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Experimental Study on Flame Chemical Composition of Coal and Ammonia Gas–Solid Jet in Flat Flame Burner

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ABSTRACT: Ammonia as a fuel to partially or completely replace fossil fuels is one of the effective ways to reduce carbon dioxide, and the research on ammonia coal cocombustion is of great significance. The combustion characteristics of ammonia are very different from those of pulverized coal, resulting in the ignition and emission characteristics of ammonia and pulverized coal gas flow that is different from traditional pulverized coal flame. In this paper, the effect of pulverized coal concentration in coal and ammonia mixed combustion jet on the ignition distance and gas-phase components at different positions of the jet flame were studied experimentally on the flat flame burner, and the conditions of ignition and ignition stability of coal and ammonia gas-solid fuel were expounded. It was found that the ammonia mixed with pulverized coal changed the temperature field of the flat flame burner and therefore the ignition characteristics of the jet were changed. The ignition delay time at the same jet speed was positively correlated with the pulverized coal concentration, but when the pulverized coal concentration continued to decrease, the influence on the ignition delay time gradually became smaller. The composition of coal ammonia gas-solid fuel changed the heat transfer path and share during combustion, and finally, the flame temperature was negatively correlated with the concentration of pulverized coal. Therefore, the reduction of the pulverized coal concentration was conducive to the stable combustion of coal ammonia mixed fuel. When HAB = 100 mm, the conversion rate of fuel N to NO_x per unit mass of coal ammonia mixture increased with the increase of pulverized coal concentration. The NO_x production amount first increased and then decreased with the increase of pulverized coal concentration, and the amount of N_2O and NO_2 decreased rapidly with the increase of HAB. The proportion of NO_x in NO exceeded 94%, which was conducive to achieving low nitrogen combustion of coal and ammonia gas-solid fuel. In general, the O2 concentration in the ammonia coal jet flame decreased, the flue gas temperature, and NO_x and CO generation increased after mixing ammonia, and the optimal pulverized coal concentration in this experiment was 0.41 kgc/kga (mass ratio of pulverized coal to the sum of N_2 and NH_3).

1. INTRODUCTION

The energy security status of coal will not be expected to change in the short term. As is widely known, hydrogen is a carbon-free fuel, but its widespread application is limited due to the high costs associated with its production, storage, and transportation. Ammonia (NH₃) is an energy carrier with a high hydrogen density of up to 17.8% by weight.^{1,2} It is a carbon-free fuel that will not generate CO_2 , SO_2 , or particulate matter, making ammonia a promising potential substitute for hydrogen. Additionally, production processes of ammonia have been commercialized for over 100 years, enabling large-scale ammonia production.^{3,4} Furthermore, the storage requirements for ammonia are similar to another commercial fuel, propane,⁵ and converting ammonia into liquid is much easier compared to

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pure hydrogen.⁶ This results in significantly lower transportation and development costs compared to those of pure hydrogen. Ammonia offers many advantages, but there are still some research gaps and obstacles that need to be addressed, such as (1) low energy density (2) low laminar burning velocity (3) poor ignition quality (4) high nitrogen oxides (NO_x) emissions (5) lower flammability limits compared to methane, hydrogen, and other hydrocarbons.

Xia and Hiraoka^{7,8} found that the flame propagation speed of coal and ammonia cocombustion is three times faster than pure coal combustion and twice as fast as pure ammonia combustion, so as to a certain extent, the problem of slow propagation of ammonia combustion flame can be solved. Studies have shown that the ammonia mixing ratio, ammonia injection method and location, combustion temperature, oxygen concentration, and gas flow rate are the main influencing factors affecting the combustion characteristics of coal and ammonia gas-solid fuel.^{9–11} The reduction of CO_2 emissions shows a good linear relationship with the mixing ratio of ammonia, while NO_x emissions show a linear increasing trend with the amount of ammonia addition.^{12,13} When the mixing ratio of ammonia is below 20%, it is possible to achieve NO_x emissions lower than or comparable to those of pure coal combustion. By adjusting the ammonia injection position and implementing air staged combustion, even lower NO_x emissions can be achieved. However, when the ammonia blending ratio exceeds 20%, the amount of NO_x generated shows an initial increase followed by a decrease, indicating the coexistence of fuel-NO_x generation and the reduction mechanism of ammonia to NO_x. Zhang¹⁴ et al. found that with the increase of ammonia blending ratio, the burnout rate of pulverized coal gradually decreases. But there has been limited research on the ignition of coal and ammonia cocombustion. Due to its advantages of stable combustion, rapid and precise adjustment over a wide range, and good optical characteristics of the Hencken burner, it is suitable for investigating the mechanism of coal and ammonia cocombustion. Li¹⁵ conducted research on the ignition mechanism of coal and ammonia cocombustion in a two-stage flat flame burner and found that adding ammonia had both positive and negative effects on the ignition of coal. The addition of ammonia advanced the coal ignition, and volatile combustion of pulverized coal is promoted because of the increase of oxygen concentration. Zhu¹⁶ found that coal and ammonia cocombustion promoted the ignition and volatile release of coal. Yantai Longyuan Power Technology Company conducted experiments on a 40 MW coal-fired boiler with the ammonia mixing ratio of 0-25% and found that it exhibited good combustion stability and burnout performance.¹⁷ The Chugoku Electric Power Company in Japan conducted experiments at the Mizushima Power Plant on a 156 MW boiler with 0.8% ammonia cofiring and found no significant changes on the flue gas temperature at the outlet of the secondary reheater, boiler NO_x emissions, and boiler output, preliminarily verifying the feasibility of a small amount of ammonia cofiring in coal-fired boilers.¹

