Influence of Operating Parameters on Chlorine Release and Pollutant Emission Characteristics of a 130 t/h BCFB Combustion System

Yaya Liu, Shanjian Liu,* Yingjie Li, Yongjun Li, and Jianjie He

ABSTRACT: A 130 t/h biomass circulating fluidized bed (BCFB) boiler combustion system model, considering the chloride release and pollutant emissions during the biomass combustion, was established using the Modelica language. The effects of the biomass feed amount, limestone amount, excess air coefficients, and different ratios of primary and secondary air on the boiler furnace temperature and flue gas composition (O2, CO2, SO2, HCl, and KCl) were investigated. Upon the biomass feed amount step change, the variation ranges of NO and KCl concentrations were very large, which were 18.58 and 21.16% of the before step value, respectively. The step change of the limestone input had little effect on bed temperature in the dense phase zone, but it could obviously reduce the SO2 concentration. The concentration of SO2 in flue gas decreased by 22.56% when the limestone input increased by 50%. The removal rate of SO2 gradually decreased with the increase of the limestone amount. The SO2 desulfurization rate decreased by 68.30% when the amount of limestone increased from 0.0275 to 0.0825 kg/s. More NO would be generated and KCl concentration would be significantly reduced with the increase of the excess air coefficient. When the ratio of primary and secondary air was 4:6, the NO concentration in flue gas was lower than 86.06 mg/Nm3.

1. INTRODUCTION
In recent years, the biomass direct combustion power generation technology, which is one of the effective ways to deal with the waste biomass resources on a large scale and realize clean energy utilization, has been rapidly promoted and applied in many countries and regions around the world. The total installed capacity of biomass direct-fired power generation units is expected to reach 7.5 GW by the end of 2020 in China. Among them, the biomass circulating fluidized bed (BCFB) is one of the most important combustion equipment due to its technical advantages in many aspects, such as favorable fuel adaptability, easy furnace temperature control, and low NOx emission level. However, the biomass entered in the BCFB generally has the characteristics of variable fuel types, high moisture content and volatile content, high alkali metal content and chlorine content, and low calorific value in actual operation. These will easily lead to many problems such as poor combustion stability, unstable thermal load, serious chlorine corrosion, and slagging. In extreme cases, it may even cause fluidization failure, which presents a serious challenge to the safety and stability of power plant units and low pollutant discharge operation.

The heat and mass transfer characteristics and pollutant discharge rules in the combustion system are the basis of optimizing operation and parameter regulation for the BCFB. It is worth noting that due to the limitation of safe operation or test cost, it is difficult to carry out a more comprehensive test study on the characteristics of power plant units. Therefore, modeling and simulation have become an important means to study the dynamic characteristics of the power plant system, as well as an important platform for operating parameter optimization and advanced control algorithm verification. Up to now, a lot of in-depth research studies on the characteristics of coal-fired circulating fluidized bed (CCFB) boiler units have been carried out. However, compared to the CCFB, the BCFB is generally smaller, with a stand-alone capacity of 20–50 MW. In general, the external heat exchanger is not set on the BCFB system. These differences make it difficult to control the bed temperature, bed pressure, and other parameters of the BCFB combustion system.

In the field of BCFB modeling, Xie et al. established a three-dimensional Eulerian–Lagrangian model to perform the full-loop simulation of the combustion process of municipal
Table 1. Volatile Content Combustion Kinetic Equations

| chemical reaction | reaction rate mol/(m$^3$s) | reaction rate constant (1/s) |
|-------------------|-----------------------------|-----------------------------|
| CO + ½O$_2$ → CO$_2$ | $r_{CO} = k_{CO}C_{CO}C_{O_2}^{0.5}$ | $k_{CO} = 1.0 \times 10^{15} \exp \left( -\frac{16000}{T} \right)$ |
| 2H$_2$ + O$_2$ → 2H$_2$O | $r_{H_2} = k_{H_2}C_{H_2}C_{O_2}$ | $k_{H_2} = 5.159 \times 10^{15} \exp \left( \frac{-24800}{T} \right)T^{-1.5}$ |
| CH$_4$ + 2O$_2$ → CO$_2$ + 2H$_2$O | $r_{CH_4} = k_{CH_4}C_{CH_4}C_{O_2}$ | $k_{CH_4} = 3.552 \times 10^{14} \exp \left( \frac{-15700}{T} \right)T^{-1}$ |
| C$_2$H$_6$ + 3½O$_2$ → 2CO + 3H$_2$O | $r_{C_2H_6} = k_{C_2H_6}C_{C_2H_6}C_{O_2}$ | $k_{C_2H_6} = 2.67 \times 10^{13} \exp \left( \frac{-20131}{T} \right)$ |
| CO + C → 2CO | $r_{CO} = N_{C,CO}C_{CO}C_{O_2}$ | $k_{CO} = 4.1 \times 10^5 \exp \left( \frac{-379.54}{T} \right)$ |

