Reduced Pollutant Emissions and Slagging Rate of Biomass Pellet Combustion by Optimizing the Multilayer Distribution of Secondary Air

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1. INTRODUCTION

Driven by the goal of carbon neutralization, the utilization of biomass energy has attracted a great amount of attention over recent years. Biomass is the only renewable carbon source that can be used to produce a wide range of high-quality fuels. However, due to the limitation of different technologies, the large-scale utilization of straw biomass as an energy source is generally based on direct or indirect combustion. In particular, biomass pellet fuel is used widely at the commercial level, overcoming many limitations of raw biomass, such as low density, low calorific value per unit volume, and difficulties in efficient combustion. Straw biomass typically contains a high content of alkali metals and ash. Serious ash slagging and agglomeration often occur in the furnace during combustion, and the pellet fuel of straw biomass further increases the agglomeration degree of ash. This is mainly due to the dense structure of pellet fuel, which contains low-melting-point compounds that polymerize easily at high temperatures. A layer of glass-like melt is formed on the outer surface of straw pellet fuel, and the fuel is not fully burned inside. This prevents sufficient contact between fuel and combustion air. Difficulties in full combustion result in high pollutant emissions in flue gas as well as serious equipment corrosion and slagging complications. Straw is the main byproduct of crop harvesting and has the advantages of a lower price, wide range of sources, and easier access compared to woody biomass. However, crop straw usage is typically inefficient, causing serious environmental pollution hazards to rural areas and towns. Previous research has investigated the pretreatment of straw-like biomass by pickling or alkaline washing, adding additives that do not easily form slag, and the co-combustion with coal, woody biomass, etc. Such methods are able to effectively reduce the degree of slagging and agglomeration. In particular, local low-temperature combustion via a suitable air distribution is a simple, easy, and low-cost strategy for the reduction of straw biomass slagging. At present, air staged combustion technology is generally used in pulverized coal burners or circulating fluidized bed boiler systems. Liu et al. employed a 50 kW small household biomass pellet burner with two secondary air ducts of different heights (9 and 21 cm above the bed). The results revealed the significant reduction of NO\textsubscript{x} emissions with the secondary air set at a higher position, while CO emissions were enhanced and the combustion efficiency was lowered. Thus, blindly increasing the secondary air proportion is not advisable; rather, it must be controlled adequately. Fan et al. employed a 20 kW...
kW pulverized coal reactor to conduct deep and medium air staged combustion tests. Under the air staged combustion of pulverized coal, the key combustion zone was in a state of insufficient air supply, resulting in a strong reducing atmosphere that inhibited the formation and production of NO during the combustion process. Therefore, the peak NO concentration in the key combustion zone exhibited a rapid drop. In addition, the deeper the classification degree, the lower the NO emission concentration. Sher et al.23 burned three pellet fuels (straw, miscanthus, and peanut shells) in a 20 kW small bubbling fluidized bed (BFB) burner in order to evaluate the influence of the secondary air injection position on the emission concentration (NOx, CO) and temperature distribution of the gas during fuel combustion. Increasing the excess air coefficient reduced CO concentrations and enhanced NOx concentrations at the outlet. Injecting the secondary air at a higher point led to the majority of fuel combustion achieving a significant reduction in NOx emissions.

There currently exist numerous applications of air-staged air distribution combustion technology for coal and biomass in large-scale combustion devices. However, the majority of studies focus on fuel combination characteristics, with typical equipment including tube furnaces, muffle furnaces, thermogravimetric analyzers, etc. Large differences between the operating conditions of the test equipment and the actual combustion device result in discrepancies between the data and conclusions and the actual fuel combustion in large furnaces. In order to overcome these limitations, we design a biomass pellet combustion test device with a multilayer secondary air distribution. The effects of different primary and secondary air (PA and SA) grading ratios and multilayer secondary air ratios on the concentration of CO, NOx, and other pollutants in the flue gas and combustion efficiency are studied, and the corresponding variations of the combustion ash composition are analyzed. Effectively controlling the multilayer secondary air distribution lowers the NOx and CO emissions from the combustion of corn stalk and rice husk pellets and increases the combustion efficiency. The results provide technical support for the reasonable combustion and air distribution of large-scale and domestic biomass combustion equipment.

2. MATERIALS AND METHODS

2.1. Multilayer Secondary Air Distribution Straw Biomass Combustion Test Bench. The structure of the biomass pellet combustion test bench with multilayer secondary air distribution is shown in Figure 1. The parameters of the designed biomass pellet combustion test bench are shown in Table 1. Nine secondary air ducts are evenly and symmetrically distributed along the height of the entire combustion chamber, and the distance between the upper and lower air ducts is 5 cm. The air ducts are divided into three groups along the height of the combustion chamber, denoted as the upper, middle, and lower secondary winds (US, MS, LS). The secondary air (room temperature) enters the combustion chamber at different heights and proportions. The upper, middle, and lower secondary air volumes are precisely controlled by the L2B-15 mass flow meter. The primary air (room temperature) passes through the grate into the combustion chamber, and the air volume is controlled by a 1000WOG valve. The air distribution at the bottom of the test bench is mainly achieved by the grate, which not only supports the material but also acts as an air distribution plate. The grate reasonably distributes the primary air supplied from the bottom of the furnace, so that the air distribution is more uniform and the combustion is more sufficient. In addition, a portion of the bottom slag is present at the bottom to act as a bed material when the test bench starts to maintain the initial material balance. The bed material is also present during the combustion process to maintain normal pressure in the furnace.

