Optimization of the Air Distribution in a Biomass Grate-Fired Furnace

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Abstract: This study utilized a combination of FLIC(1D3.2C) and FLUENT(2021R2) software to optimize the primary air distribution along the grate and the performance of a straw briquette combustion furnace of a 7 MW unit in China used to produce hot air for drying grain. Three air distribution modes, namely front-enhanced, uniform, and rear-enhanced modes, were analyzed to determine their effect on the flue gas components above the grate, the temperature field in the furnace, and the nitrogen oxide concentration at the furnace outlet. The results of the calculations showed that the NOx emissions for the front-enhanced, uniform, and rear-enhanced modes were 133.5 mg/Nm³, 104.4 mg/Nm³, and 76.6 mg/Nm³, respectively. It was found that the rear-enhanced mode can expand the biomass drying, devolatilization, and combustion zone, thus improving the furnace combustion performance and decreasing NOx emissions. These findings can provide useful guidance for optimizing biomass chain-grate-firing furnaces.

Keywords: biomass; hot-air furnace; grate firing; numerical simulation; NOx emission

1. Introduction

Biomass energy represents the energy form of solar energy stored in biomass as a carrier of chemical energy. Biomass has the initial characteristics of carbon neutrality and low pollution, and its effective utilization can realize zero emission of carbon dioxide [1,2]. In China, biomass energy reserves are extremely abundant, while the effective utilization rate of biomass energy is currently extremely low. With the increasingly prominent environmental problems and energy shortages, more attention is being paid to the utilization of biomass energy. Many countries are actively involved in the development and utilization of biomass energy [3]. Direct combustion utilization is one of the more important ways for large-scale utilization [4]. Large-scale utilization of discarded biomass is conducive to not only promoting energy saving and emission reduction but also to increasing farmers’ income. Therefore, the effective and reasonable use of biomass not only has environmental benefits but also has social benefits, and it is of great significance to social and economic growth and ecological environment improvement [5].

At present, the main ways of large-scale combustion of biomass include grate firing and fluidized bed combustion [6]. However, in small-scale combustion, grate systems and fluidized bed systems each have advantages and disadvantages. However, grate systems have some technical advantages and are particularly suitable for biomass fuels with large particle size variations and high moisture and ash contents [7]. In addition, they have a cost advantage as they do not require high-pressure fans. They are therefore more suitable for decentralized utilization of biomass resources. In the northeast region of China, grate-firing hot air furnaces are usually used to produce hot air for drying grain. However, the
existing coal-fired drying furnaces have the features of a relatively small scale, a large number, and higher pollutant emissions. According to environmental protection requirements, boilers with a capacity smaller than 10 t/h must be eliminated. The grain drying industry has already obtained an extension period depending on its particularity, but it has to find new technology. Additionally, resource allocation and cost factors make it difficult to replace coal with electricity or gas in the future. Considering the abundant resource of biomass, developing a biomass grate-firing furnace is the feasible solution. However, after changing the fuel to biomass, there were problems such as insufficient output, low combustion efficiency, and excessive pollutant emissions, so it is still urgent to optimize its combustion, especially by optimizing the air distribution mode [8,9].

For grate-firing furnaces, a reasonable air distribution mode is important for ensuring the combustion of the upper-layer material on the grate and improving the reliability, high efficiency, and low-pollutant-emission performance of the boiler. Given the above considerations, the air distribution mode should be optimized to guide its actual operation.

Traditionally, the choice of the air distribution mode for chain-grate furnaces relied mainly on the experience of the operators. Due to the lack of thorough theoretical understanding, the primary research methods are field adjustments or the use of cold flow fields in the furnace and the homogeneous combustion simulation of the gas phase [10]. To address this issue, Chang studied the effect of different ratios of the air on the process of combustion [11], while Wang used cold air to simulate flue gas behavior to guide the design of furnace arches [12]. Wang also compared literature experimental results to furnace flow and temperature fields for various arch types, based on a uniform distribution of flue gas inlet velocity and temperature [13]. Xu optimized the furnace arch and air distribution method and conducted a comparative analysis of the furnace interior flow field, temperature, and grate surface heat flux density distribution before and after adjusting the furnace arch size and air distribution method [14]. Ji et al. used natural gas to simulate the volatiles released from coal and investigated the unsteady combustion mechanism of an industrial moving grate boiler under two typical air distribution modes [15]. Zhao et al. conducted a numerical simulation study using FLIC + Fluent [16] software to analyze the combustion characteristics of straw direct-firing boilers at a specific load, only changing the ratio of primary and secondary air [17]. However, due to the difference in combustion characteristics between coal and biomass, there is limited research on air distribution modes in grate-firing boilers for biomass combustion.

