Numerical analysis was used to study the deposition and burning characteristics of combining co-combustion with slagging combustion technologies in this paper. The pyrolysis and burning kinetic models of different fuels were implanted into the WBSF-PCC2 (wall burning and slag flow in pulverized co-combustion) computation code, and then the slagging and co-combustion characteristics—especially the wall burning mechanism of different solid fuels and their effects on the whole burning behavior in the cylindrical combustor at different mixing ratios under the condition of keeping the heat input same—were simulated numerically. The results showed that adding wood powder at 25% mass fraction can increase the temperature at the initial stage of combustion, which is helpful to utilize the front space of the combustor. Adding wood powder at a 25% mass fraction can increase the reaction rate at the initial combustion stage; also, the coal ignitability is improved, and the burnout efficiency is enhanced by about 5% of suspension and deposition particles, which is helpful for coal particles to burn entirely and for combustion devices to minimize their dimensions or sizes. The results also showed that adding wood powder at a proper ratio is helpful to keep the combustion stability, not only because of the enhancement for the burning characteristics, but also because the running slag layer structure can be changed more continuously, which is very important for avoiding the abnormal slag accumulation in the slagging combustor. The theoretic analysis in this paper proves that unification of co-combustion and slagging combustion technologies is feasible, though more comprehensive and rigorous research is needed.

Keywords: Biomass; Co-combustion; Numerical simulation; Pulverized coal; Slagging combustion

INTRODUCTION

SO\textsubscript{x}, NO\textsubscript{x}, CO\textsubscript{x}, and dust emission from the coal combustion is one of the major causes of acid rain, holes in the ozone layer, and the greenhouse effect. Among coal combustion methods, cyclone slagging combustion may be regarded as one of
the more controversial technologies in the early years of the twentieth century for its high NOx emission due to the high combustion temperature, in spite of its contribution to the high combustion efficiency and low dust emission. Fortunately, advances in low NOx technology in recent decades have been made. The combination of technologies of slagging combustion and low NOx combustion, which have focused more and more on industrial operations of coal combustion devices, showed that the low NOx emission also can be realized in the slagging combustion as long as the proper auxiliary methods were selected. For example, using air-staged technology, pulverized coal particles carried by primary air are ejected into a combustor chamber, and the strong swirling air from another duct (i.e., secondary air) flows into the chamber and makes the particles swirl and burn under the reducing atmosphere. Most particles will move toward the wall by the strong swirling force, and the ash slag will be captured by wall. For the high combustion temperature, the ash will be melted and then removed at the liquid state. The high-temperature flue gas with some unburnt char particles will enter furnaces or boilers and react with tertiary air until burnout. Obviously, the slagging process happens in the combustor, which is the core part of the whole combustion system. The current research results (Wang et al., 2005a) showed that for some bituminous coals, the combustion efficiency can reach 99%, slag capture efficiency is higher than 90%, NOx emission is lower than 615 mg/Nm³ (163 g/GJ), and the flame is clean even if the stoichiometric ratio in the combustor is lower than 1. However, for some coal with high sulfur, nitrogen, and ash contents, it was also found that the removal efficiency of fly ash, sulfur dioxide, and nitrogen oxides were not satisfying without flue gas treatment equipment, such as dust precipitator and desulfurization device. The operating cost is still somewhat high. In a word, the combustion technology needs further modification and development.

Biomass is the world’s fourth largest energy, and its contribution fraction is about 14%. At present, co-combustion research of coal and biomass showed that the addition of biomass can not only improve the ignition characteristics of coal, but it also can reduce overall emissions of pollutants. The lower the nitrogen and sulfur and higher volatile contents in biomass, the more significant reduction effect. Recent work (Anders, 1995; Sam et al., 2001) showed that the low pollutant emission from coal and biomass co-combustion is not only due to the cleanliness of biomass itself, but it is also due to the synergistic controlling effect of pollutant generation. Thus, as for the environmental problems in the coal slagging combustor mentioned above, adding biomass content may be a possible solution. Additionally, adding biomass also can change the slag chemical components for its high alkali components in ash. According to some research results (Mao et al., 2003; Vladimirov et al., 2001), for acid coal slag, upon adding some alkali oxides, the slag will become more watery and easy to flow. The characteristics, which used to be considered as the severe problem in the biomass-fired furnaces or boilers (Abd-Elhady et al., 2007; Kær et al., 2006), can be used as the benefit to increase the slag capture and removal performance of the coal slagging combustor. However, its technical feasibility needs to be proved by experimental test or theoretical analysis.