“In Table 1, the unit of reaction rate of CO$_2$ is mol/s. NC is the number of coke particles.

solid waste (MSW) and coal in an industrial-scale circulating fluidized bed boiler. The numerical results showed that serious wall erosion took place in the horizontal flue duct and the entrance zone of the cyclone. The concentration distribution of CO$_2$ was almost opposite to that of O$_2$ in the whole boiler. The emissions of NO and N$_2$O decreased, while the emission of SO$_2$ increased with the increase of the coal mass share. The NO$_x$ emission could be effectively reduced by the increase of the secondary air ratio, while the variation trend of SO$_2$ emission was not obvious. Using the Fortran language, Gungor$^{12}$ established a circulating fluidized bed model for mixed combustion of different biomass (rice husk, wood, olive cake, and sawdust) and coal. The riser temperature, solid particle concentration, and concentration distribution of pollutants (e.g., O$_2$, CO, and NO) were studied. The simulation results showed that the air stage could enhance combustion. For the industrial-scale BCFB combustor, with the reduction of excess air coefficient, the reduction of NO$_x$ would lead to higher CO emission.

Song et al.$^{13}$ established a 220 t/h simplified two-dimensional BCFB furnace model using Fluent software to study the combustion status of biomass materials, the internal temperature field, and concentration distribution of components such as O$_2$ and CO$_2$ in the furnace. The simulation results revealed that the drastic combustion position was at a height of 4 m above the bottom of the furnace, where the vast majority of primary air was consumed. Through the analysis of the combustion of biomass fuels with different particle sizes in the furnace, it was found that the combustion of small particles was more complete and the consumption of O$_2$ was higher.

Compared with coal, due to the high content of chlorine in biomass, the chloride gases generated during the combustion will cause high-temperature corrosion problems of various alloys. The reason was that the chloride gases (e.g., Cl$_2$, HCl, NaCl, and KCl) caused direct corrosion by accelerating the oxidation of the metal alloys, and the phenomenon was the active oxidation.$^{14}$ However, most of the BCFB models established at present rarely did consider the chloride emissions in the biomass combustion process, which was difficult to reflect the characteristics of high chlorine content in biomass. This is also an important difference in combustion characteristics between biomass and coal. Therefore, a 130 t/h BCFB boiler combustion system model based on the object-oriented Modelica language was established on the Mworks simulation platform in this paper. Among them, the generation of chloride in the biomass combustion process was considered and the influence of operating parameters (e.g., the biomass feed amount, primary and secondary air volume, excess air coefficient, different primary, and secondary air ratios) on the internal temperature of the furnace and emission character-

istics of compositions (O$_2$, CO$_2$, SO$_2$, HCl, and KCl) in flue gas were investigated. These studies can provide guidance and data reference for system optimization operation and control. Compared with the computational fluid dynamics (CFD) modeling, the combustion system model based on Mworks did not pay too much attention to the detailed description of heat transfer, mass transfer, and internal flow field but only paid attention to the variation of outlet parameters of equipment or the subarea. Most of the simulation results could be obtained within 1 s. The fast calculation speed is conducive to further process-oriented control and optimization.