This study utilizes numerical simulation with the combination of FLIC and FLUENT software to investigate the impact of air distribution mode on biomass combustion in a grate-firing furnace designed for hot air supply. The findings offer valuable insights for optimizing the operation of these boilers in real-world settings.

2. Biomass Grate-Firing Furnace for Hot Air Supply

The subject of study in this paper is a grate-firing furnace for hot air supply that burns straw briquettes in northeast China. This furnace has a rated heating power of 7 MW, illustrated in Figure 1. The specified values for the furnace can be found in Table 1.

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Designed Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power of furnace</td>
<td>MW</td>
<td>7.00</td>
</tr>
<tr>
<td>Fuel lower heating value</td>
<td>kJ/kg</td>
<td>12,790.00</td>
</tr>
<tr>
<td>Fuel feed rate</td>
<td>t/h</td>
<td>2.40</td>
</tr>
<tr>
<td>Initial fuel layer height</td>
<td>m</td>
<td>0.25</td>
</tr>
<tr>
<td>Design efficiency</td>
<td>%</td>
<td>83.12</td>
</tr>
<tr>
<td>The effective length of the grate</td>
<td>m</td>
<td>4.50</td>
</tr>
<tr>
<td>Width of grate</td>
<td>m</td>
<td>2.50</td>
</tr>
<tr>
<td>The heat load of the grate</td>
<td>kW/m²</td>
<td>875.00</td>
</tr>
</tbody>
</table>
Excess air ratio - 2.00

Figure 1. The schematic diagram of the furnace.

The furnace is adiabatic, and the hot flue gas enters the gas–air heat exchanger after the combustion chamber. The flue gas temperature at the outlet of the furnace chamber is controlled by recirculating cold flue gas. The straw briquette fuel has sectional dimensions of 4 cm × 4 cm. The lower heating value of the fuel is 12,790 kJ/kg. The ultimate analysis and proximate analysis are listed in Table 2.

Table 2. Ultimate and approximate analyses of fuel.

<table>
<thead>
<tr>
<th>Ultimate (ar)/%</th>
<th>Car</th>
<th>Har</th>
<th>Oar</th>
<th>Nar</th>
<th>Sar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>38.05</td>
<td>4.30</td>
<td>35.45</td>
<td>0.49</td>
<td>0.09</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proximate (ar)/%</th>
<th>M</th>
<th>V</th>
<th>FC</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.10</td>
<td>65.10</td>
<td>13.20</td>
<td>13.60</td>
</tr>
</tbody>
</table>

The chain grate has an effective length of 4.5 m and a width of 2.5 m. The front 1.0 m section of the grate has no primary air wind box; following it, there are four primary air wind boxes, namely A, B, C, and D, sequentially. These boxes have lengths of 0.76 m, 1.02 m, 0.76 m, and 0.76 m, respectively. The secondary air nozzles are situated on the front wall and the top of the furnace.

3. Modeling Method and Calculation Conditions

The combustion process of straw briquettes in the furnace comprises two processes: the grate firing and gas combustion in the combustion chamber, which have significant differences and affect each other. At present, the more mature method is to simulate the two separately, by transferring data flow, and the convergence is obtained by iteration. In this study, the grate firing was carried out through the FLIC bed simulation platform developed by the University of Sheffield [18–20]. The mathematical model of FLIC not only considers the basic conservation equations but also considers the sub-models of material drying, the precipitation and combustion of volatile gas, and solid-phase mixing and reactions. It can predict the concentration and temperature of gas components near the surface of the bed and can be used as the boundary conditions for gas combustion in the furnace chamber.

The calculation of gas-phase combustion in the furnace chamber was carried out using commercial software FLUENT. Considering the strong jet and swirl in the furnace, the realizable $k-\varepsilon$ turbulence model was selected [21,22]. The finite rate/eddy dissipation
model was chosen for the turbulent chemical reaction model, the P-1 model was chosen for the radiation model, and the wall boundary condition of the hot air furnace wall was set as adiabatic. The coupling between pressure and velocity was calculated using the Simple algorithm. Three-dimensional full-scale CFD modeling of the furnace was adopted. The mesh was divided by unstructured mesh, and local refinement was applied at the inlets of primary and secondary air and recycled flue gas. The total number of grid cells was 10.6 million, and the maximum size of the grid was $1.69 \times 10^4 \text{m}^3$.

