
Continuity equation (gas phase)	$rac{\partial (heta_{ m f} ho_{ m f})}{\partial t} + abla \cdot (heta_{ m f} ho_{ m f} u_{ m f}) = \delta \dot{m}_{ m s}$
Momentum equation (gas phase)	$\frac{\partial(\theta_{\rm f}\rho_{\rm f}u_{\rm f})}{\partial t} + \nabla \cdot (\theta_{\rm f}\rho_{\rm f}u_{\rm f}u_{\rm f}) = -\theta_{\rm f}\nabla p + F + \theta_{\rm f}\rho_{\rm f}g + \nabla \cdot (\theta_{\rm f}\tau_{\rm f})$
Species equation	$\frac{\partial(\theta_{t}\rho_{f}Y_{f,i})}{\partial t} + \nabla \cdot \left(\theta_{f}\rho_{f}Y_{f,i}u_{f}\right) = \nabla \cdot \left(\theta_{f}\rho_{f}D_{f,i}\nabla Y_{f,i}\right) + \delta \dot{m}_{k,\text{react}}$
Energy equation	$\frac{\partial(\theta_{\mathbf{f}}\rho_{\mathbf{f}}h_{\mathbf{f}})}{\partial t} + \nabla \cdot \left(\theta_{\mathbf{f}}\rho_{\mathbf{f}}h_{\mathbf{f}}u_{\mathbf{f}}\right) = \theta_{\mathbf{f}}\left(\frac{\partial p}{\partial t} + \mu_{\mathbf{f}} \cdot \nabla p_{\mathbf{f}}\right) - \nabla \cdot \left(\theta_{\mathbf{f}}q\right) + S_{\mathbf{f}p} + S_{\mathbf{f}w} + \dot{Q}_{D} - H_{r\mathbf{f}}$
Transport equation (particle phase)	$rac{\partial f}{\partial t}+rac{\partial (f v_{ m p})}{\partial x_{ m p}}+rac{\partial (f A)}{\partial v_{ m p}}=0$
Particle trajectory [30,31]	$rac{\mathrm{d}}{\mathrm{d}t}(v_\mathrm{p}) = D_\mathrm{s}(v_\mathrm{f}-v_\mathrm{p}) - rac{ abla p}{ ho_\mathrm{p}} - rac{ abla \tau_\mathrm{p}}{ ho_\mathrm{p}} + g + rac{\overline{v}_\mathrm{p} - v_\mathrm{p}}{2 au_\mathrm{p}} + F_\mathrm{p}$
Wenyu–Ergun drag model	$F = -\iiint f \left\{ m_{\rm s} \left[D_{\rm s} \left(v_{\rm f} - v_{\rm p} \right) - \frac{\nabla P}{\rho_{\rm p}} \right] \right\} \mathrm{d}m_{\rm p} \mathrm{d}u_{\rm p} \mathrm{d}T_{\rm p}$
Energy exchange	$m_{\rm p}C_V \frac{dT_{\rm p}}{dt} = Q_{\rm sg} + Q_{\rm radi} + Q_{\rm react} Q_{\rm pf} = \frac{\lambda_{\rm p}Nu}{d_{\rm p}} A_{\rm p} (T_{\rm f} - T_{\rm p}) Q_{\rm radi} = \sigma \varepsilon_{\rm p} A_{\rm p} (T_{\rm e}^4 - T_{\rm p}^4)$

2.1.2. Chemical Reaction Models

To simplify the calculation, a one-step reaction kinetic equation is employed to describe the combustion process of volatile gases released from three fuels [34–37]. The combustion reaction models of relevant components are shown in Table 2. Furthermore, it is assumed that the coke consists solely of carbon, with no other elements present, and that the N and S in the fuels are completely volatilized. The composition and content of the coal volatiles are calculated based on the prediction model proposed by Maffei et al. [38]. Meanwhile, it is assumed that the composition and content of the oil sludge volatiles are consistent with those of coal. Additionally, the content of gaseous pollutants is determined through ultimate analysis. The composition and content of biomass volatiles are obtained from experimental data provided by Kong et al. [39–41].

Table 2. Combustion reaction kinetic model.