In contrast with conventional pulverized coal combustion, which must avoid slagging and clinkering, the slagging combustion needs good slag meltability and flowability in order to remove most of ash in the liquid state. Due to the
multi-phase change process, the slagging combustion characteristics are so complex that they should be studied further. Considering the high investment and long period of pilot tests, the numerical simulation method is used in this paper to study the characteristics of slagging co-combustion, which means the slagging combustion when biomass/coal mixture fuels feeding. Obviously, there are two major characteristics that should be considered when modeling: slagging and co-combustion. As to the former, it is well-known that the temperature is sufficiently high that slag will be melt and the molten layer will capture the particles more easily. If these particles contain combustible matters, they will continue to burn and flow with the running slag, which makes the total amount of ash deposition greater than that in the dry-wall combustor, and the total heat flux through deposition surface will change greatly. For these complicated physical phenomena, Wang et al. (2005b, 2007) developed the coal slagging combustion models, including process descriptions of particle deposition, wall burning, and slag flow. In those papers, it is reported that the numerical results approach good agreement with experimental data. For the simulation method of co-combustion characteristics, it is somewhat complicated. Because of the diversity of the biomass, the combustion properties are so different. Thus, choosing the relevant kinetic models becomes difficult. In current research, the bituminous coal and wood powder are the computational fuels, for which combustion and pyrolysis kinetic constants are selected from the published literature. Integrated with these models, the computational code, named WBSF-PCC2 (wall burning and slag flow in pulverized co-combustion), is developed and used as the simulation program. The slagging co-combustion characteristics, especially the wall-burning mechanism of different solid fuels and their effects on the whole burning behavior in the combustor, will be analyzed. The applicability of slagging co-combustion technology in industrial furnaces will also be evaluated theoretically.

**METHODS**

**CFD Model Framework**

Figure 1 shows the geometrical model of a cyclone slagging combustor. The angle of combustor to horizon is 5°. The length of combustor is 1.2 m and diameter is 0.5 m. The secondary air is ejected into the combustor chamber through the annular vane with 30 mm width at the position between \( r = 210 - 240 \) mm; the vane deflection angle is 80°; and secondary air temperature is 673 K. The primary air with fuel particles is ejected into the place very near the secondary air, which will make the primary air gain the largest tangential momentum. The temperature of fuel and primary air is 300 K. The external wall surface is cooled by water stream with 373 K temperature; the average heat resistance of water stream, steel tube, flame retardant coating, and solid slag layer is \( 0.032 \) \( \text{m}^2 \cdot \text{K}/\text{W} \).

In the cyclone slagging combustor, as shown in Figure 1, the suspension combustion, particle deposition, and wall burning will take place in a certain position near the wall. At the same time, the molten slag will cover the wall and carry the deposition particles to flow forward. Thus, the computational models should consider the following processes: suspension combustion, particle deposition, wall-burning, and slag flow, as shown in Figure 2. These four models will communicate with
each other through some physical parameters, such as temperature and viscosity. Integrated with the aforementioned models, the computational code WBSF-PCC2 is developed and used as the simulation program, as shown in Figure 3.

In the simulation process, the discretized Navier-Stokes governing equations are solved using the SIMPLE algorithm. The Lagrangian separated model is adopted to treat particle flow, and the particle source in cell (PSIC) method is used to calculate the source terms come from every kind of solid particles. Compared with conventional combustion process, some difficulties should be emphasized in the numerical simulation for slagging combustion, such as:

- how to differentiate the suspension and deposition particles;
- how to unite these two kinds of combustion patterns; and
- how to design the whole computational subsequence.

To solve these problems, the algorithm of “group division” is developed. In following discussion, the trajectory of particles in a certain parcel $i$ is analyzed as an example.
At the entrance, the suspended parcel $i$ contains $N_0$ particles with the same position ($x_0, r_0$) and history time $t_0$. At the history time $t_1$, particles move to the position ($x_1, r_1$); $dN_1$ particles impinge the deposit surface and stick to it. Therefore, the residual particle number in the suspended parcel is $N_1 = N_0 - dN_1$, and these residual ones are carried by gas again; at the history time $t_2$, the residual ones will arrive at another position ($x_2, r_2$). According to the similar deposit mechanism, other $dN_2$ particles will deposit here, too. Then, the particle number in the suspended parcel is updated again, which changes to $N_2 = N_1 - dN_2$. According to this rule, at the time $t_m$ and the position ($x_m, r_m$), $dN_m$ particles deposit, and the particle number in the suspended parcel $i$ decreases to $N_m = N_{m-1} - dN_m$. Obviously, particles in the same computational parcel should be tracked by two kinds: suspended particles and deposit particles. In this paper, the conceptions of “suspended parcel” and “deposit parcel” are introduced, which are used to describe the special properties of initial parcel changing. If the deposit particles at the position $x_1$ belong to the deposit parcel marked with $i_1$, at the position $x_2$ belong to the deposit parcel marked