For a chain-grate furnace, there are generally four air distribution modes, namely front-enhanced, uniform, rear-enhanced, and strong air supply [23]. Front-enhanced air distribution refers to the introduction of a larger air volume in the early stages of combustion. Uniform air distribution means that the same air volume is introduced into each air chamber. Rear-enhanced air distribution involves introducing a small amount of air in the early stages of combustion, with the initial air volume primarily relying on air leakage from adjacent air chambers. However, as an extreme case, the strong air supply mode is only suitable for refractory coal; otherwise, it will cause serious slagging in the grate. Therefore, this study mainly focused on the combustion performance and pollutant emission under the first three air distribution modes. As listed in Table 3, the air fractions of the four wind boxes with the front-enhanced air distribution (FAD) mode were 30%, 40%, 15%, and 15%, respectively. Similarly, these values were 23%, 31%, 23%, and 23% with the uniform air distribution (UAD) mode and 15%, 20%, 35%, and 30% with the rear-enhanced air distribution (RAD) mode. The total excess air ratio was 2.0, and the total air supply and fuel supply were kept the same under the three air distribution modes.

Table 3. Air volume distribution of different air distribution modes.

<table>
<thead>
<tr>
<th>Primary Air Wind Box</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lengths of wind boxes, m</td>
<td>0.76</td>
<td>1.02</td>
<td>0.76</td>
<td>0.76</td>
</tr>
<tr>
<td>FAD, %</td>
<td>30.00</td>
<td>40.00</td>
<td>15.00</td>
<td>15.00</td>
</tr>
<tr>
<td>UAD, %</td>
<td>23.00</td>
<td>31.00</td>
<td>23.00</td>
<td>23.00</td>
</tr>
<tr>
<td>RAD, %</td>
<td>15.00</td>
<td>20.00</td>
<td>35.00</td>
<td>30.00</td>
</tr>
</tbody>
</table>

4. Results and Discussion

4.1. Grate-Firing Process

4.1.1. UAD Mode

Figure 2 shows the rates of moisture evaporation, volatile release, and char combustion. At the grate position of 0–0.3 m, only moisture evaporation occurs. Volatiles begin to be released at 0.3 m, and the release rate rapidly increases to a high value. The devolatilization process is intensive at 1–1.5 m and ends at about 1.8 m. Under the condition of moisture evaporation, the combustion rate of char is relatively low. Later, as volatile matter escapes and burns, the gas temperature increases significantly, as shown in Figure 3, resulting in a significant increase in the combustion rate of carbon, which results in the complete burnout of carbon at the tail of the furnace.
Figure 2. Release rate curves of moisture, volatiles, and fixed carbon.

Figure 3. Gas temperature distribution curve above the grate.

Figure 4 shows the mass fraction distribution curve of the flue gas components above the grate under UAD conditions. It can be seen that oxygen is in an excess state at both ends of the grate. At the start of the combustion process, the oxygen content decreases rapidly due to the release of volatiles and the combustion of some of the carbons and reaches the minimum value of 1.56% between 0.3 and 1.8 m. During the entire combustion process, the mass fraction of oxygen changes in a “sawtooth” shape. The reason is that after the burning out of the surface carbon, the ash shell will enwrap the internal carbon, by hindering the continuous diffusion of oxygen to the inside, so there is a brief slight rebound; after that, with the forward movement of the grate, the mutual extrusion between the fuels and the continuous primary air blowing will peel off the surface ash shell; as result, the direct contact between the carbon and the primary air will promote the intensive combustion of the carbon and reduce the oxygen mass fraction. This process repeats in turn, resulting in a sawtooth shape for the oxygen mass fraction.

The peak values of H₂, CO, and CH₄ all appear at 0.3–1.8 m on the grate, with mass fraction values of 0.17%, 8.5%, and 7.3%, respectively. The mass fraction distribution curve
of CO₂ also has a sawtooth shape because it corresponds to the consumption of oxygen with the peak value of 31.65%.

![Figure 4](image_url)

**Figure 4.** Mass fraction distribution curve of gas components above the grate under UAD condition.

### 4.1.2. FAD Mode

Figure 5 shows the mass fraction distribution curve of the flue gas components above the grate under the FAD mode. Since there is no primary air inlet at the front 1.0 m of the grate, the air required for fuel combustion at the front 1 m of the grate depends entirely on the air diffusion in the adjacent wind chamber. The mass fraction distribution curve at the front 0.3 m of the grate has no obvious difference compared with the UAD mode, but at the same position of the grate, the oxygen content of the FAD mode is higher. Similar to the UAD mode, the oxygen content under the FAD mode is also excessive at both ends of the grate, and the minimum O₂ mass fraction is 2.2%.