Number	Reaction	Rate Equation	Reaction Rate (mol $m^{-3} s^{-1}$)
1	$H_2O_{(moisture)} \rightarrow H_2O_{(g)}$	$R1 = k1 [H_2O]$	$k1 = 5.13 \times 10^{10} \exp(-10,585/\text{T})$
2	Volatile $\rightarrow \alpha_1 \text{Tar} + \alpha_2 \text{CO} + \alpha_3 \text{CO}_2 + \alpha_4 \text{CH}_4 + \alpha_5 \text{H}_2$ + $\alpha_6 \text{H}_2 \text{O}(\text{g}) + \alpha_7 \text{NH}_3 + \alpha_8 \text{HCN} + \alpha_9 \text{H}_2 \text{S}$	R2 = k2 [Volatile]	$k2 = 0.5T \exp(-5500/T)$
3	$CO + 0.5O_2 \rightarrow CO_2$	$R3 = k3 [CO] [O_2]$	$k3 = 10^{10} \exp(-15,119/\mathrm{T})$
4	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	$R4 = k4 [CH_4] [O_2]$	$k4 = 5.01 \times 10^{11} \exp(-3430/\text{T})$
5	$H_2 + 0.5O_2 \rightarrow H_2O$	$R5 = k5 [H_2]^{1.5} [O_2]$	$k5 = 1.03 \times 10^{14} \mathrm{T}^{-1.5} \exp(-3430/\mathrm{T})$
6	$Tar + O_2 \rightarrow CO_2 + 2H_2O$	$R6 = k6 [Tar] [O_2]$	$k6 = 3.8 \times 10^7 \exp(-6710/T)$
7	$C + 0.5O_2 \rightarrow CO$	$R7 = k7 [O_2]$	$k7 = 1.47 \times 10^8 \theta_{\rm c} T \exp(-6710/T)$
8	$C + H_2O \rightarrow CO + H_2$	$R8 = k8 [H_2O]$	$k8 = 6.36m_{\rm c}T \exp(-13,590/T)$
9	$CO + H_2 \rightarrow C + H_2O$	$R9 = k9 [H_2] [CO]$	$k9 = 5.218 \times 10^{-4} m_{\rm c} T^2 \exp(-6319/T - 17.29)$
10	$C + CO_2 \rightarrow 2CO$	$R10 = k10 [CO_2]$	$k10 = 6.36m_{\rm c} T \exp(-22,645/T)$
11	$2CO \rightarrow C + CO_2$	R11 = k11 [CO]	$k11 = 5.218m_{\rm c}T^2 \exp(-2363/T - 20.92)$
12	$H_2S + 1.5O_2 {\rightarrow} H_2O + SO_2$	$R12 = k12 [H_2S] [O_2]$	$k12 = 5.2 \times 10^8 \exp(-19,300/\text{RT})$

According to previous studies [42,43], thermal NO_x and fast NO_x in CFB boilers could be ignored due to the furnace temperature typically being below 1000 °C, and the anoxic combustion occurs in the dense phase region. A suitably simplified NO_x mechanism is adopted to describe NO_x generation, assuming that all N and S in the coal and biomass are contained in volatiles. The relevant NO_x models are listed in Table 3 [24–26,37].

Table 3. NO_x formation and reduction kinetic model.

Number	Reaction	Rate Equation	Reaction Rate (mol m ^{-3} s ^{-1})
13	$HCN + 0.5O_2 \rightarrow CNO + 0.5H_2$	$R13 = k13 [O_2] [HCN]$	112 14 2 14 · · 105 · · · (10 000 /T)
14	$CNO + 0.5O_2 \rightarrow NO + CO$	$R14 = k14 [O_2] [CNO]$	$k_{13}-14 = 2.14 \times 10^{5} \exp(-10,000/1)$
15	$NH_3 + 1.25O_2 \rightarrow NO + 1.5H_2O$	$R15 = k15 [O_2] [NH_3]$	$k_{15} = 2.73 \times 10^{14} \exp(-38,160/\mathrm{T})$
16	$NO + CO \rightarrow 0.5N_2 + CO_2$	R16 = <i>k</i> 16 [CO] [NO]	$k_{16} = 2.51 \times 10^{11} \exp(-10,000/T)$
17	$NO + C \rightarrow 0.5N_2 + CO$	R17 = <i>k</i> 17 [NO]	$k17 = 1.17 \times 10^5 \exp(-13,221/T)$
18	$NH_3 + NO + 0.5O_2 \rightarrow N_2 + 1.5H_2O$	R18 = $k18$ ([NO] [O ₂] [NH ₃]) ^{0.5}	$k18 = 1.11 \times 10^{12} \exp(-29,400/\mathrm{T})$