2. MATHEMATICAL MODELS

Compared with coal, the biomass fuels had the characteristics of high oxygen content, high volatile content, and low carbon and ash contents as the power plant fuel.$^{15}$ There are significant differences in the release and migration mechanism of chlorine for different kinds of biomass under different combustion atmospheres. Currently, a large number of studies$^{16−19}$ have shown that chlorine enters the gas phase mainly in the form of HCl and KCl during the combustion of biomass. At 700−900 °C, chlorine basically enters 100% into the gas phase, while potassium partially enters the gas phase.$^{20−23}$ All of the potassium volatilized from the biomass existed in the form of KCl in the gas phase, while the remaining chlorine entered the gas phase in the form of HCl within the operating temperature range of the BCFB. The proportion of solid potassium transformed into gaseous potassium in the biomass fuel used in the CBFB was 5% (700 °C), 10% (800 °C), and 30% (900 °C), respectively. The proportion of gaseous potassium at different temperatures was determined by the interpolation method. The productions of HCl and KCl in the gas phase were calculated by the mass conservation of each element.

2.1. Volatilization Characteristic Models and Combustion Models for Volatiles. The volatile components of different types of biomass devolatilization almost differ little, mainly including CO, CO$_2$, H$_2$, CH$_4$, and C$_2$H$_6$. C$_n$H$_m$ generally refers to the hydrocarbons with higher molecular weights, such as ethylene (m = 2, n = 4), ethane (m = 2, n = 6), etc. C$_2$H$_6$ is selected in this paper.

The variations of the above component content with the combustion temperature were calculated according to the following formulas.$^{25,26}$

\[
\begin{align*}
\text{[CO]} &= 120.72 - 0.1183T + (5.0 \times 10^{-5})T^2 \\
\text{[CO$_2$]} &= 140.51 - 0.1991T + (7.0 \times 10^{-5})T^2 \\
\text{[H$_2$]} &= 74.44 + 0.1467T - (5.0 \times 10^{-5})T^2
\end{align*}
\]
The volatile content combustion reaction and the kinetic equations are shown in Table 1.\textsuperscript{25,27}

2.2. Chloride Calculation Model. The kinetic conversion equation of solid chlorine into gaseous chlorine is:

$$\frac{dX}{dr} = 3.32 \times 10^{-2} \exp \left( \frac{-2667}{T} \right) (1 - X)$$ \hspace{1cm} (6)

The interpolation function between the potassium precipitation ratio and the temperature was established by a piecewise linear interpolation method:

$$p_{K}(i) = \{5, 10, 30\}; \ T(i) = \{973, 1073, 1173\}$$ \hspace{1cm} (7)

If $T(i) \leq T < T(i + 1)$, then

$$p_{K} = p_{K}(i) + (T - T(i)) \left( \frac{p_{K}(i + 1) - p_{K}(i)}{T(i + 1) - T(i)} \right)$$ \hspace{1cm} (8)

$$n_{K} = \frac{K_{K}p_{K}N_{K}}{100N_{K}}$$ \hspace{1cm} (9)

$$n_{HCl} = \frac{(XCl_{fl} - p_{C}/100)N_{HCl}}{N_{Cl}}$$ \hspace{1cm} (10)

where $p_{K}(i)$ is the precipitation ratio set of potassium at different temperatures, $T(i)$ is the set of the BCFB combustion temperature range, $K_{K}$ is the percentage of Cl consumed to form KCl.

The chloride composition concentration in flue gas is

$$\frac{dX_{HCl}}{dr} = D_{in,k}C_{in,k}n_{HCl} + W_{bio}n_{HCl}$$

$$- D_{out,k}n_{HCl}c_{HCl}$$ \hspace{1cm} (11)

$$\frac{dX_{KCl}}{dr} = D_{in,k}C_{in,k}n_{KCl} + W_{bio}n_{KCl}$$

$$- D_{out,k}n_{KCl}c_{KCl}$$ \hspace{1cm} (12)

2.3. NO\textsubscript{x} Generation and Reduction Model. The nitrogen oxides produced during the biomass combustion consist of NO, NO\textsubscript{2}, and N\textsubscript{2}O. Among them, the volume fraction of NO accounted for more than 90\%,\textsuperscript{28,29} which was the main removal component considered in the denitration process. Therefore, it is necessary to study the variation of fuel-NO production here.