2.2. Analysis of Raw Material Characteristics. Rice husks and corn stalks are typical biomass available across the globe, with a huge annual output. Research has demonstrated that the burning of biomass is prone to problems such as high pollutant emissions and insufficient combustion.

Table 1. Specific Parameters of Combustion Test Bed

| Parameters                      | Values          |
|---------------------------------|-----------------|
| design materials                | corn stalks, rice husks |
| rated feeding volume            | 3.0 kg/h        |
| rated combustion efficiency     | 95%             |
| distance between adjacent ports | 13.0 cm         |
| design rated power              | $48 \times 10^3$ kJ/h |
| overall height                  | 0.90 m          |
| combustion chamber volume       | 0.02 m$^3$      |
| secondary air diameter          | 3.0 cm          |
| inner diameter of secondary air | 5.0 mm          |

Figure 1. Test bench for burning straw biomass.
Table 2. Characteristic Analysis of Corn Stalks and Rice Husk Raw Materials on an As-Received Basis

| sample        | moisture | volatiles | fixed carbon | ash | [C]    | [H]   | [O]   | [N]   | [S]   | LHV (MJ/kg) |
|---------------|----------|-----------|--------------|-----|--------|-------|-------|-------|-------|-------------|
| corn stalks   | 10.22    | 66.24     | 14.81        | 8.73| 41.97  | 5.81  | 48.21 | 1.12  | 0.06  | 15.72       |
| rice husks    | 6.31     | 71.09     | 7.69         | 14.91| 39.22  | 5.51  | 49.9  | 0.34  | 0.08  | 15.43       |

Table 3. Inorganic Elemental Composition of Corn Stalks and Rice Husks

| sample        | elemental composition (wt %) |
|---------------|-----------------------------|
|               | [Na]           | [Mg]      | [Al]     | [Si]   | [P]   | [S]   | [Cl]  | [K]  | [Ca] | [Fe] |         |
| corn stalks   | 0.060          | 0.313     | 0.194    | 3.090  | 0.167 | 0.201 | 0.838 | 3.180 | 1.230 | 0.204 | 0.062 |
| rice husks    | 0.085          | 0.132     | 0.081    | 8.520  | 0.101 | 0.010 | 0.360 | 1.130 | 0.222  |        |         |

extremely high, reaching more than three times that of the rice husks.

Table 3 presents the results of the X-ray fluorescence spectrometry (XRF, Rigaku ZSX100e) of corn stalks and rice husks. Both the chlorine and potassium contents in rice husks and corn stalks are relatively high, and the high content of potassium is the main factor causing the slagging of biomass combustion.\(^{39}\) Potassium content generally exists as K\(_2\)O, KOH, K\(_2\)SO\(_4\), K\(_2\)CO\(_3\), etc. in the ash. The melting points of these substances tend to be low. With the exception of a few compounds (e.g., K\(_2\)SO\(_4\)), the melting points of most substances are between 350 and 800 °C. In fact, at higher combustion temperatures, these may even be reduced by the carbon-hydrogen fuel matrix to metal vapor. These alkali species will readily react with the ubiquitous water vapor to form alkali hydroxides.\(^{30}\) A large amount of hydroxides combined with the unburned coke pellets, resulting in problems including insufficient combustion and slagging. This causes serious harm to the biomass boiler. Note that the silicon contents in both rice husks and corn stalks are relatively high, accounting for more than 40% of the total inorganic elements. The silicon content in the rice husks accounts for 90% of the total inorganic elements and has an important effect on the post-combustion ash composition of rice husks.

2.3. Combustion Efficiency (\(\eta_c\)). The combustion efficiency can reflect the combustion effect of fuels under different working conditions. The amount of fly ash discharged from the combustion chamber of biomass pellet fuel is relatively low, and thus only the heat loss caused by combustible gas and unburned carbon in the bottom ash is considered.

\[
\eta_c = 100 - q_1 - q_2
\]

(1)

\[
q_1 = 3.2\alpha\phi(CO)
\]

(2)

where \(\eta_c\) is the combustion efficiency, \(\%\); \(q_1\) is the heat loss due to unburned gas, \(\%\); \(q_2\) is the heat loss due to unburned carbon, \(\%\); \(\alpha\) is the excess air coefficient; and \(\phi(CO)\) is the CO content in the flue gas, \(\%\).

For biomass combustion, the unburned carbon generally remains in the ash, and the formula of \(q_2\) can be simplified as

\[
q_2 = \frac{33727A_{u,c}C_2}{Q_r(100 - C_2)}
\]

(3)

where \(A_{u,c}\) is the ash content of the raw material received, \(\%\); \(C_2\) is the content of unburned carbon in the ash, \(\%\); and \(Q_r\) is the low caloric value of the raw material received, kJ/kg.