Figure 3 Flow chart illustration of computation code WBSF-PCC2.

Input initial conditions (Grid generation, particle properties, combustion condition, etc.)

- Computation of gaseous field without particles (Velocity, temperature, turbulent properties, etc.)
- Computation of solid phase
- Computation of source terms generated from particles in spatial space and on wall surface (Mass, momentum, energy, etc.)

Modification of heat boundary condition

Convergence?

Yes
End and output results

Particle combustion in spatial space (Turbulent dispersion, devolatilization, char combustion, radiation heat transfer by particles, etc.)

Particle deposition (Impact efficiency, sticking efficiency, deposition rate, etc.)

Wall burning for deposition particles (Group partition, devolatilization, char combustion, etc.)

Running slag flow (Thickness, velocity, additional heat resistance, etc.)

Particle combustion in spatial space (Turbulent dispersion, devolatilization, char combustion, radiation heat transfer by particles, etc.)

Particle deposition (Impact efficiency, sticking efficiency, deposition rate, etc.)

Wall burning for deposition particles (Group partition, devolatilization, char combustion, etc.)

Running slag flow (Thickness, velocity, additional heat resistance, etc.)
with $i_2$, and at the position $x_{_{im}}$ belong to the deposit parcel marked with $i_m$, one initial computational parcel that is totally composed of suspended particles should be divided into one suspended parcel for which the particle number is decreasing step by step and $m$ deposit parcels during the slagging combustion process, as shown in Figure 4. For $N$ initial parcels, the suspended parcel and every deposit parcels total up to $N(1+m)$ have been tracked in this paper. Using the “group division” method, the suspension and wall burning characteristics can be united and calculated.

Sub-Models Description

As mentioned above, the simulation process needs sub-models of flow, pyrolysis, combustion, deposition, wall burning, and slag running, among others. For gaseous turbulent flow, the $k$-$\varepsilon$/RNG model is used because of its good precision and low computational CPU load for strong swirling flow simulation. An overall one-step reaction mechanism is used for the gaseous combustion, for which reaction rates are calculated by an eddy break-up/Arrhenius controlling model using a combination of chemical kinetics and turbulent mixing. The four-flux model is selected to simulate gaseous radiation heat transfer, and the Lagrangian separated model is adopted to treat particle flow. The details on these standard models can be found in the literature (see Eaton et al., 1999; Guo & Chan, 2000). For their great effect on the slagging properties and coal/wood co-combustion characteristics, coal and wood pyrolysis, char combustion, and slagging models will be presented in detail as follows.

Pyrolysis modeling. A two competing steps model (Kobayashi et al., 1976) is selected for coal pyrolysis description. The model uses a pair of first-order irreversible reactions to represent the variation in the yield of volatile with temperature:

\[
\text{Fuel} \xrightarrow{k_{v1}} (1 - a_1)\text{Char} + a_1\text{Volatile}
\]

\[
\text{Fuel} \xrightarrow{k_{v2}} (1 - a_2)\text{Char} + a_2\text{Volatile}
\]

Figure 4 Particle group division algorithm.
\(a_1\) and \(a_2\) are the mass stoichiometric coefficients representing the overall mass fraction of coal that evaporates into the gas phase via the two competing reactions. Generally, \(a_1\) is defined as the volatile matter content of coal obtained from proximate analysis, and \(a_2\) is specified as the empirical value under the high-temperature pyrolysis condition. Arrhenius form is used to describe their reaction rates \(k_{vn}\):

\[
k_{vn} = A_{vn} \exp \left( -\frac{E_{vn}}{RT_p} \right) \quad (n = 1, 2)
\]

where \(A_{v1}\) and \(A_{v2}\) are the pre-exponential factors, and \(E_{v1}\) and \(E_{v2}\) are the activation energy of two competing reactions.