The conversion rate of fuel-NO can be calculated by the following empirical formula:\textsuperscript{30}

$$X_{NO} = -2.8412 \times 10^{-4}Z^3 + 0.0136Z^2$$

$$-0.3063Z + 15.756$$ \hspace{1cm} (13)

$$Z = 100X_{VP} - 30.637$$ \hspace{1cm} (14)

In the high-temperature environment in the furnace, the reduction reactions will occur between NO with bio-char and CO:\textsuperscript{31}

$$NO + C \rightarrow \frac{1}{2}N_{2} + CO$$ \hspace{1cm} (15)

$$NO + CO \rightarrow \frac{1}{2}N_{2} + CO_{2}$$ \hspace{1cm} (16)

$$r_{NO+C} = k_{NO}N_{C}C_{NO}$$ \hspace{1cm} (17)

$$r_{NO+CO} = k_{NO}C_{NO} + k_{2}C_{CO} + k_{3}$$ \hspace{1cm} (18)

where $k_{1} = 0.1826$, $k_{2} = 0.00786$, and $k_{3} = 0.002531$.

The reaction kinetic constants in formulas (17) and (18) are:

$$k_{NO} = 5.85 \times 10^{5} \exp \left( \frac{-12000}{T} \right)$$ \hspace{1cm} (19)

$$k_{NOCO} = 1.952 \times 10^{10} \exp \left( \frac{-1900}{T} \right)$$ \hspace{1cm} (20)

2.4. Reaction Formation Model and Reduction Reaction Model for SO\textsubscript{2}. It is assumed that the sulfur released from biomass is preferentially oxidized to SO\textsubscript{2} and released in the dense phase area. The reaction processes are as follows:

$$S + O_{2} \rightarrow SO_{2}$$ \hspace{1cm} (21)

$$CaCO_{3} \rightarrow CaO + CO_{2}$$ \hspace{1cm} (22)

$$CaO + SO_{2} + \frac{1}{2}O_{2} \rightarrow CaSO_{4}$$ \hspace{1cm} (23)

Then, the SO\textsubscript{2} removal rate is as follows:

$$r_{SO_{2}} = \gamma_{SO_{2}}C_{SO_{2}}$$ \hspace{1cm} (24)

$$k_{v} = 490 \exp \left( \frac{-17500}{RT} \right)S_{R}$$ \hspace{1cm} (25)

$$S_{R} = \left\{ \begin{array}{ll}
5.6 \times 10^{4} - 38.4T, & T \leq 1253 \\
-3.67 \times 10^{4} - 35.9T, & T > 1253
\end{array} \right.$$ \hspace{1cm} (26)

2.5. Conservation of Mass and Energy in Each Zone. 2.5.1. Mass Conservation Equation. The mass conservation equation for class $i$ solid particle in each zone:

$$\frac{dM_{i,k}}{dr} = W_{in,i,k} + W_{g,i,k} - W_{r,i,k} - W_{out,i,k}$$ \hspace{1cm} (27)

The mass conservation equation of flue components in each zone:

$$\frac{dC_{i,k}}{dr} = V_{i}N_{i} = D_{in,i,k}C_{in,k}N_{i,k} + G_{in,i,k}X_{i} + F_{i}kN_{V} - R_{i,k}N_{V}$$

$$- D_{out,i,k}C_{out,k}N_{i,k}$$ \hspace{1cm} (28)

If the chemical reaction of substances entering the cyclone separator is ignored and there is no accumulation of particles inside the separator, the separation efficiency $\eta$ of the cyclone separator is calculated as follows\textsuperscript{32}

$$\eta = 1 - \exp \left( -2(F_{i}y) / (2b+2) \right)$$ \hspace{1cm} (29)

The mass conservation equation of the separator is
The solid mass conservation equation of the return valve is

$$\frac{dM}{dr} = W_{\text{loop},i} - W_{\text{loop},f}$$

The energy conservation equation in each zone is

$$\frac{dT}{dr} = \frac{Q_{\text{in}} - Q_{\text{out}} - Q_{\text{exc}}}{M_p \cdot c_p \cdot k}$$

3. MODELING AND SIMULATION

3.1. Physical Objects of the BCFB. This boiler is equipped with a 30 MW high-temperature and high-pressure condensing steam turbine generator set. The structure and the operating parameters of the BCFB are shown in Figure 1a and Table 2. The BCFB combustion system consisted of a combustion chamber, a cyclone separator, and a U-shaped loop-seal device.