3. RESULTS AND DISCUSSION

3.1. Emission Law of Combustion Pollutants. In the fuel combustion process, the proper amount of air entering will have a great influence on the oxidation or reduction atmosphere of the combustion area and consequently affect the emission level of particulate matter, nitrogen oxide, and other pollutants. We employed rice husks and corn stalks as fuels to investigate the flue gas pollutant emissions and the combustion chamber temperature changes using the above biomass combustion test bench (Figure 1). All the combustion experiments were performed at a feeding rate of 1.5 kg/h biomass briquette. In order to mark the various air distribution conditions of the experiments, we propose a primary air application, with excess air coefficients of 1.1, 1.2, 1.3, and 1.4 (EAC1.1, EAC1.2, EAC1.3, EAC1.4, respectively). The primary and secondary air ratios are set as PA:SA = 70%:30% or 60%:40%, respectively. The secondary air enters the furnace from the upper, middle, and lower entrances (US, MS, LS), labeled US (30%), MS (30%), and LS (30%) or US (40%), MS (40%), and LS (40%), respectively. When the primary and secondary air ratios are PA:SA = 60%:40%, the lower, middle, and upper three layers of the secondary air are allocated according to the following proportions (1/2, 0, 1/2), (1/3, 1/3, 1/3), (0, 1/2, 1/2), and (1/2, 1/2, 0) and marked as \(W_1\), \(W_2\), \(W_3\), and \(W_4\) respectively. In order to compare with the fuel combustion case of the presence of just primary air, the following conditions are selected as the control groups. The experimental data of corn stalk pellet combustion condition EAC1.2 is used for control group (CG), while the experimental data of rice husk combustion condition EAC1.3 is also selected for control group (CG).

Figure 2 presents the variations of the NO\(_x\) and CO concentrations and combustion zone temperature \(T_z\) of the rice husk pellet under different air distribution conditions. The NO\(_x\) emission concentrations at the combustion outlet are approximately 200–260 mg/m\(^3\) when the excess air coefficient is 1.1, 1.2, 1.3, and 1.4. Moreover, the NO\(_x\) emissions during the staged combustion of the primary and secondary air range within 150–250 mg/m\(^3\), which is lower than the non-staged combustion concentrations. Temperature \(T_z\) under these working conditions is between 650 and 800 °C and increases with the excess air coefficient. This may be attributed to the high ash and silicon content in the rice husks, preventing the fixed carbon to fully burn out.\(^{31}\) Consequently, the increase of excess air coefficient helps to burn out the rice husks. In addition, the thermocouple is located just above the fuel bed. Usually, this implies that the measured temperature is very sensitive to the exact position as well as process conditions in
that position, which means that considerable variations in measured temperature can be obtained.

Following the comparison of the operating conditions EAC1.1–EAC1.4 during the rice husk burning, we select the staged air distribution combustion test at EAC1.3 for subsequent analysis. Under this condition, as the proportion of the secondary air in the total air volume increases (from 30% to 40%), the NO\textsubscript{x} emission concentration is significantly reduced. This is consistent with the results of previous work.\textsuperscript{52}

When the secondary air equals 30% of the total air volume, NO\textsubscript{x} emissions exhibit a significant reduction with the increasing secondary air height, from 300 mg/m\textsuperscript{3} of LS (30%) to 180 mg/m\textsuperscript{3} of US (30%). However, no significant changes are observed in the NO\textsubscript{x} emissions at 40%, with values remaining close to 150 mg/m\textsuperscript{3}. The reduction effect is obvious, and the variation in the secondary air height under the condition of primary and secondary air classification (40%) has a limited impact on the NO\textsubscript{x} emission concentration. Under the four secondary air multilayer air distributions, the NO\textsubscript{x} emission concentration at the outlet during combustion does not change greatly, with values at around 180 mg/m\textsuperscript{3} (Figure 2c). The outlet NO\textsubscript{x} emissions in the primary and secondary air distribution combustion conditions exceed those of CG (with the exception of LS (30%)), while other operating conditions are reduced (Figure 2b). Rice husks also have lower NO\textsubscript{x} emissions. However, under the multilayer secondary air distribution combustion condition, NO\textsubscript{x} emissions during the rice husk combustion are similar to those under the primary secondary air staged distribution combustion outlet.

Figure 2 depicts the NO\textsubscript{x} and CO concentrations and combustion zone temperature \(T_1\) of the corn stalks under different air distribution conditions. In the absence of a graded air distribution, the CO emissions initially decrease and then subsequently increase with the increasing excess air coefficient (Figure 2a), differing to the results of Liu et al.\textsuperscript{33} This can be explained by the relatively small amount of air entering the combustion chamber at the EAC1.1, with the insufficient amount of oxygen causing insufficient combustion and emitting more CO.\textsuperscript{34} At the same time, due to insufficient oxygen, temperature \(T_1\) at the lower part of the combustion chamber is relatively low. At EAC1.2 and EAC1.3, as the excess air coefficient increases, the fuel is fully combusted in the combustion chamber, and the generated CO and sufficient oxygen will undergo an oxidation reaction to form CO\textsubscript{2}. Therefore, CO concentrations under these two combustion conditions are relatively low, and temperature \(T_1\) is relatively high. However, note that the corresponding NO\textsubscript{x} concentration at the fire outlet is also relatively high. As the excess air coefficient continues to increase, the inlet velocity of low-temperature air entering the combustion chamber from the lower part increases, which enhances the heat transfer rate inside the combustion chamber and shortens the flue gas residence time. This consequently reduces the internal combustion temperature and NO\textsubscript{x} emission concentration. However, as the volatile matter stays in the combustion chamber for a short time period, the combustion is not complete, and the corresponding CO concentration increases.