2.2. Computational Geometry and Mesh

2.2.1. Boiler Structure and Geometry

The computational geometry for this study is a CFB boiler with a capacity of 130 t h⁻¹. As depicted in Figure 1, the boiler system in investigation is engineered with a solitary drum structure, underpinned by a natural circulation mechanism. It incorporates an adiabatic cyclone for gas–solid separation to reduce heat loss. The convection heating surface is meticulously arrayed within the convection flue of shaft to optimize thermal exchange. Pertaining to its performance characteristics, the boiler is rated with a saturated steam pressure of 9.81 MPa and a saturated steam temperature is 310 °C. Moreover, it operates with a thermal efficiency that exceeds 90%. The symmetrical half of the boiler is applied as the computing domain to simplify and speed up the calculations.



Figure 1. Geometric model of CFB boiler (a) Boundary conditions (b) Dimensions.

2.2.2. Meshing and Validation

In this study, the Cartesian meshing technique is applied to generate a high-quality grid. To reduce the difficulty of grid generation and computational cost, the complex structures are appropriately simplified. To capture the fine structure, the mesh of the fine structure is refined. Figure 2 illustrates the meshing.



Figure 2. Computational grid.

To confirm the effect of the grid on the calculation results, the average temperatures of the cross-section of height direction alone the furnace are compared under the 491,000, 689,000, and 885,000 grids in this study. As shown in Figure 3, the results indicate that the average temperature varies significantly when 491,000 grids are employed. The cross-section average temperature tends to remain stable as the grids number rises from 689,000 to 885,000, demonstrating that the computation accuracy is comparable. Therefore, 689,000 grids are chosen for ensuring simulation accuracy and simultaneously minimizing computational expense and time.



Figure 3. Average temperature distribution versus the furnace height for various meshes.

2.2.3. Model Validation

To verify the accuracy of the model, the simulation results are compared with the measured data. As shown in Table 4, the numerical simulation results are in good agreement with the measured data. The relative errors of bed temperature, bed pressure, and furnace outlet flue gas temperature are of less than 1.13%, 2.69%, and 0.84%, respectively. Therefore, the simulation results could be considered credible.

Parameter	Numerical Result	Measured Data	Relative Error
Bed temperature	922.3 °C	912.0 °C	1.13%
Bed pressure	6.15 kPa	6.32 kPa	2.69%
Outlet gas temperature	856.6 °C	851.0 °C	0.65%

Table 4. Comparison of simulation results with measured data.

2.3. Materials Property and Simulation Conditions

2.3.1. Fuels and Bed Material

In this study, coal, biomass, and oil sludge are selected for analysis (collected from Karamay, Xinjiang Province, China). These three fuels have low calorific values of 19.28, 16.12, and 7.99 MJ/kg, respectively. The results of the ultimate and proximate analyses of the three fuels are shown in Table 5.

Table 5. Ultimate and proximate analyses of coal, biomass, and oil sludge (wt %, as received basis).

Samplas	Ultimate Analysis			Proximate Analysis					
Samples -	С	Н	O ^a	Ν	S	FC ^a	M	A	V
Coal	52.74	2.77	11.19	1.04	0.61	43.08	22.00	9.66	25.26
Biomass	43.29	5.15	37.74	0.46	0.04	16.08	6.70	6.61	70.61
Oil sludge	21.12	3.10	0.27	0.17	0.52	2.23	41.6	33.22	22.95

^a By difference.

The main components of the bed material are sand and ash. The bed material is viewed in the simulation as a single, inert entity. The maximum particle size of bed material should not be more than 3 mm, and the mass proportion of less than 100 mm should not be more than 25%. The biomass particle size complies with the following standards: less than 5 mm in diameter, less than 10 mm in cross-sectional dimension, and less than 30 mm in length. Less than 5% of them have a mass percentage of less than 10 mm in diameter and length. The particle size distribution of coal/oil sludge is shown in Figure 4.



Figure 4. Particle size distribution of coal/oil sludge.