For bituminous coal, the model constants \(k, A, a\), given in Table 1, are accepted by many researchers (e.g., Sun, 2001). However, wood pyrolysis simulation is more complicated. Because of its variety and diversity of reaction conditions in different studies, these kinetic constants vary greatly. In much of the research on wood pyrolysis, the three parallel kinetic model developed by Shafizadeh and Chin (1977) depicts a common pattern (see Colomba et al., 1998; Shafizadeh & Chin, 1977). The model does not consider the biomass components and puts up three parallel competing reactions directly focusing on three important products—solid char, gaseous volatile, and liquid tar. Assuming that the liquid tar is gasified very fast for high temperature in the slagging combustor, and the tar yield can be added to the overall volatile yield after the wood pyrolysis, the three-parallel kinetic pattern can be reduced to the two competing steps model, just like coal. The wood pyrolysis constants \(k, A, a\) summarized from the research (Colomba et al., 2008) and verified by the lab-scale tube furnace experiments, is adopted.

Char combustion. The char combustion of pulverized coal is simulated by first-order diffusion/dynamics combined rate model (Baum & Street, 1971). Assuming that the particle shape is spherical, the particle size is kept constant during the combustion processes, and the char combustion product is only CO at the particle’s surface, the governing equation is:

\[
\frac{dm}{dt} = -\pi d_p^2 \frac{1}{k_{\text{diff}} + k_s} P_{O_2,g}
\]

where \(m\) is the single char mass, \(d_p\) is the char diameter, \(P_{O_2,g}\) is partial pressure of oxygen in the free gas stream around the particle, and \(k_{\text{diff}}\) and \(k_s\) are specific oxygen diffusion rate and char oxidation rate coefficients:

\[
k_{\text{diff}} = \frac{\beta \Sh D_{O_2} W_{O_2}}{d_p RT_g}
\]

| Fuel  | \(a_1\) | \(a_2\) | \(A_{v1}\) (1/s) | \(A_{v2}\) (1/s) | \(E_{v1}\) (J/mol) | \(E_{v2}\) (J/mol) |
|-------|---------|---------|-----------------|-----------------|-------------------|-------------------|
| Coal  | 0.32    | 0.8     | \(3.7 \times 10^3\) | \(1.46 \times 10^{13}\) | \(73.7 \times 10^3\) | \(251 \times 10^3\) |
| Wood  | 0.65    | 0.9     | \(2.4 \times 10^5\) | \(4.4 \times 10^9\) | \(95.4 \times 10^3\) | \(141 \times 10^4\) |
\[
k_s = \frac{1}{6} \rho_p d_p A_c \exp \left( -\frac{E_c}{RT_p} \right)
\]

where \( \beta \) is mass-based stoichiometric ratio of heterogeneous oxidation with a value here of 0.75, \( \text{Sh} \) is Sherwood number, \( D_o \) is mass diffusivity of oxygen, \( W_o \) is molecular mass of oxygen, \( \rho_p \) is particle density, \( T_p \) is particle temperature, and \( T_g \) is gas temperature. \( A_c \) is the pre-exponential factor and \( E_c \) is activation energy of char heterogeneous oxidation.

In conventional biomass combustor, the size range of particles is several millimeters, and the reaction pattern of such large particles will be governed by internal temperature and concentration gradients. The conventional volume-averaged models should be modified by considering the porous structure of biomass char. But in this paper, the model is simplified. It is necessary to explain that the wood powder size can be controlled down to 0.1 mm nowadays (for example, using multi-stage cracking devices) so that the effect of char porosity on the combustion rate may be controlled to a low extent. Thus, the wood char combustion also adopts the conventional volume-averaged pattern like that of coal char combustion, but uses the different pre-exponential factor and activation energy calculated from experimental data. This simplification may be not very exact, but it still can reflect the difference between coal and wood char combustion. Assuming the reaction order is about 1.0, the kinetic constants from literature (Kastanaki & Vamvuka, 2006) are shown in Table 2.