The subsequent staged air distribution combustion test was performed at EAC1.2. At the primary and secondary air ratio of PA:SA = 70%:30%, the CO concentration increases under US (30%) and LS (30%) compared with CG (Figure 2b). Lower CO emissions are observed under MS (30%). This indicates that a suitable secondary air height will significantly reduce the CO concentration in the flue gas and facilitate the combustion process. In addition, distributing the primary and secondary air can reduce the NO\textsubscript{x} concentration of the vent, with a decreasing trend as the height of the secondary air increases. Similar trends in the CO and NO\textsubscript{x} concentrations at the vent are observed for the primary and secondary air ratio of 60%:40%. As the secondary air height increases, CO concentrations initially decrease and subsequently increase, while NO\textsubscript{x} concentrations gradually decrease. For CO
emissions, the difference caused in the pre-combustion period is relatively minor. The main difference might be attributed to the oxidation reaction of CO with O\textsubscript{2} to form CO\textsubscript{2} in the high temperature region of the main combustion. Therefore, the minor differences of \( T \textsubscript{1} \) obtained under LS (40%), MS (40%), and US (40%) are in the range of 45 \(^\circ\)C, which indicates that the oxidation reaction dominated by the flue gas displacement plays a decisive role. However, MS (40%) is less efficient for flue gas replacement of the generated volatiles and CO. MS (40%) is more likely to maintain CO in the main combustion high temperature zone in the middle of the furnace and below. The oxidation reaction is also easier, resulting in a lower CO concentration at the outlet. However, CO and NO\textsubscript{x} emissions are lower for the primary and secondary air ratio of 60%:40% compared to those at 70%:30%.

CO emissions in the flue gas under the four secondary air multilayer air distribution conditions are very high, reaching 900 mg/m\(^3\) (Figure 2c). It is obvious that \( W \textsubscript{3} \) represents the condition with the strongest secondary air stage, while the \( W \textsubscript{4} \) condition represents the condition with the weakest secondary air stage. Therefore, the combustion should be correspondingly sufficient under \( W \textsubscript{4} \). In addition, for such a secondary air position, the generated CO is more likely to stay in the high temperature zone of the main combustion and undergo an oxidation reaction with O\textsubscript{2} to reduce the CO concentration. However, the temperature \( T \textsubscript{1} \) will decrease accordingly due to the increase in the heat transfer rate. The theoretical combustion efficiency decreases under \( W \textsubscript{6} \), but the appropriate excess air coefficient makes the combustion efficiency slightly lower than that of \( W \textsubscript{5} \) and the CO concentration increases accordingly. However, the air distribution of \( W \textsubscript{4} \) allows the heat transfer efficiency to dominate and the resulting CO is less likely to remain in the high temperature zone of the main combustion for oxidation reactions, resulting in a higher CO concentration than \( W \textsubscript{3} \). In contrast, NO\textsubscript{x} concentrations are low, with a minimum close to 140 mg/m\(^3\). This indicates the opposing change trends of CO and NO\textsubscript{x} concentrations in the flue gas, which is consistent with previous research.\(^{22}\) In summary, NO\textsubscript{x} concentrations in the fire outlet are reduced across all secondary air multilayer distributions compared with the two control groups, while CO concentrations are increased. Biomass has comparable nitrogen content to coal but almost no sulfur. Therefore, the biomass combustion device hardly needs to install desulfurization equipment. As for the emissions of NO\textsubscript{x} after staged air distribution combustion of biomass, the NO\textsubscript{x} emission concentration we obtained is lower than that of coal combustion under optimal conditions (350–250 mg/m\(^3\)). In summary, the optimized staged air distribution combustion of biomass presents a greater advantage than coal combustion in terms of controlling NO\textsubscript{x} emissions.

3.2. NO\textsubscript{x} Reduction Rate of Straw Pellet Combustion.

The NO\textsubscript{x} reduction rate (\( \eta \)) was used to determine the degree of reduction in the NO\textsubscript{x} concentrations under rice husk combustion for each air distribution condition compared with the CG. The larger the value of \( \eta \), the greater the degree of NO\textsubscript{x} reduction, that is, the lower the NO\textsubscript{x} concentrations and the better the effect. \( \eta \) is calculated as follows:

\[
\eta = \frac{\text{NO}_x(\text{CG}) - \text{NO}_x(y)}{\text{NO}_x(\text{CG})} \times 100\%
\]

where NO\textsubscript{x}(CG) is the NO\textsubscript{x} concentration in CG; NO\textsubscript{x}(y) is the NO\textsubscript{x} concentration obtained when the primary and secondary air is divided into different levels and the secondary air is multilayered; and \( y \) refers to US (30%), MS (30%), LS (30%), MS (40%), LS (40%), W\textsubscript{1}, W\textsubscript{2}, W\textsubscript{3}, and W\textsubscript{4}.

Figure 3 shows the NO\textsubscript{x} reduction rate of rice husks and corn stalks under different combustion conditions. NO\textsubscript{x} emissions from rice husk combustion are minimized when the secondary air accounts for 40% of the total air volume, with a NO\textsubscript{x} reduction rate close to 50% (Figure 3). At 30%, the NO\textsubscript{x} reduction rate increases significantly with the secondary air height, yet this is not true at 40%. Under the multilayer secondary air distribution condition, the overall level of NO\textsubscript{x} reduction rate ranges between 36% and 41%, with minimal variation. For the combustion of corn stalks at the EAC1.2, the use of the primary and secondary air graded air distribution can effectively reduce NO\textsubscript{x} concentrations in the flue gas compared with just applying the primary air. The NO\textsubscript{x} reduction rate exceeds 14% under this scenario (Figure 3). Note that irrespective of the secondary air height in the upper, middle, and lower layers, when the primary and secondary air ratio is 60%:40%, the NO\textsubscript{x} reduction rate exceeds that of the PA:SA at 70%:30%. This demonstrates that the proportion of the secondary air in the total air volume is enhanced, helping to reduce the NO\textsubscript{x} concentration in the flue gas. In addition, applying multilayered secondary air can further reduce the NO\textsubscript{x} concentration, with a NO\textsubscript{x} reduction rate between 38% and 53% and an obvious NO\textsubscript{x} reduction effect. In particular, the NO\textsubscript{x} reduction rates of \( W \textsubscript{1} \) and \( W \textsubscript{2} \) are significantly higher than those of \( W \textsubscript{3} \) and \( W \textsubscript{4} \).