The peaks of H₂, CO, and CH₄ appear at 0.3–1.6 m of the grate, and the combustion of volatiles and fixed carbon finishes earlier than that in the UAD mode, with peak values of 0.15%, 8.2%, and 5.4%, respectively. Compared with UAD mode, the peak values of H₂, CO, and CH₄ are decreased. In principle, the FAD mode strengthens the combustion rate in the front part of the grate, and the formation of volatile gas should be increased. However, due to more air feeding into the front part, the mass fraction of gases does not increase but decreases by dilution.

The peak of CO₂ mass fraction with a value of 28.17% appears at 0.3–1.6 m of the grate and is lower than that of the UAD mode. Similarly, it is consistent with the change in the volatile gas mass fraction. The reason was that excessive air was introduced into the front of the grate, which led to a decrease in the CO₂ mass fraction in this zone. As shown in Figure 5, the fuel combustion on the grate will finish earlier, and the amount of oxygen will quickly recover after about 2 m along the moving direction of the grate. It also can be seen that the combustion condition at the rear is not good, the grate length is not fully utilized, and the efficiency will be greatly reduced.
4.1.3. RAD Mode

Figure 6 shows the mass fraction distribution curve of the flue gas components above the grate under the RAD mode. As in the first two cases, the combustion at the front of the grate still depends on the adjacent air diffusion, so even in the RAD mode, the mass fraction distribution of the flue gas composition above the front part of the grate also has no obvious difference from those in the first cases mentioned above. Since more than 60% of the air is passed in through the rear two wind boxes, the burning area is delayed accordingly. According to the oxygen content, the air supply in the first two air chambers is relatively small, so the combustion is only in the ignition phase. The minimum oxygen value is about 1.1%, and the stage with low oxygen content extends backward with a slow rise, after about 1.8 m, until 3.7 m. It can be seen that the utilization rate of the grate can be improved under the RAD mode.

The peaks of H₂, CO, and CH₄ appear at 0.3–2 m of the grate, with peaks of 0.18%, 8.9%, and 8.3%, respectively. The volatile gas production in the RAD mode is the highest out of the three air distribution modes, which can indirectly reflect the best combustion condition in the RAD mode. The volatile gas release can extend to about 2 m along the grate, which extends the effective length of the grate.

The peak value of CO₂ mass fraction appears at 0.3–2 m of the grate with a value of 34.07%, which is the highest out of the three air distribution modes. Theoretically, it can also reflect that the fuel combustion condition is the best in the RAD mode.
Figure 6. Mass fraction distribution curve of gas components above the grate under RAD mode condition.

4.2. Gas Combustion in Furnace Chamber

The flue gas mixing and temperature distribution in the furnace chamber under three air distribution modes were numerically calculated for this section. Three important indices for measuring combustion performance, namely the oxygen concentration, CO concentration, and temperature fields, were compared and analyzed.

4.2.1. Oxygen Concentration Field

Figure 7 is the contour map of oxygen concentration in the furnace under three air distribution modes. It can be seen that the oxygen concentration distributions under the three air distribution modes are all “saddle”-shaped. However, compared with the UAD mode, the oxygen concentration in the FAD mode is higher in the whole section of the grate, and the width of the low oxygen concentration in the middle is shorter. In contrast, the oxygen concentration in the RAD mode is lower, and the width of the low oxygen concentration in the middle of the grate is longer. It is clear to find, in the FAD mode, that a large amount of air is introduced into the front of the grate, so the oxygen concentration in the front part is higher, and the combustion is intensive; such excessive oxygen causes the earlier finishing of combustion, so the oxygen content quickly returns to the air level. However, in the RAD mode, only a small amount of air is injected into the front of the grate, so the oxygen concentrations in the front and middle of the grate are lower than those of the UAD mode, because the oxygen is not sufficient in the whole combustion process, so the combustion duration is longer. In the condition of RAD mode, the range of low oxygen content covers the longer part of the grate, and the recovery of oxygen content is relatively slow; even in the end part of the grate, the oxygen concentration is still lower than that of the other air distribution modes.
Figure 7. O₂ concentration distribution in a furnace: (a) FAD, (b) UAD, (c) RAD.