**Particle slagging.** In the current simulation, particle slagging processes include particle deposition, wall burning, and slag flow. For particle deposition process, which should be considered first in slagging simulation, Wood’s empirical equations (Wood, 1981) and Walsh’s sticking mechanism (Walsh et al., 1992) are used to simulate the particle impingement efficiency and particle sticking rate, respectively. It should be emphasized that the viscosities of particle and deposit surface are the key parameters to calculate the sticking probability in Walsh’s research results. In coal combustion, the viscosity function with the temperature and ash components dependences can be described by the Urbain viscosity model (Vargas et al., 2001). Furthermore, the viscosity of each particle is compared with the ash critical viscosity (\( \mu_{crit} \)). If the particle viscosity is less than \( \mu_{crit} \), this particle is considered as a sticky one on the deposition surface. In this paper, the critical viscosity is regarded as the value at the ash critical temperature \( T_{crit} \), which is estimated from the empirical equation:

\[
T_{crit} = 0.75(ST - 273) + 753
\]

where \( ST \) is the slag softening temperature. The above empirical equation is summarized from viscosity experiments of some bituminous coal slag by some
Chinese researchers (Zhang et al., 1979). Being a similarity assumption, the wood particle viscosity is also calculated by the viscosity model using the experimental data of wood ash and slag components accordingly. It is an alternative simulation method, as the exclusive experimental data for wood have not yet been comprehensively studied by researchers.

For the wall burning and slag flow process, the particles on the running slag will continue to volatilize and combustion, which is regarded as the surface combustion similar to that of suspended particles controlled by diffusion/dynamics mixed mechanism. The only difference is that the suspension combustion is impacted by gaseous flow, while wall burning takes place on the running slag layer with a certain velocity and thickness. Running slag thickness is defined as the radial displacement from the position at critical temperature to the surface of slag layer. If the surface temperature is lower than critical temperature, the thickness of running slag layer is regarded as zero. The deduced process and some detail information will be found in the earlier literature (Wang et al., 2007).

**COMPUTATIONAL CASES**

**Computational Grid**

Considering the cylindrical structure of the combustor, as shown in Figure 1, it is assumed that the parameters are even in the $\theta$ tangential direction and the axisymmetrical computational grid is used. As shown in Figure 5, after being checked the grid-independence, the grid numbers in $r$, $x$, and $\theta$ directions are 50, 120, and 1, respectively.

**Fuel Properties**

The fuel is selected as the mixed particles of wood and coal, the density of which is 750 and 1200 kg/m$^3$, respectively. The proximate analysis, elemental analysis, and slag analysis of coal and wood are carried on in the Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, which are shown in Tables 3–5.

![Figure 5 Computational grid.](image-url)
### Table 3
Coal proximate analysis, ultimate analysis, and XRF analysis of slag

| Moisture | Ash | Volatile matter | Fixed carbon |
|----------|-----|-----------------|--------------|
| 8.29     | 8.93| 32.07           | 50.71        |

**Coal ultimate analysis (dry ash-free basis)**

| C (%) | H (%) | O (%) | N (%) | S (%) | Heat value (MJ/kg) |
|-------|-------|-------|-------|-------|--------------------|
| 80.78 | 4.63  | 13.18 | 1.12  | 0.29  | 26.51              |

**Oxide wt% of ash**

| SiO2 | Al2O3 | TiO2 | Fe2O3 | CaO | MgO | Na2O | K2O | P2O5 | MnO |
|------|-------|------|-------|-----|-----|------|-----|------|-----|
| 33.4 | 18.2  | 0.94 | 22.7  | 16.8| 3.36| 0.36 | 0.47| 0.11 | 0.47|

### Table 4
Wood powder proximate analysis, ultimate analysis and XRF analysis of slag

| Moisture | Ash | Volatile matter | Fixed carbon |
|----------|-----|-----------------|--------------|
| 9.25     | 1.38| 72.31           | 17.06        |

**Wood powder ultimate analysis (dry ash-free basis)**

| C (%) | H (%) | O (%) | N (%) | S (%) | Heat value (MJ/kg) |
|-------|-------|-------|-------|-------|--------------------|
| 56.52 | 5.90  | 37.28 | 0.28  | 0.02  | 16.52              |

**Oxide wt% of ash**

| SiO2 | Al2O3 | TiO2 | Fe2O3 | CaO | MgO | Na2O | K2O | P2O5 | MnO |
|------|-------|------|-------|-----|-----|------|-----|------|-----|
| 6.39 | 7.03  | 3.39 | 1.37  | 42.35| 11.13| 1.43 | 22.67| 3.68 | 0.81|

### Table 5
Melting point of slag

| Fuel   | DT (K) | ST (K) | HT (K) |
|--------|--------|--------|--------|
| Coal   | 1473   | 1508   | 1553   |
| Wood   | 1493   | 1553   | 1658   |

*Note.* DT is deformation temperature, ST is softening temperature, HT is hemispherical temperature.