Note that under the multilayer secondary air distribution combustion conditions, the NO\textsubscript{x} emission concentration during the burning of rice husks is similar to that of corn stalk burning. However, the NO\textsubscript{x} reduction effect is not obvious compared with the corn stalk combustion.

3.3. Characteristics of the Furnace Temperature Distribution.

The results in Section 3.2 reveal that the reduction in the NO\textsubscript{x} emissions of rice husk combustion under the multilayer secondary air distribution is not obvious compared with that of corn stalks. Therefore, the outlet of the multilayer secondary air distribution combustion condition exhibits higher NO\textsubscript{x} emissions for the combustion of rice husks and corn stalk fuel. NO content accounts for more than 90% of
NO\textsubscript{x} and the production of NO is closely related to the furnace temperature during combustion. In order to further investigate the high NO\textsubscript{x} emissions during combustion, temperature measurement points were set at heights of 10, 20, 30, and 40 cm above the grate. We monitored and analyzed the internal temperature during combustion and selected the temperature data of different furnace heights in the stable combustion stage. This data was employed to calculate the average temperature value, allowing us to evaluate the subsequent reduction of NO\textsubscript{x} emission concentrations. Figure 4 presents the temperature measurement points of corn stalks along the height of the combustion test bench.

Under the application of just primary air, the furnace temperature is observed to change for excess air coefficients of 1.2, 1.3, and 1.4 (Figure 4a). The temperature changes at different combustion chamber heights follow the same trend. More specifically, the temperature decreases as the measuring points increase. The lower the height of the measuring point, the more severe the temperature change. Moreover, increasing the excess air coefficient continues to decrease the temperature.
of each measuring point accordingly. When the excess air coefficient is 1.2, compared with just the primary air distribution, applying the graded air distribution of the primary and secondary air results in the gradual decrease of temperature $T_1$ as the position of the secondary air entering the combustion chamber increases, while temperatures $T_2$, $T_3$, and $T_4$ increase significantly (Figure 4b). Increasing the height of the secondary air entrance will form a relatively oxygen-deficient area at the bottom of the combustion chamber, resulting in a reduction in the combustion temperature of the fuel. In addition, for both primary and secondary air ratios 60%:40% and 70%:30%, $T_3$ exceeds $T_2$ when the secondary air enters the center of the combustion chamber. This is attributed to the incomplete burning of part of the volatile matter in the principle combustion zone at the bottom of the combustion chamber. Due to the addition of the secondary air, the unburned volatile matter is fully burned here, and temperature $T_3$ rises. Compared with CG, under the four secondary air multilayer air distribution modes ($W_1$, $W_2$, $W_3$, and $W_4$), the temperature of each measurement point in the combustion chamber is reduced (Figure 4c). The temperature changes at $T_1$ and $T_4$ are most obvious, which is also a key influencing factor of the NOx concentration reduction in the flue gas. This is a key advantage brought by the use of the secondary air multilayer air distribution, yet an excessively low temperature in the combustion chamber may impact the combustion efficiency of the corn stalks.

Figure 5 presents the temperature distribution characteristics at different heights in the furnace during the burning of rice husks and corn stalks. The temperatures $T_2$, $T_3$, and $T_4$ during rice husk burning exceed those of the corn stalk burning (Figure 5a). The opposite is true under the primary and secondary air staged combustion conditions (Figure 5b). The primary air is the main source of oxygen required for combustion in the furnace. It is the basis for stable combustion in the furnace and plays a key role in the combustion of volatile in the biomass. Compared with corn stalk, the pre-combustion process of rice husk is slower. When the secondary air enters the furnace from different positions, a relatively oxygen-deficient area is gradually formed at the bottom of the combustion chamber, and the combustion stability of rice husk is not as good as that of corn stalk. Therefore, the combustion temperature of rice husk is slightly lower than that of corn stalk. This is mainly due to the change in the combustion conditions of rice husk and corn stalk after the entry of secondary air. However, the temperatures of corn stalk and rice husk burning are generally similar, with temperature differences between $T_1$ and $T_4$ in all working conditions ranging within 100–200 °C. Note that $T_4$ is higher than $T_1$ in the MS (30%) working condition during the burning of corn stalks. This is due to the change in corn stalk burning conditions following the entry of the secondary air. Under burning conditions $W_1$ and $W_2$, the burning temperature of corn stalks at different heights exceeds that of rice husks by approximately 40 °C (Figure 5c). The combustion temperature change trends of the two fuels at different heights are consistent.

### 3.4. Combustion Efficiency of Straw Pellets

The heat loss and combustion efficiency of rice husk pellet combustion under different air distribution conditions were calculated using eqs 1–4 (Table 4). At EAC1.1, the combustion efficiency of corn stalks is low, reaching just 99.05%, while at EAC1.2–EAC1.4, the combustion efficiency exhibits a narrow range of 99.20%–99.22%. Compared with CG with only primary air, the combustion efficiency of corn stalks gradually decreases as the position of the secondary air entering the combustion chamber increases at EAC1.2. When the secondary air enters from the uppermost layer, the combustion efficiency is reduced to 99.12%. The combustion efficiency is further reduced under the four secondary air multilayer air distribution modes ($W_1$, $W_2$, $W_3$, and $W_4$), with $W_4$ exhibiting the greatest reduction to 98.89%. This indicates that at high secondary air entrance areas or reduced secondary air volumes, the combustion of corn stalks can be incomplete, with a high carbon content in the ash, and a significant increase in CO emission concentrations. In addition, the temperature at the bottom of the combustion chamber decreases, thus reducing the combustion efficiency.