4.2.2. CO Concentration Field

Figure 8 shows the distribution of the CO concentrations in the furnace under three air distribution conditions. Under the condition of the FAD mode, the CO precipitation zone is narrower than those in the other two modes, followed by UAD mode and RAD mode in turn. In addition, the CO precipitation amount of the RAD mode is more than that in the other two modes. Therefore, the furnace is more likely to form a reducing atmosphere in such a delayed air distribution mode, and the reducing atmosphere is very beneficial to NOₓ emission reduction.
4.2.3. Temperature Field

The performance of the temperature field usually depends on two indicators; one is the average temperature, and the other is the uniformity of the temperature distribution in the combustion chamber. Figure 9 shows the contour maps of temperature distribution under three modes.

With the calculated data derived from Fluent, the average temperatures in the furnace chamber under the conditions of the FAD mode, UAD mode, and RAD mode are obtained as 996.5 K, 1002.3 K, and 1051.3 K, respectively. For a chain-grate furnace, the thermal radiation of the front and rear arches is an effective means for heating the bed, which is beneficial to the burnout of fuel in the moving bed. Therefore, the average temperature of the space below the throat of the furnace should be maintained at a relatively high level, which can reduce the carbon content in the bottom slag and improve the efficiency of the boiler. According to the calculation, the average temperatures of the lower part below the throat are 1074.3 K, 1081.0 K, and 1084.1 K under the above three modes. By comparison, the last mode is more favorable for the re-radiation of the furnace arch and the burning of the bed material.
In both the UAD mode and the FAD mode, the burning is violent in the front and middle part of the grate where the throat is located. Therefore, the flame will carry a higher amount of heat from the lower part through the throat to the tail of the furnace, resulting in a worse uniformity of temperature distribution in the furnace. The strong combustion zone of the RAD mode is located further than that of the other two modes, and a relatively uniform high-temperature environment can be obtained in the whole furnace. In addition, the flame may adhere to the wall under the condition of the FAD mode.

In summary, the RAD mode shows the best combustion performance in numerical simulation. Firstly, the amount of CO released is the highest, which is conducive to the
formation of a reducing atmosphere beneficial for NOx reduction. Secondly, the highest average temperature provides a high-temperature environment for the burnout of the combustible contents.

4.3. NOx Emissions

Due to the lack of comparability in NOx volume fraction for exhaust gases with different volumes and temperatures, to compare the volume fraction of NOx under different conditions, it is generally converted to the emission concentration under the standard state of an oxygen concentration of 6%, as listed in Table 4. The order of NOx emission concentration is FAD mode > UAD mode > RAD mode.

**Table 4.** NOx emission at furnace outlet under different air distribution modes (6% O2).

<table>
<thead>
<tr>
<th></th>
<th>FAD</th>
<th>UAD</th>
<th>RAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration, mg/Nm³</td>
<td>133.50</td>
<td>104.40</td>
<td>76.60</td>
</tr>
</tbody>
</table>

The formation mechanism of NOx shows that the main way to reduce fuel NOx is to reduce the amount of oxygen and create a reducing atmosphere during the combustion process, which can reduce intermediate products such as HCN and NH₃ to N₂ [24]. As mentioned above, in the whole furnace, the order of oxygen concentration from high to low is [O₂]RAD > [O₂]UAD > [O₂]FAD. For the CO concentration in the main combustion zone, the order from high to low is [CO]RAD > [CO]UAD > [CO]FAD. Combined with low oxygen concentration and high CO concentration, the NOx emission concentration can reach the minimum under the condition of the RAD mode.

5. Conclusions

In this study, the influence of the air distribution mode on the combustion performance of a 7 MW biomass grate-firing boiler used to produce hot air for drying grain in northeast China was numerically studied. The simulation results of biomass combustion on the grate and in the furnace were obtained under the conditions of three different air distribution modes, namely the FAD mode, UAD mode, and RAD mode. The RAD mode can not only enlarge the length of the combustion zone and increase the utilization rate of the grate but also effectively reduce the nitrogen oxide concentration at the furnace outlet by combining a low oxygen concentration and a high CO concentration.

**Author Contributions:** Conceptualization, N.H. and H.Y.; methodology, H.Y. and Y.J.; software, F.X.; validation, Q.W. and H.Y.; formal analysis, F.X. and N.H.; investigation, F.X. and H.Y.; resources, M.Z.; data curation, M.Z. and N.H.; writing—original draft preparation, F.X., H.W. and Q.W.; writing—review and editing, F.X. and H.W.; visualization, N.H.; supervision, H.Y. and M.Z.; project administration, N.H.; funding acquisition, N.H. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** Data are available on request from the authors. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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