2.3.2. Simulation Conditions

Before the simulation, the state of fluid state and its particle makeup are specified in the computational domain. The flow of gas is parallel to the surface. Based on industry data, the gas parameters are additionally provided. A specific number is chosen for the boundary pressure at the top outflow of cyclone. The thermal wall is employed to characterize the remaining constraints. The surface of the cyclone separator and the conical portion of the furnace bottom are believed to be adiabatic walls. There is a radiative emissivity of 0.7 for the wall. The simulation lasts 30 s with the standard scenario of using coal as fuel. Table 6 provides a summary of the main simulation parameters and base case operational circumstances.

Table 6. Operating conditions and simulation settings.

Parameters	Value
Initial height of bed (mm)	500
Coal feed (kg/s)	2.382
Primary air (kg/s)	14.5805
Primary air temperature (°C)	180.0
Primary air pressure (Pa)	109,030.5
Secondary air (kg/s)	5.1292
Secondary air temperature (°C)	170.0
Secondary air pressure (Pa)	102,634.0
Return air (kg/s)	0.293
Return air temperature (°C)	38.0
Return air pressure (Pa)	113,127.0
Water wall temperature (°C)	332.0
Particle normal-to-wall retention coefficient	0.99
Particle tangential-to-wall retention coefficient	0.3
Radiation emissivity (%)	70
Time step (s)	$5 imes 10^{-4}$

3. Results and Discussion

3.1. Co-Combustion of Coal and Biomass

To investigate the effect of blending ratio on co-combustion characteristics of coal and biomass. The blending ratios of biomass are selected as 40%, 50%, 60%, 80%, and 100%, respectively. To ensure constant boiler output, the total amount of fuel is calculated based on the weighted average low calorific value of the mixed fuel. The air amount calculation process is as follows: Firstly, the theoretical air amount is calculated according to the ultimate analysis of the three fuels. Then, according to the field operation data, the excess air coefficient is selected to be 1.28, so that the actual air amount could be calculated. Finally, according to the air amount ratio in the actual operation process, the air amount of primary air, secondary air and return air is obtained. Table 7 lists the simulation parameters for different cases.

Table 7. Simulation parameters for different cases.

Case	Mixing Ratio (Coal/Biomass, wt%)	Feeding Amount (kg/s)	Primary Air Amount (kg/s)	Secondary Air Amount (kg/s)	Return Air Amount (kg/s)
Case 1	60:40	2.550	14.234	5.007	0.286
Case 2	50:50	2.595	14.140	4.972	0.284
Case 3	40:60	2.642	14.041	4.940	0.282
Case 4	20:80	2.742	13.834	4.868	0.278
Case 5	0:100	2.849	13.611	4.788	0.274

3.1.1. Flow Characteristics

Taking case 2 as an example, Figure 5 illustrates the variation in flow pattern with time from 0 to 30 s. Within 0–10 s, the particles gradually fluidize, and the bed rises, with some particles entering the cyclone separator to participate in circulation. After 18 s, the flow pattern of the particles gradually stabilizes, which is similar to the results of Shen et al. [36]. To reduce the impact of particle migration on the results, 20–30 s are selected for time average statistical analysis.





3.1.2. Combustion Characteristics

The distribution of the average temperature of the furnace in various cases is shown in Figure 6. It can be seen from the figure that the furnace temperature distribution is basically the same under different biomass blending ratios. Because of the combustion of fuel and the circulation of a large amount of high-temperature materials from the cyclone separator, the furnace temperature rises sharply. The furnace temperature achieves its maximum at approximately 0.5 m from the bottom. The introduction of a large amount of low-temperature air at the secondary air inlet reduces the furnace temperature. The water-cooled walls arranged along the height of the furnace absorb a large amount of heat, causing the temperature of the furnace to gradually drop. As the biomass blending ratio increases, the furnace temperature gradually decreases, which may be related to the lower calorific value of the material and the larger particle size. The furnace outlet flue temperature decreases from 1122.2 to 1114.2 K as the biomass blending ratio goes from 40% to 100%.



Figure 6. Average temperature distribution along furnace height for various cases.