### Table 6
Parcel partitions

| Case             | $M_c$ (kg/s) | $M_w$ (kg/s) | $N_{pc}$ | $N_{pw}$ | $M_{pc}$ (kg/s) | $M_{pw}$ (kg/s) |
|------------------|--------------|--------------|----------|----------|-----------------|-----------------|
| 100% coal        | 0.0417       | 0            | 50       | 0        | 0.000834        | 0               |
| 75% coal + 25% wood | 0.0340    | 0.0113       | 50       | 50       | 0.000680        | 0.000226        |
| 50% coal + 50% wood | 0.0248    | 0.0248       | 50       | 50       | 0.000497        | 0.000497        |
| 25% coal + 75% wood | 0.0137    | 0.0413       | 50       | 50       | 0.000274        | 0.000826        |
| 100% wood        | 0            | 0.0616       | 0        | 50       | 0               | 0.001232        |
Computational Cases

The reducing atmosphere combustion is selected in the combustor under stoichiometric ratio 0.9. For every kind of fuel, particles are divided into 50 parcels with the same mass feed rate and different particle size from 50 to 110 μm. Based on the mass flow ratio of coal to wood, five cases are set as Table 6, where the total heat input is kept same as the pure coal combustion. $M_c$ and $M_w$ represent the feed rate of coal and wood, $N_{pc}$ and $N_{pw}$ represent computational parcels, and $M_{pc}$ and $M_{pw}$ represent the feed rate per parcel.

RESULTS AND DISCUSSION

Combustion Characteristics

Figure 6 gives the temperature distributions of pure coal and pure wood combustion. As seen from the figure, the average temperature and temperature gradient are lower while wood firing. Due to the wood volatile releases and char burning fast, the temperature from inside the wood-fired combustor is higher than in the coal-fired combustor, whereas at the rear of combustor, as the combustible matter in wood decreases, heat release and the temperature are lower than that of coal-fired condition. As the wood heat value is lower than that of coal, the more mass feed rate is needed while wood firing in order to keep the same heat input. In a finite-volume combustor chamber, excessive wood feed rate should lead to a highly volatile pyrolysis and incomplete combustion loss. As shown in Figure 7, there is much un-burnt volatile at the rear of the combustor in pure wood combustion. These combustion properties will result in the lower average temperature in wood-fired combustor, and the peak temperature is only 2040 K, as compared to about 2320 K in coal combustion.

Figure 8 gives the comparison of temperature distribution at the axis under different mixing ratios. The greater the mixing amount of wood, the more even

![Figure 6](image)

(a) Coal

(b) Biomass

Figure 6 Temperature distribution in the combustor (K).
the axial temperature distribution is in the combustor. While feeding wood with a certain percentage less than 25%, the average temperature will increase. For pure coal combustion, the particles may be hard to burn out entirely, but its combustion efficiency can be improved by adding a certain percentage wood. At the initial combustion stage, the high volatile content of wood will release and burn intensely, which can increase the local temperature and then increase the ignition performance of coal particles. In the finite-volume chamber, the high ignition speed means the combustion area become wider, which is helpful for increasing the combustion efficiency, and which is why adding certain percentage wood can increase the total heat release and average temperature. But when continuing to add wood powder,
the average temperature in the combustor begins to decline again due to the low heat value of wood and incomplete combustion loss of the volatile.

Figure 9 gives the comparison of temperature distribution at the slag layer surface under the different mixing ratio. As seen in the figure, there are different peak points on the temperature curves, which is due to two reasons. First, it is the fuel-enriched region, and many burning particles impact the surface by strong swirling force. Second, the slag layer at that place is becoming thicker for the particle deposition mechanism and its heat resistance increases. When the fraction of wood is higher than 50%, the average surface temperature is lower than the slag melting point, which means that the running slag layer disappears and combustor slag-capturing performance becomes worse.