Table 4 reveals the combustion efficiency to be inversely proportional to the bottom ash carbon content. The CO emissions of the designed combustion test bench range between 0.04% and 0.16%, while the bottom ash carbon content is between 5.5% and 7.5%. For general biomass pellet burners, the combustion efficiency exceeds 95%, which is mainly due to the characteristics of rice husk fuel and its inability to burn out readily. The combustion test results of the combustion test bench designed in this paper demonstrate a maximum combustion efficiency of 97.78% for rice husks as the fuel and generally a relatively good combustion effect. Under the combustion of straw biomass, the CO concentration and the bottom ash carbon content are key in determining the combustion efficiency. For rice husks, fuels with a high silicon content in ash require the design of a specific boiler for

| carbon content/% | CO/%  | $q_1/%$ | $q_2/%$ | $\eta/%$ |
|------------------|-------|---------|---------|---------|
| CS   | RH   | CS   | RH   | CS   | RH   | CS   | RH   |
| EAC1.1 | 3.70 | 7.76 | 0.056 | 0.123 | 0.215 | 0.512 | 0.726 | 2.382 | 99.05 | 97.11 |
| EAC1.2 | 3.40 | 7.46 | 0.034 | 0.148 | 0.130 | 0.616 | 0.665 | 2.269 | 99.20 | 97.12 |
| EAC1.3 | 3.30 | 7.32 | 0.033 | 0.112 | 0.126 | 0.467 | 0.645 | 2.216 | 99.22 | 97.32 |
| EAC1.4 | 3.30 | 6.84 | 0.037 | 0.044 | 0.142 | 0.185 | 0.645 | 2.037 | 99.21 | 97.78 |
| LS(40%) | 3.33 | 6.86 | 0.029 | 0.106 | 0.112 | 0.441 | 0.651 | 2.045 | 99.23 | 97.51 |
| LS(40%) | 3.35 | 6.86 | 0.014 | 0.054 | 0.053 | 0.227 | 0.655 | 2.046 | 99.29 | 97.73 |
| US(40%) | 3.50 | 7.31 | 0.050 | 0.075 | 0.192 | 0.311 | 0.685 | 2.209 | 99.12 | 97.48 |
| $W_1$ | 3.45 | 8.21 | 0.091 | 0.128 | 0.349 | 0.532 | 0.675 | 2.549 | 98.97 | 96.92 |
| $W_2$ | 3.60 | 8.24 | 0.077 | 0.076 | 0.295 | 0.318 | 0.706 | 2.564 | 98.99 | 96.12 |
| $W_4$ | 3.50 | 8.32 | 0.110 | 0.105 | 0.422 | 0.436 | 0.686 | 2.595 | 98.89 | 95.97 |
| $W_4$ | 3.20 | 8.12 | 0.090 | 0.134 | 0.345 | 0.559 | 0.625 | 2.528 | 99.02 | 95.92 |

The value of CO is obtained by converting mg/m$^3$ to units in %.

Table 4. Heat Loss and Combustion Efficiency of Corn Stalks and Rice Husks under Different Working Conditions
combustion research. In order to evaluate the degree of combustion and slagging of corn stalks under different air distribution conditions, we collected and weighed the burned ash and placed it on a SC-600 vibrating screen with a 6 mm screen for sieving for 30 s. After screening, the slag lump remaining on the screen was collected and weighed. The slagging rate (SR) is determined as follows:

\[ C = \frac{G_1}{G_2} \times 100\% \quad \text{and} \quad SR = \frac{G_1}{G_2} \tag{5} \]

SR is the slagging rate, %; \( G_1 \) is the slag with a pellet size greater than 6 mm, g; and \( G_2 \) is the total amount of ash formed, g.

Table 5 reports the fuel bed temperature \( T_1 \) and slagging rate of the corn stalk combustion chamber under different working conditions. Compared with CG, the slagging rate of the corn stalks exhibited a decreasing trend following the application of the primary and secondary air grading. This is particularly true when the secondary air enters the middle position of the combustion chamber (MS), with a reduction in the slagging rate by about 11.2%. When the secondary air multilayer air distribution is adopted, the slagging rate under the four working conditions (\( W_1, W_2, W_3, \) and \( W_4 \)) is greatly reduced, and minimized under \( W_4 \) (4.5%). This is associated with the low temperature at the bottom of the combustion chamber at this time, and the addition of the secondary air multilayer air distribution has an impact on the gas phase release of elements such as K and Na in the ash at the bottom layer. The slagging rate of the corn stalks is highly correlated with temperature \( T_1 \) of the fuel bed. When \( T_1 \) is between 670−740 °C, the slagging rate is approximately 5%, while when \( T_1 \) is higher than 760 °C, the slagging rate will rapidly increase to over 11%. This indicates the key influencing role of \( T_1 \) in the combustion and slagging of corn stalks. Note that several air distribution conditions in Table 5 did not exhibit a higher temperature and slagging rate. Corn stalks are prone to severe ash slagging when burning, and NO\(_x\) emissions are high. Therefore, the NO\(_x\) emissions and ash slagging rate at the flue gas outlet are used as evaluation indicators to study the operating conditions for low NO\(_x\) emissions and slagging rates under corn stalk burning with air distribution conditions (Figure 6a). There is no slagging during rice husk combustion; thus, the export NO\(_x\) and CO emission concentrations are used as the evaluation index to select the optimal working conditions (Figure 6b). During the burning of corn stalks, considering that various countries are implementing more stringent requirements for NO\(_x\) emission concentrations, the NO\(_x\) concentration is set as the key indicator for the selection of the optimal working conditions, and the lower slagging rate as the second indicator. From the test results, \( W_1 \) is considered to be the optimal air distribution condition for corn stalk combustion. If the low CO emission concentration in flue gas is considered as the selection standard, \( W_3 \) is the optimal condition. For general biomass boilers, the CO emission concentration is within 0.2%, while the CO emission concentration of the designed combustion test bed is between 0.04% and 0.16%, which is lower than that of conventional biomass boilers. Among these operating conditions, only MS (40%) showed lower NO\(_x\) and CO emissions than 200 and 550 mg/m\(^3\), respectively. More specifically, the outlet NO\(_x\) and CO emission concentrations simultaneously reach low levels, and thus MS (40%) is selected as the optimal air distribution condition.