3.1.3. Gas Emission

Figure 7 shows the gas component distribution along the height direction of the furnace under different cases. It can be seen from the figure that the average mole fraction of O_2 first decreases rapidly along the height direction of the furnace, indicating that the fuel particles burn rapidly, increase at the secondary air inlet, and then gradually decrease overall. Table 8 illustrates the temperature and main gas mole fractions of furnace outlet under cases 1 to 5. An upward adjustment of the biomass blending ratio from 40% to 100% correlates with a rise in the mole fraction of O_2 at the furnace outlet, ascending from 0.0541 to 0.0640. Concurrently, there is an observed decrement in the mole fraction of CO_2 , which diminishes from 0.1357 to 0.1267. Upon introduction of the heterogeneous fuel into the furnace, an intense combustion reaction is initiated, precipitating a localized deficit of O_2 and, consequently, the incomplete oxidation of a fraction of the fuel. The NO_x distribution changes along the furnace height direction in different cases are almost the same, increasing rapidly at first and then gradually decreasing. N-containing volatiles release a large amount of NO_x through violent combustion; so, the NO_x mole fraction increases rapidly. Subsequently, NO_x is reduced to N₂ by coke and CO, and the mole fraction gradually decreases. As the biomass blending ratio increases from 40% to 100%, the NO_x mole fraction at the furnace outlet decreases from 4.5867 \times 10⁻⁵ to 3.9096×10^{-5} . The SO₂ mole fraction drops from 2.8253×10^{-4} to 4.6635×10^{-5} , which corresponds to the ultimate analysis results of coal and biomass (see Table 5).

Cases	Temperature (K)	O ₂	NO _x	SO ₂
Case 1	1122.2	0.0541	$4.5867 imes 10^{-5}$	$2.8253 imes10^{-4}$
Case 2	1119.7	0.0549	$4.3185 imes 10^{-5}$	$2.5978 imes10^{-4}$
Case 3	1119.5	0.0608	$4.2585 imes 10^{-5}$	$2.1631 imes10^{-4}$
Case 4	1117.2	0.0637	$3.9170 imes 10^{-5}$	$1.3463 imes10^{-4}$
Case 5	1114.2	0.0640	3.9096×10^{-5}	$4.6635 imes 10^{-5}$

Table 8. Temperature and main gas mole fractions of furnace outlet under cases 1 to 5.



Figure 7. Gas mole fractions distribution along furnace height for various cases.

3.2. Tri-Combustion of Coal, Biomass, and Oil Sludge

Five distinct blending ratios are selected to examine the tri-combustion characteristics of coal, biomass, and oil sludge. As mentioned before, the total fuel feeding amount is determined by the low calorific value of the three fuels. The excess air coefficient is 1.28. The simulation parameters for several cases are listed in Table 9.

Table 9. Simulation parameters for various cases.

Case	Blending Ratio (Coal/Biomass/Oil Sludge, wt%)	Feeding Amount (kg/s)	Primary Air Amount (kg/s)	Secondary Air Amount (kg/s)	Return Air Amount (kg/s)
Case 6	50:35:15	2.787	14.554	5.120	0.292
Case 7	45:35:20	2.886	14.658	5.156	0.295
Case 8	45:45:10	2.745	14.361	5.052	0.289
Case 9	40:45:15	2.841	14.456	5.084	0.291
Case 10	35:45:20	2.945	14.559	5.122	0.293

3.2.1. Furnace Temperature Distributions

The distribution of the average temperature of the furnace section along the furnace height direction under various cases is shown in Figure 8. Similar to the co-combustion of coal and biomass, the furnace temperature change trends in different calculation examples are essentially the same. The furnace temperature initially increases rapidly, decreases at the secondary air inlet, then increases slightly, and finally decreases gradually along the height direction of the furnace. The increase in the blending ratio of sludge and biomass reduces the average temperature of the furnace. The furnace outlet flue gas temperature ranges from 1117.9 to 1120.4 K under different cases.



Figure 8. Average temperature distribution along furnace height under different excess air ratios.

3.2.2. Gas Emission

The distribution of the average mole fraction of gas components along the furnace height direction for different cases is illustrated in Figure 9. It is obvious that the average mole fraction of O_2 decreases rapidly initially, increases at the secondary air inlet, and then decreases slowly, which indicates that the fuel particles combust rapidly at the bottom of the furnace. Table 10 shows the temperature and main gas mole fractions of furnace outlet under cases 6 to 10. An augmented biomass proportion is associated with a diminished requisite for O_2 . As the biomass blending ratio is escalated from 35% to 50%, there is a discernible increment in the molar fraction of O_2 at the furnace outlet, which intensifies from 0.0606 to 0.0667. The average mole fraction of CO_2 shows an opposite trend to that of O_2 . When the blended fuel enters the dense phase zone, it burns violently, resulting in a local lack of oxygen and incomplete combustion of part of the fuel. Therefore, optimization of the secondary air could be considered to ensure complete combustion of the blended fuels.