Particle Deposition Characteristics

Figure 10 gives the particle deposition rate at the axial position of the wall. With wood mixing fraction increase, the peak point on the deposit curve moves to the front of combustor. According to the Walsh’s deposition mechanism, the local deposit surface and particle viscosities have a negative effect on the particles deposition rate. With wood mixing, the heat release and temperature in front of the combustor increase. According to the temperature-dependence viscosity model, as the viscosities of particle and deposit surface decrease, the particle sticking probability becomes higher, and the actual deposition rate increases. Compared with the temperature distribution in Figure 9, the place of deposition peak point is almost the same as that of temperature peak point. However, with the wood addition, the slag critical temperature \( T_{\text{crit}} \) will be lowered. In current numerical research, the selected critical temperature is the maximum of coal and wood slag, not the mixed data. That is to say, the true critical temperature is enhanced artificially. In the actual
co-combustion, the addition of wood makes the critical temperature decrease and the particle deposition rate is even higher than the simulation results. Thus, it is reasonable to consider that the deposit curve moves to the front of the combustor, and it will become more obvious if using the true mixing slag critical data.

As seen from Figure 10, total particle deposition rate decreases with wood fraction increasing. In the current deposition model, deposition rate is determined by both the particle impact efficiency and sticking probability, where particle impact efficiency has the close relation with the particle density. In the computational cases, where the coal density is 1200 and wood density is 750 kg/m$^3$, low density results in the low impact efficiency under the conditions of same temperature and particle size. At the same time, sticking probability is strongly affected by the ash fraction and components of the impact particles. As the ash content in wood powder is only 1.38% compared to 8.93% in coal, this great difference makes the actual deposition rate decrease with wood mixing in spite of total feeding mass rate increasing. If using pure wood fuel, the surface temperature is so low that few particles can deposit and almost all ones flow with the gaseous phase at suspension state. It can be deduced that the deposition ability of coal is much stronger than that of wood, due to the difference of physical properties (such as density) and chemistry structure between coal and wood.

**Wall Burning Characteristics**

In slagging combustor, mixed particles combustion will be divided into two types: suspension combustion, in which particles flow with the gaseous phase, and wall burning, in which deposit particles burn on the slag layer. For mixing coal with wood powder in current research, the wall burning process will change and affect the whole combustion characteristics greatly.
Figure 11 gives the distribution of residue deposition rate in the axial direction on the slag layer. Distribution of particle deposition rate can only represent the initial particle deposit condition. If the deposit particles contain combustible matters, they will continue to burn and flow with the running slag, which makes the actual amount of ash deposition in slagging combustor differ from that in dry-wall combustor. In this paper, the residue deposition rate can be described as the difference between the initial particle deposition rate and deposit particle burning rate in the same computational grid. For showing the effect of wood mixing fraction on the wall burning process more clearly, Table 6 gives mass rate fraction of the residue combustible matter in the slag, which is defined as follows:

\[ \eta_{res} = \frac{m_{res}}{m_{feed}} \]  

where \( m_{res} \) is the residue mass rate of combustible matter in the slag, and \( m_{feed} \) is the total combustible matter in the feeding fuel mass rate. From Figure 11 and Table 7, it is known that the residue fraction \( \eta_{res} \) will change with the different wood mixing fraction. With the appropriate wood mixing, the residue fraction can decrease to zero. Compared with pure coal combustion, the 25% wood mixed fraction will lead to the max wall burning fraction, 86.1% for char, and 3.27% for volatile. It means that the appropriate wood adding can make particle deposit earlier and burn fast. For the very long residence time of deposition particles, the char burnout efficiency can be enhanced about 5%.
Unlike other combustion technology, the slagging combustion will make the char have a much longer residence time than the several minutes for wall burning mechanism, which is very useful to increase char burnout efficiency. Commonly, gaseous combustion has the high competitiveness for oxygen, and heterogeneous char is very hard to burn out entirely in the finite-volume combustor chamber. However, in the slagging combustion known from Table 7, most of the char will deposit on the running slag layer, while the gaseous unburned components, such as volatile and CO, will transport to suspension space to burn. It means that the gaseous combustion and char burning have different reaction regions, which can avoid the “violent competition” for the oxygen and is helpful to char heterogeneous combustion. At the same time, the proper wood mixing can further strengthen wall burning ability and enhanced the burnout efficiency.

In actual combustion, the overall combustion efficiency as well as char burnout efficiency should be concerned. Figure 12 gives the volatile mass concentration distribution at the combustor outlet in the radial direction under different mixing ratios. From the figure, the excessive wood adding makes a more volatile release from fuel particles and not be consumed up entirely in the finite-volume combustor. Though 50% wood mixing also makes residue fraction of wall burning low to 0 from the simulation results, the volatile combustion efficiency is not very satisfying.