3.5. Variations in the Ash and Inorganic Elements of Corn Stalks and Rice Husks. 3.5.1. Variations in the Ash and Inorganic Element Composition of Corn Stalks. As a typical straw-like biomass, corn stalks not only produce higher NO\(_x\) emissions when burned, but the fuel layer is also prone to slagging seriously affecting the air distribution and burnout. Therefore, we focus on investigating the effect of different air distribution methods on the burning of corn stalks and slagging. The corn stalk ash and slag obtained from the combustion of the biomass pellet combustion test device are crushed, ground, and analyzed using a polycrystalline X-ray diffractometer (XRD, Bruker AXS D8 Advance, Germany). Figure 7 presents the variation of the main inorganic element content in the corn stalk ash with the combustion conditions. The ash obtained from the combustion of corn stalks is in a soft state, relatively broken and has a low hardness level. However, the corn stalk residue is a glassy substance in

Table 5. \( T_1 \) and Slagging Rate Corresponding to the Corn Stalk Combustion in Each Working Condition

| working conditions | EAC1.2 | EAC1.3 | EAC1.4 | LS(40%) | MS(40%) | \( W_1 \) | \( W_2 \) | \( W_3 \) | \( W_4 \) |
|-------------------|--------|--------|--------|---------|---------|--------|--------|--------|--------|
| \( T_1 \)/°C      | 790    | 760    | 750    | 800     | 761     | 701    | 752    | 671    | 743    |
| slagging rate/%   | 14.4   | 16     | 14.5   | 13      | 11.2    | 5      | 7.8    | 5.8    | 4.5    |

Figure 6. Analysis of optimal combustion condition of corn stalks (a) and rice husks (b).
appearance, with a high hardness, and the internal components of corn stalks that are not fully burned. As the Si content in the corn stalk raw materials accounts for approximately 5% of the total, a large amount of SiO$_2$ will be formed after combustion, and the K content is second only to the Si content. Therefore, there is a large amount of SiO$_2$ and KCl in the ash and slag from the combustion of corn stalks. When there is a local high temperature area in the combustion chamber, these two compounds easily form a low melting point co-crystal compound, and a large amount of slagging will be formed, complicating the air distribution and slag removal. A large amount of slagging is caused by the high alkali metal element content in the bottom ash for the corn stalk combustion and the low alkali earth metal element content (e.g., Ca and Mg). Therefore, we evaluate the elemental composition of the bottom ash of corn stalks under different combustion conditions. The Si content in the corn stalks ash exhibits minimal variations (between 24% and 26%). The Mg and Fe content change trends are opposing under each EAC1.1–EAC1.4 combustion condition, while the K and Ca content follow the same change trend.

The properties of ash are a function of its composition. At present, there is no suitable slagging judgment standard for different types of biomass combustion, and determining the slagging method of coal is the main reference point. Four commonly used slagging indexes were selected to analyze the combustion slagging tendency of corn stalks under different air distribution conditions. The silica ratio (G), alkali/acid ratio (B/A), Na content index (Na (index))\(^{(5)}\), and alkalinity index (Al\(_c\))\(^{(39,40)}\) are calculated using formulas 6–9.

Silica ratio (G):
\[
G = \frac{\text{SiO}_2}{\text{equivalent Fe}_2\text{O}_3 + \text{SiO}_2 + \text{MgO} + \text{CaO}}
\]  
where equivalent Fe$_2$O$_3$ = Fe$_2$O$_3$ + 1.11FeO + 1.43Fe.

Alkali/acid ratio (B/A):
\[
B = \frac{\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O}}{\text{SiO}_2 + \text{Al}_2\text{O}_3}
\]

Na (index):
\[
\text{Na (index)} = \frac{(\text{Na}_2\text{O} + 0.659\text{K}_2\text{O})\text{A}_\text{ad}}{100}
\]

Alkalinity index (Al\(_c\)):
\[
\text{Al}_c = \frac{\text{A}(\text{K}_2\text{O} + \text{Na}_2\text{O})\%}{\text{HHV}} \quad \text{and} \quad \text{Al}_c = \frac{\text{A}_\text{ad}(\text{Na}_2\text{O} + \text{K}_2\text{O})\%}{\text{HHV}}
\]

where A\(_{ad}\) refers to the ash content of the fuel as air dried basis (wt %); HHV is high calorific value of fuel at dry base.