The changes in the average mole fraction of NO_x along the furnace height direction are almost the same in different cases, with an initial rapid increase and then a gradual decrease. The violent combustion of volatiles releases a large amount of NO_x, causing its mole fraction to increase rapidly. Subsequently, NO_x is reduced to N₂ by coke and CO. The NO_x mole fraction at the furnace outlet is between 4.1173×10^{-5} and 4.2556×10^{-5} . The distribution of SO₂ along the furnace height is tightly related to the blending ratio of different fuels. In general, the rise in the coal and oil sludge blending ratio promotes the increase in the average mole fraction of SO₂, which corresponds to the ultimate analysis results (see Table 3). It is worth noting that when the oil sludge ratio increases from 10% to 20%, the SO₂ mole fraction at the furnace outlet increases from 3.3041×10^{-4} to 4.7043×10^{-4} . Therefore, attention should be paid to the removal of SO₂ when blending oil sludge.



Figure 9. Gas mole fractions distribution along furnace height for various excess air ratios.

Cases	Temperature (K)	O ₂	NO _x	SO ₂
Case 6	1120.4	0.0626	$4.2556 imes 10^{-5}$	4.1735×10^{-4}
Case 7	1117.9	0.0623	$4.1440 imes 10^{-5}$	4.7043×10^{-4}
Case 8	1119.7	0.0606	$4.1404 imes10^{-5}$	$3.3041 imes10^{-4}$
Case 9	1119.6	0.0631	$4.1207 imes 10^{-5}$	$3.9482 imes10^{-4}$
Case 10	1118.6	0.0667	$4.1173 imes10^{-5}$	$4.3007 imes10^{-5}$

Table 10. Temperature and main gas mole fractions of furnace outlet under cases 6 to 10.

3.3. Effect of Biomass Inlet Position

To study the effect of biomass inlet position on combustion characteristics, in addition to feeding biomass from the feed inlet, two other biomass inlet positions are selected, namely the secondary air inlet and the new inlet (1 m above the secondary air inlet).

3.3.1. Furnace Temperature Distributions

Figure 10 shows the gas phase temperature distribution of the entire CFB boiler under different biomass inlet positions. It can be seen from the figure that the overall temperature trend in the furnace is similar under different inlet positions. Compared with feeding biomass fuel through the feed inlet and secondary air inlet, the temperature distribution of



the biomass furnace fed from the new inlet is more uniform, which indicates that feeding biomass from the new inlet is beneficial to promoting the combustion of the blended fuel.

Figure 10. Temperature distribution for different biomass inlet positions.

3.3.2. Gas Emission

Figure 11 shows the distribution of different gas components in the CFB boiler under different biomass inlet positions. It can be seen from the figure that since the total air amount remains unchanged, the distribution of O_2 and CO_2 in the furnace is almost the same under different biomass inlet positions. The uniformity of O₂ and CO₂ distribution under the three biomass inlet positions is that the new inlet has the best uniformity, followed by the secondary air inlet and the feed inlet has the worst. This phenomenon corresponds to the distribution of the temperature field (see Figure 10). Upon the introduction of biomass particulates via the feed inlet, secondary air inlet, and new inlet, the mole fractions of NO_x at the furnace outlet are 3.9096 \times 10⁻⁵, 4.1022 \times 10⁻⁵, and 5.1537 \times 10⁻⁵, respectively, while the mole fractions of SO₂ are 2.5978 \times 10⁻⁴, 2.5738 \times 10⁻⁴, and 2.5278 \times 10⁻⁴, respectively. As the reaction proceeds, the formation of NO_x is limited by the increase in CO content. The increase in coke particles is also conducive to the reduction of NO_{x_i} and the content of NO_x is in a dynamic fluctuation. The mole fraction of NO_x at the furnace outlet increases after the biomass is fed through the new inlet, which may be related to the shortening of the reaction range in the reduction zone. Since the total amount of fuel input and air volume remain unchanged, the concentration of SO₂ changes slightly.