The combustion system of a 130 t/h BCFB boiler (manufactured by Jinan Boiler Group Co., Ltd., China) in a power plant was modeled on the Mworks simulation platform using Modelica language, which is an object-oriented structured modeling language based on the idea of noncausal modeling. It has the advantages of high model reuse and flexible and efficient modeling for complex physical objects.

The combustion system simulation model of the BCFB is shown in Figure 1b. It consisted of the input module (e.g., biomass fuel feed (Bio), limestone feed (Lim), primary air (PA), and secondary air (SA)), combustion chamber module (e.g., dense phase zone (DeZ), suspension phase zone (SuZ), and dilute phase zone (DiZ)), cyclone separator module, and loop-seal module.

The main fuel used in the operation of the boiler was a mixture of bark (40%), sawdust (30%), firewood (20%), wheat straw (5%), and corn straw (5%). The proximate analysis and ultimate analysis of the mixed biomass fuel are shown in Table 3.

3.2. Model Reliability Verification. The reliability of the established 130 t/h BCFB boiler combustion system was verified. The Dassl integration algorithm was used for the simulation because it is an implicit, high-order multistep integration algorithm. This algorithm shows a very stable performance in solving the complex model and provides good control of errors and calculation efficiency of numerical solutions.

Under the 100% BMCR conditions of BCFB, the outlet parameters of the combustion system model were compared with the actual measured value, as shown in Table 4. The relative errors between the oxygen content, NO concentration, SO2 concentration of flue gas at the furnace outlet of the model and the corresponding measured values were all within 6%, which indicated that the established BCFB boiler combustion system model had high reliability. The emission concentration of SO2 in BCFB operation could meet the emission standard of SO2 (50−100 mg/Nm$^3$) in Shandong province, China, when the limestone was not added into the combustion system. This is due to the fact that most of the biomass raw materials are with low sulfur content.

The calculation results of HCl and KCl gas generated during combustion were compared with the potassium and chlorine release of Swedish wood explored by FactSage in the literature. Based on 1000 kg of fuel, the molar quantities of potassium and chlorine in Swedish wood were 3.41 and 2.6, respectively. The comparisons between the results of the
methods in the paper of could be predicted HCl, KCl amount and reflected the both ones change trends to a certain extent.

4. RESULTS AND DISCUSSIONS

4.1. Dynamic Response Simulation Research. The combustion system of the BCFB boiler is a complex nonlinear system with strong parameter coupling and large combustion response hysteresis. There are many factors affecting the BCFB boiler, such as the primary air volume, secondary air volume, biomass feed amount, slag discharge amount, and circulation ratio. The changes of these operating parameters have a complex interleaving effect on the BCFB. At the same time, the safety requirement of boiler systems is high and some system parameters are difficult to be measured directly. It is difficult to obtain the coupling relationship between the above-mentioned factors and the bed temperature, bed pressure, and pollutant concentration in flue gas through simple tests. Therefore, it was important means to obtain the qualitative and quantitative effects of parameter disturbance on system output through numerical simulation.

4.1.1. Step Test of the Biomass Feed Amount. The analysis of the influence of input parameters on the output parameters, including the response time and the variation history, is helpful to realize the dynamic characteristics of the BCFB boiler system. When the boiler load needs to be changed, the biomass feed amount is changed first and the primary and secondary air volumes are changed proportionally to complete this control process. Assuming that the BCFB boiler was under a stable 100% BMCR condition, the biomass feed increased by 10% (from 9.8 to 10.78 kg/s) at 2000 s. Meanwhile, the excess air coefficient was set at 1.2 and the ratio of primary and secondary air was 1:1. The variations of furnace temperature, bed heat transfer coefficient, and flue gas components (O\(_2\), CO\(_2\), NO, SO\(_2\), HCl, and KCl) at the outlet of the BCFB combustion system are shown in Figure 3.

As can be seen from Figure 3a, the temperatures in the dense phase zone, the suspension phase zone, and the dilute phase zone in the furnace gradually increased when the biomass feed amount was increased by 10%. The temperature in the suspension zone was slightly higher than the temperature in the dense phase zone. This phenomenon was consistent with the similar conclusions in the literature that the temperature in the upper part of the riser was higher than that in the bottom. However, the heat transfer coefficient in the dense phase zone was higher than that in the dilute phase zone and suspension phase zone because there were more solid particles in the dense phase zone. The reason for this phenomenon was that the heat transfer coefficient between the bed and the wall in a circulating fluidized bed increased with the increase of temperature but decreased significantly with the increase of void ratio.