According to the inorganic element content of the slagging ash obtained under different air distribution conditions, four slagging prediction indexes can be calculated. The slagging index results in Table 6 are used to derive the relations of the four slagging indexes with temperature $T_1$. We combine the judgment range of each slagging index for analysis.\(^{(39,40)}\) For silica ratio $G$, the slagging index reveals mild slagging, and $G$ exhibits an upward trend with temperature $T_1$. Thus, the higher the temperature $T_1$, the less likely $G$ is to form slag, which is contrary to the actual test data. For the alkali/acid ratio (B/A), the slagging index denotes moderate slagging, yet increasing temperature $T_1$ lowers the corresponding predicted slagging degree, which is also inconsistent with the actual situation. Similarly, the Na (index) and alkalinity index (Al\(_c\)) present serious slagging according to the slagging index, yet increasing temperature $T_1$ also lowers the corresponding predicted slagging degree. This is also inconsistent with the actual test results. Therefore, none of the above four slagging indexes can accurately predict the slagging tendency of different fuel areas based on the inorganic elements content in the slagging of corn stalk combustion under varying temperature $T_1$ changes. Note that the slagging rate of corn stalks is strongly related to temperature $T_1$. In addition, a high fitting degree is observed between $G$ and temperature $T_1$ under different combustion conditions. Therefore, temperature $T_1$ is introduced as a variable in the silicon ratio $G$. Following several amendments, the formula is described as follows:
\[
G_t = G \times 1.1 - T_1 \times 0.03\%
\]

Figure 8 shows the modified predictive index ($G_t$) results when the temperature $T_1$ of the different combustion zone is calculated. As temperature $T_1$ in the combustion zone continues to increase, $G_t$ exhibits a downward trend, enhancing the slagging tendency. When temperature $T_1$ is close to 800 °C, $G_t$ is between 0.66 and 0.67 and denotes a severe slagging risk. At the $T_1$ temperature of 680 °C, the $G_t$ value is relatively large, with a moderate slagging tendency. Therefore, the $G_t$ can effectively predict the slagging tendency of corn stalks with
temperature $T_1$ and provides a basis for the prediction of slagging under secondary air multilayer combustion.

### 3.5.2. Variations of Inorganic Elements in the Rice Husk Ash

When rice husks are burned on the biomass combustion test bench, a large amount of black bottom ash is produced, irrespective of the working conditions. The production of black ash from rice husks is the result of unburned carbon. The incomplete carbon combustion may be related to the relatively short combustion time and insufficient air contact. When the combustion test is performed on the combustion test bench, after a certain period of time, new fuel enters the furnace, causing the unburned rice husk ash to backlog to the bottom. In the subsequent combustion, the contact with air is not sufficient while at the same time the combustion time is not long enough for black ash to form. This is attributed to the special Si framework of rice husk ash, which prevents the diffusion combustion from proceeding and prolongs the burnout time. In addition, since the rice husk ash is totally dominated by Si, with a considerable lack of corresponding cation forming elements like K, Ca, Na, etc., the ash will be dominated by SiO$_2$ that do not form slag in the present conditions. This may explain why rice husks do not produce slagging when burning on the combustion test bench. Figure 9 depicts the varying content of several elements in rice husk ash under different working conditions.

The Si content exhibits limited variations in the rice husk ash (fluctuating around 40 ± 2%) under both an increasing excess air coefficient and varying primary and secondary air staged combustion conditions. This may be linked to the limited precipitation of the Si element when the rice husks are burned, with the majority remaining in the bottom ash. The K percentage in rice husk ash is generally higher in the primary and secondary air staged air distribution combustion (Figure 9). This is caused by the lower temperature $T_1$ of the fuel layer during air staged combustion. Numerous studies have proven that the amount of K precipitation increases with the combustion temperature and combustion heating rate. This is because during the pre-combustion stage when biomass volatiles are precipitated, the fuel will undergo pyrolysis and generate H-based free radicals. The chemical reaction between the H radical and char sample breaks the chemical bond between the carbon base and the alkali metal, resulting in the precipitation of the alkali metal element during the pyrolysis process. The chemical formula of the process is as follows:

$$\text{R} + \text{C} \rightarrow \text{C} + \text{R}$$

where C is a carbon base; Y is an alkali metal substance; and R is a free radical.

In the volatilization analysis stage, the reaction temperature and resultant energy are low. This does not meet the conditions required to destroy most of the chemical bonds during the second pyrolysis, and thus the free radicals in the reaction are not easily formed. The reaction of formula 11 is inhibited to a certain extent, and the alkali metal does not have enough energy to break away from the carbon group and cannot be precipitated. Hence, the reaction temperature is very important for the precipitation of alkali metal elements during the combustion of biomass fuel.

### 4. CONCLUSIONS

1. The use of multilayer secondary air distribution can significantly reduce the NO$_x$ concentration for both corn stalks and rice husks. Compared with rice husks, the multilayer secondary air distribution exerts a more obvious reduction effect on the NO$_x$ emission concentration of the corn stalk combustion. The CO and NO$_x$ concentration changes in the flue gas are opposing, demonstrating a competitive relationship.

2. The combustion slagging rate of corn stalks is highly correlated with the temperature of fuel layer $T_1$, which is an important factor affecting combustion slagging. When the NO$_x$ concentration and slagging rate are used as the evaluation indicators for the optimal conditions of corn stalk combustion, $W_1$ is the optimal air distribution condition.

3. The proposed $G_t$ can effectively predict the slagging tendency of corn stalks with the combustion zone temperature $T_1$.

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