Figure 11. Cont.



Figure 11. Gas mole fractions distribution for different biomass inlet positions.

4. Conclusions

In this study, the CPFD method is employed to examine the combustion characteristics of coal, biomass, and oil sludge in a 130 t h^{-1} CFB boiler. The co-combustion of coal and biomass, tri-combustion of coal, biomass, and oil sludge, and the effect of biomass inlet position are evaluated. The conclusions that can be reached are as follows:

- (1) After 18 s of simulation, the flow of particles reaches a quasi-steady state. As the water wall continues to absorb heat, the temperature gradually decreases along the height of the furnace. When the biomass blending ratio rises from 40% to 100%, the O₂ mole fraction at the furnace outlet increases from 0.0541 to 0.0640, while the CO₂ mole fraction decreases from 0.1357 to 0.1267. The average NO_x mole fraction in the furnace height direction changes similarly, growing rapidly at first and then gradually decreasing, which could be related to the reduction of NO_x to N₂. As the biomass blending ratio increases from 40% to 100%, the NO_x mole fraction at the furnace outlet decreases from 4.5867 × 10⁻⁵ to 3.9096 × 10⁻⁵. The SO₂ mole fraction drops from 2.8253 × 10⁻⁴ to 4.6635 × 10⁻⁵.
- (2) The change trend of furnace temperature is essentially constant in different cases. When the biomass blending ratio increases from 35% to 50%, the O₂ mole fraction at the furnace outlet increases from 0.0606 to 0.0667. CO₂ shows the opposite distribution pattern. The NO_x mole fraction initially increases rapidly and then gradually decreases, with a range from 4.1173×10^{-5} to 4.2556×10^{-5} at the furnace outlet. The distribution of SO₂ along the furnace height is tightly related to the blending ratio of different fuels. As the oil sludge blending ratio rises from 10% to 20%, the mole fraction of SO₂ at the furnace outlet increases from 3.5176×10^{-4} to 4.7043×10^{-4} .
- (3) Compared with feeding biomass fuel through the feed inlet and secondary air inlet, the temperature distribution of the biomass furnace fed from the new inlet is more uniform. The uniformity of O₂ and CO₂ distribution is that the new inlet has the best uniformity, followed by the secondary air inlet and the feed inlet is the worst. When biomass particles are fed from the feed inlet, secondary air inlet, and new inlet, the mole fractions of NO_x at the furnace outlet are 3.9096×10^{-5} , 4.1022×10^{-5} , and 5.1537×10^{-5} , respectively, while the mole fractions of SO₂ are 2.5978×10^{-4} , 2.5738×10^{-4} , and 2.5278×10^{-4} , respectively.

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Nomenclature

$C_{\rm s}$	Function of the Reynolds number	$S_{\mathrm{p}\xi,k}$	Interpolation function
$D_{\rm f,i}$	Turbulent mass diffusion	t	Time
D_s	Momentum transfer coefficient	$u_{\rm f}$	Gas phase velocity
Fp	Particle fractional force	V_{ξ}	Grid cell volume
F	Momentum exchange rate	$v_{\rm p}$	Particle velocity
$h_{\rm f}$	Enthalpy of the gas phase	$x_{\rm p}$	Particle spatial position
$m_{\rm p}$	Particle mass	$Y_{\rm f,i}$	Mass fraction
Nu	Nusselt number	θ_{f}	Gas phase volume fraction
N_{p}	Total number of particles	$ ho_{ m f}$	Gas phase density
n_{pk}	Number of real particles	$ ho_{ m p}$	Particle density
P	Gas phase pressure	Δ	Length scale along the x , y , and z directions
Q _{radi}	Radiation heat transfer	$\Delta H_{\rm rf}$	Heat of reaction of the gas phase
Q_{pf}	Convective heat transfer	$\tau_{\rm D}$	Collision damping time
Q_{react}	Chemical reaction heat	$ au_{ m f}$	Stress tensor of the gas phase
Q _D	Enthalpy diffusion term	$ au_{p}$	Particle normal stress
9	Heat flux	$\mu_{\rm f}$	Shear viscosity
$S_{\rm fw}$	Heat transfer rate	μ_{t}	Turbulent viscosity

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