It can be seen from Figure 3b that the O\(_2\) content in flue gas at the outlet of the furnace first increased rapidly, then decreased slowly, and reached a new steady-state value. The reason for this phenomenon was that the step-increased
biomass feed amount and air volume at 2000 s led to an increase in the O₂ content in flue gas because of the limitation of the biomass combustion speed. Then, the O₂ content in flue gas decreased because a large amount of oxygen was consumed by the biomass combustion. The new steady-state value of the O₂ content was slightly higher than the original value. In this process, the variation trend of the CO₂ content was almost opposite to that of the O₂ content. As can be seen from Figure 3c, the concentrations of NO and SO₂ in the flue gas showed a trend of first increasing and then slowly decreasing. The new steady-state value of the NO concentration was far less than the value before the step, which was decreased by 18.58% of the before value. The variation of the SO₂ concentration was relatively insignificant. The new steady-state value of the KCl concentration was far higher than the value before the step, which was increased by 21.16% of the before value. This indicated that the step change of the biomass feed amount has a great influence on the concentration of NO and KCl in flue gas. The variation of SO₂ concentration was relatively insignificant.

The concentration of KCl in flue gas gradually increased, while the concentration of HCl decreased. In addition, the difference between HCl and KCl concentration decreased from 22.92 to 1.65 mg/Nm³.

4.1.2. Step Test of the Limestone Input. In the combustion process of sulfur-containing carbon fuel, the input of limestone has an important practical significance for the removal of SO₂ in flue gas. The input amount of limestone designed for the BCFB under 100% BMCR was 0.056 kg/s. On this basis, the limestone was increased (or decreased) by 5, 10, 20, 30, 40, and 50%, respectively. The variation trends of bed temperature in the dense phase zone and the concentration of SO₂ at the furnace outlet are shown in Figure 4.

Comparison between Figure 4a,b shows that the step change of the limestone input had no obvious effect on bed temperature in the dense phase zone of the BCFB. For instance, the dense zone temperature decreased by only 0.028% compared to the value when the limestone input increased by 50%. The reason for this phenomenon was that the amount of limestone added to the BCFB boiler system was relatively small compared to the amount of bed materials and biomass fuel in the furnace. The addition of limestone had little effect on the variation of total solids in the dense phase zone. The concentration of SO₂ in flue gas decreased by 22.56% when the limestone input increased by 50%. In addition, the effect of an increase or decrease in the amount of limestone on the bed temperature in the dense phase zone was approximately symmetrical distribution, while the variation trend of SO₂ concentration in flue gas at the furnace outlet was
asymmetric distribution. The decrease process of the limestone input amount had a great impact on the SO2 concentration. The reason for this phenomenon may be that the addition of a desulfurizer such as limestone would affect the desulfurization reaction and reduce the concentration of SO2, thus influencing the desulfurization rate. As shown in Figure 4c, the SO2 desulfurization rate decreased by 68.30% when the amount of limestone increased from 0.0275 to 0.0825 kg/s. The decrease of SO2 concentration would not be obvious when the amount of the desulfurizer was higher. This also indicated that the addition of limestone should be determined by the economic cost and desulfurization efficiency in the process of SO2 removal from limestone.

4.2. Excess Air Coefficient Variation Test. The excess air coefficient is the most important parameter that affects the boiler combustion efficiency and has a great influence on the variations of combustion temperature and flue gas composition. It was assumed that the biomass feed amount was maintained at 9.8 kg/s in the simulation test, and the ratio of primary to secondary air was 1:1. The excess air coefficient increased from 1.1 to 1.3. The temperature distribution in the furnace, the heat transfer coefficient between the bed and the wall distribution, and the flue gas composition (O2, CO2, NO, SO2, HCl, and KCl) at the furnace outlet are shown in Figure 5.

It can be seen from Figure 5a that with the increase of the excess air coefficient, the temperatures and heat transfer coefficients in the dense phase zone, suspension zone, and dilute phase zone decreased. The reason for this phenomenon is that the exhaust heat loss is closely related to the flue gas flow. The greater the excess air ratio was, the greater the flue gas flow would be, and the exhaust heat loss increased significantly, resulting in the temperatures decreased in all zones.