![Figure 12](image)

**Figure 12** Volatile mass concentration at the rear of the combustor (kg/kg).

| Cases                      | 100% coal | 75% coal + 25% wood | 50% coal + 50% wood | 25% coal + 75% wood | 100% wood |
|---------------------------|-----------|---------------------|---------------------|---------------------|-----------|
| Wall burning fraction of volatile | 0.0002    | 3.27                | 0.412               | 0.008               | 0.28      |
| Residue fraction of volatile | 0         | 0                   | 0                   | 0                   | 0         |
| Wall burning fraction of char | 79.8      | 86.1                | 70.9                | 45.3                | 2.7       |
| Residue fraction of char  | 4.95      | 0                   | 0                   | 0.06                | 0.007     |
Considering the overall combustion efficiency of char and volatile, 25% is a suitable wood mixing fraction.

**Slag Flow Characteristics**

With the time increasing, the depositing particles will accumulate on the wall, and the thickness of slag layer will increase. Based on the heat transfer mechanism, the temperature of the layer will continue to increase until it is higher than the fusion temperature of bulk ash. At this time, the thickness of slag layer will not change, and the process of deposition is regarded as stable. Under the stable combustion condition, the running slag has a stable velocity distribution along the deposition surface. Though the magnitude of this velocity is small, it can have an important effect on the slag thickness distribution, which can make the heat transfer through the wall change sharply. Some equilibrium relationships for the stable running slag will be needed, as introduced previously (Wang et al., 2007). In those equilibrium equations, the running slag thickness and velocity play the important role on the running slag characteristics. Figure 13 gives their distributions in the axial direction under the different wood mixing fraction. With the fraction increase, the running slag thickness decreases and finally disappears. In the current slag flow model, the running slag thickness and velocity are affected by three mechanisms. The first is particle deposition rate. The more the particles deposit, the more likely the slag thickness increases and running velocity decreases. The second is impelling force of deposition particles on the slag layer. The stronger this force is, the higher the slag flowability. The third is gravity force, which has the positive effect on the slag thickness changing. Obviously, the slag gravity force makes the slag flow more easily and running velocity higher, which can avoid the abnormal slag accumulation in the combustor.

In pure coal combustion, the poor coal ignition performance makes the heat release in front of the combustor very low, which means the low local temperature and the deposit particles cannot be melted entirely. When adding 25% wood powder, the combustion of initial stage is enhanced, slag is molten more easily, and it is helpful to form a continuous and stable running slag layer. When wood mixing fraction exceeds 50%, the running slag layer disappears and the combustion stability will be worse again, the reason for which can be explained from the low wall temperature shown in Figure 9.

![Figure 13](image-url)  
*Figure 13 Distributions of slag thickness and velocity.*
CONCLUSIONS

Based on the new idea of the unification of co-combustion and slagging combustion technologies put forward in this paper, the pyrolysis and burning kinetic models of biomass were implanted into the WBSF-PCC code, which includes several sub-models of particle deposition, wall burning, and slag flow. The co-combustion characteristics of coal and wood powder under different mixing ratio were simulated numerically. The results show that the whole combustion situation is affected by both co-combustion properties and wall burning characteristics:

- When burning pure coal, the main combustion region is at the rear of the combustor, whereas the heat release in front is low. As the wood volatile release and char combustion rate are greater than those of coal, adding wood powder at proper ratio can increase the heat release at the initial stage of combustion and the main combustion region moves near to the fuel inlet, the whole temperature distribution is more even, which is helpful to utilize the front space of the combustor.
- Compared with pure coal combustion, adding wood powder at 25% mass fraction can increase the reaction rate at the initial combustion stage, the coal ignitability is improved, and the burnout efficiency is enhanced by about 5% of suspension and deposition particles, which is helpful for coal particles to burn entirely and to minimize the dimensions/sizes of combustion devices.
- In high-temperature slagging combustion, the impingement efficiency of wood particles to wall is low, which makes its deposit ability weaker than that of pure coal, especially for little size particles. Based on its characteristics, conventional slagging combustor cannot capture the wood ash efficiently. In actual application, the problem of wood fly-ash emission should be addressed.
- Adding wood powder at a proper ratio is also helpful to maintain combustion stability, not only because of the enhancement for the burning characteristics, also because the running slag layer structure can be changed more continuously. Thus, it is very important for avoiding the abnormal slag accumulation in the slagging combustor. The theoretic analysis in this paper proved that the unification of co-combustion and slagging combustion technologies is feasible.

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