Figure 5b shows that the oxygen content of flue gas gradually increased and the CO2 concentration decreased with the increase of air volume. When excess air increased up to 1.3, the O2 concentration in the flue gas at the outlet of the furnace was close to 6%. To ensure the combustion efficiency of the BCFB boiler, the O2 concentration at the outlet of the furnace is generally kept below 6%.

It can be seen from Figure 5c that the concentrations of HCl and SO2 in the flue gas gradually decreased with the increase of the excess air coefficient, but the influence was not significant. The change of the excess air coefficient had a great influence on the concentrations of NO and KCl in flue gas. Meanwhile, the increase of the excess air coefficient would improve the NO
formation. The reason may be that the increase of the excess air coefficient enhanced the formation of the oxidizing atmosphere in the combustion chamber, which promoted the NO generation because the NO emission was shown to be more sensitive to the oxygen concentration. Reduction of the excess air coefficient could reduce the concentration of NO. However, too low excess air coefficient would lead to incomplete combustion of fuel and reduce boiler efficiency.

To control NO emissions and ensure high boiler efficiency, the excess air coefficient of the BCFB boiler should be between 1.15 and 1.25. The decrease of the KCl concentration was mainly caused by the dilution of the flue gas concentration due to the increase of the air volume, and the decrease of gaseous KCl generation due to the decrease of the furnace temperature.

4.3. Ratio of Primary and Secondary Air Test. At present, air staged combustion is one of the most effective and attractive technology to reduce nitrogen oxide emissions because it does not require expensive new equipment. Proper air distribution can not only reduce the nitrogen oxide emissions but also ensure the efficient combustion of biomass. Assuming that the BCFB boiler was under a stable 100% BMCR condition, the biomass feed amount was kept at 9.8 kg/s. The limestone was not added to the BCFB boiler, and the ratio of primary to secondary air (PA/SA) was 6:4, 5:5, and 4:6, respectively. The temperature distribution in the furnace, the heat transfer coefficient between the bed and the wall distribution, and the composition of flue gas at the outlet of the furnace (O<sub>2</sub>, CO<sub>2</sub>, NO, SO<sub>2</sub>, HCl, and KCl) are shown in Figure 6. Three schemes with primary and secondary air ratios of 6:4, 5:5, and 4:6 were considered for comparative analysis to ensure the normal fluidization of the circulating fluidized bed.

It can be seen from Figure 6a that the temperature in the dense phase zone increased with the decrease of the primary air share. The reason is that the heat carried by the flue gas away from the dense phase zone was decreased due to the decrease of primary air. Compared with PA/SA = 5:5, the dense phase temperature decreased significantly with the increase of the primary air share (PA/SA = 6:4). When the PA/SA = 4:6, the temperature of the whole furnace was more uniform, and the temperature difference between the suspension zone and the dense phase zone reduced more obviously. Figure 6b shows that the reduction of primary air share will lead to a slight increase of the O<sub>2</sub> content and CO<sub>2</sub> content in flue gas at the furnace outlet.

As can be seen from Figure 6c, the NO concentration at the furnace outlet decreased with the decrease of the primary air...
share. From the perspective of uniform temperature distribution in the furnace and reduction of nitrogen oxides, the optimal air staged ratio is PA/SA = 4:6. Although the concentrations of SO2 and KCl increased when PA/SA = 4:6, the increase of the above substances did not significantly vary.

5. CONCLUSIONS

Based on the Modelica language, a 130 t/h BCFB combustion system model considering chloride release and pollutant emissions (e.g., SO2 and NO) in flue gas was established on the MWorks platform. The effects of operating parameters on the bed temperature, heat transfer coefficient, and pollutant emissions of the combustion system were studied. The relative errors between the oxygen content, NO concentration, SO2 concentration of flue gas at the furnace outlet of the model, and the corresponding measured values were all within 6%. When the biomass feed amount increased, there was a great influence on the concentrations of NO and KCl. The concentrations of NO and SO2 showed a trend of first increasing and then slowly decreasing. The KCl concentration gradually increased, while the HCl concentration decreased, and the difference between the KCl concentration and the HCl concentration decreased. The step change of the limestone input amount had little effect on bed temperature in the dense phase zone, but it could obviously reduce the SO2 concentration. The effect of the limestone amount increasing or decreasing on the bed temperature in the dense phase zone was approximately symmetrical distribution, while the variation trend of SO2 concentration was asymmetric distribution. The decrease of the limestone input amount had a great impact on the SO2 concentration. When the excess air coefficient increased, more NO was generated and KCl concentration decreased significantly. From the point of minimum NO generation, the optimal air staged combustion was PA/SA = 4:6.

■ AUTHOR INFORMATION

Corresponding Author
Shanjian Liu — School of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo 255049, China; orcid.org/0000-0002-8756-9595; Email: liushanjian08@163.com

Figure 6. Influence of the ratio of primary and secondary air on the heat transfer coefficient, temperature of the furnace, and the composition of flue gas. (a) Heat transfer coefficient and temperature of the furnace. (b) Concentrations of O2 and CO2 contents in flue gas at the furnace exit. (c) Concentrations of NO, SO2, HCl, and KCl in flue gas at the furnace exit.
Authors
Yaya Liu – School of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo 255049, China; orcid.org/0000-0001-7420-096X
Yingjie Li – School of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo 255049, China
Yongjun Li – School of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo 255049, China
Jianjie He – School of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo 255049, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c00270

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NOMENCLATURE

| Symbol | Description | Unit |
|--------|-------------|------|
| \( j \) | volume percentages of species \( i \) in the volatile matter, \% |
| \( C_i \) | molar concentration of species \( i \) in flue gas, mol/m³ |
| \( c_{p,k} \) | specific heat in each zone, J/(kgK) |
| \( d_i \) | coke particle diameter, m |
| \( D_{in,k} \) | volume flow of flue gas entering in each zone, m³/s |
| \( D_{out,k} \) | volume flow of flue gas leaving from each zone, m³/s |
| \( P_i \) | formation rate of \( j \) component in each zone, kmol/(m³s) |
| \( G_{vol} \) | volume flow of flue gas entering in each zone, m³/s |
| \( K_i \) | reaction rate constant, 1/s |
| \( M_{i,k} \) | inventory amount of class \( i \) solid particle in each zone, kg |
| \( m_i \) | chlorine generation amounts per kilogram of fuel, kg |
| \( N_j \) | molar mass of \( j \) component, g/mol |
| \( R_{i} \) | release ratio of \( i \) at a temperature \( T \), % |
| \( Q_{in,k} \) | energy entering each zone, J/s |
| \( Q \) | heat released by fuel combustion, J/s |
| \( Q_{out,k} \) | energy leaving each zone, J/s |
| \( Q_{exc,k} \) | heat exchanged between each zone and the heat exchange equipment, J/s |
| \( r_i \) | reaction rates, mol/(m³s) or mol/s |
| \( T \) | temperature, K |
| \( W_{in,j,k} \) | mass flow of class \( i \) solid particle entered in each zone, kg/s |
| \( W_{gl,k} \) | mass flow of class \( i \) solid particle generated in each zone, kg/s |
| \( W_{r,j,k} \) | amount of class \( i \) solid particle consumed by the reaction, kg/s |
| \( W_{out,j,k} \) | mass flow of class \( i \) solid particle that leave from each zone, kg/s |
| \( W_{ch,j} \) | mass flow of class \( i \) solid carried into the separator by the flue gas, kg/s |
| \( W_{loop,i} \) | mass flow of class \( i \) solid entering the loop-seal, kg/s |
| \( W_{bio} \) | biomass fuel amount, kg/s |
| \( X \) | chlorine release rate per kilogram of fuel |
| \( X_{NO} \) | conversion rate of NO, % |
| \( X_{Fe} \) | volatile content |

GREEK LETTER

| Symbol | Description | Unit |
|--------|-------------|------|
| \( \eta \) | separation efficiency, % |
| \( \rho \) | density, kg/m³ |
| \( \gamma \) | activity coefficient |
| \( \psi \) | modified Stokes number |
| \( \tau \) | time, s |
| \( \theta \) | vortex index, usually in the range of 0.5 < \( \theta \) < 0.7 |

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