The ignition characteristics of pulverized coal gas flow and gas emission characteristics of coal and ammonia jet flame are the key to the combustion of coal and ammonia gas—solid fuel, but there are few reports of gas components along the combustion process (especially the generation characteristics of N_2O and NO_2), which will provide basic verification data for exploring the mechanism of ammonia coal cocombustion reaction and provide data support for the accurate evaluation and prediction of combustion processes and flow field characteristics through three-dimensional simulations.

2. EXPERIMENTAL AND METHODOLOGIES

2.1. Fuel Property. The bituminous coal used in this study is from Inner Mongolia of China, and the average particle size of coal was 28.6 μ m and was dried at 110 °C for 2 h before experiments. The results of proximate and ultimate analysis were shown in Table 1.

Table 1. Fuel Property

analysis	project	numerical value
proximate	V _{ar}	32.30
	FC _{ar}	57.83
	A _{ar}	5.73
	M_{ar}	4.14
	calorific value/(MJ/kg)	24.85
ultimate	C _{ar}	72.90
	H_{ar}	4.15
	O _{ar}	11.93
	\mathbf{N}_{ar}	0.86
	S _{ar}	0.30

2.2. Flat Flame Burner and Operating Conditions. The experiment was conducted on a flat flame burner, as schematically exhibited in Figure 1.¹⁵ In order to ensure a better performance of the burner, a high-temperature-resistant circular honeycomb was used. The circular structure could reduce the nonuniformity of the gas composition and temperature distribution in the reaction zone. The diameter of the honeycomb was 72 mm, and more than 500 stainless steel tubes were inserted into the honeycomb with a tube-hole ratio of 1:2. Thick silicone gaskets and stainless steel tubes were used to separate the oxidizer and fuel gas (CO + CH₄) to flow through the burner surface, which allowing them to diffuse and burn separately. Eventually, the combustion products flow out of the burner plane.

To eliminate the noisy effect of soot produced from gaseous fuel, a very small amount of methane was introduced to enhance the ignition of CO ignition. The constant-pressure adiabatic postflame temperature was set to 1500 K, the flue gas velocity was set to 1 m/s, and the oxygen content of postflame was set to 20%. The different flow rates of fuel gases were calculated by solving equations for conservation of energy, momentum, elements. The coal feeding was performed using a microfeeding device manufactured by Sankyo of Japan, and the feeding error was $\pm 5\%$. A dispersed and uniformly stable flow of coal particles was produced by this device. The outer diameter of the center feed pipe was 2 mm, and the carrier gas (N₂) volumetric flow rate was 0.186 L/min, so the jet velocity was 0.39 m/s. The coal and ammonia gas—solid fuel was injected on the surface of the flat flame burner under the carrying of nitrogen gas.

The fuel composed of coal and ammonia in different proportions was defined as coal and ammonia gas—solid fuel. The total calorific value of the fuel was remained constant. When it is pure coal combustion, the feed rate of coal was 0.25 g/min. As the coal supply decreased, the amount of ammonia increased. The concentration of pulverized coal was defined as the ratio of the mass of coal to the mass of gas (NH₃ + N₂) in the center feed pipe. The pulverized coal concentration was set to 1.08 (pure coal combustion), 0.67, 0.41, 0.23, 0.10, and 0 (pure ammonia combustion) kgc(coal)/kga (N₂ + NH₃), and the corresponding



Figure	1.	Schematic	diagram	of	a flat	flame	burner
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			gas flow in honeycomb tubes			fuel flow in the center feed pipe	
case	ammonia mixing ratio (%)	pulverized coal concentration (kgc/kga)	$N_2\left(L/min\right)$	O_2 (L/min)	CO (L/min)	$\mathrm{NH}_{3}\left(\mathrm{L/min} ight)$	coal (mg/min)
1	0	1.08	22.60	9.56	5.22	0	250
2	20	0.67	22.60	9.56	5.22	0.086	200
3	40	0.41	22.60	9.56	5.22	0.17	150
4	60	0.23	22.60	9.56	5.22	0.26	100
5	80	0.10	22.60	9.56	5.22	0.34	50
6	100	0	22.60	9.56	5.22	0.43	0

mixing ratio of ammonia (heat fractions) was set to 0, 20, 40, 60, 80, and 100%, respectively. The specific experimental conditions were shown in Table 2.

2.3. Experimental Methods. The flame of coal and ammonia gas-solid during combustion was captured by a Nikon D90 camera. The Camera Measure software was used to measure the ignition distance of coal. The flat flame burner plane was set as the starting point, and the measurement points set at the heights above the burner (HAB) were 5, 20, 40, 60, 80, and 100 mm. A quartz glass cover was placed above the burner to isolate the ambient air during experiments. The height of the glass cover was 300 mm, which was much higher than the maximum height of the measurement points, and the influence of the flue gas entraining ambient air in the experimental results was reduced. The gas composition and postflame temperature after combustion were measured using a MRU VARIO PLUS enhanced flue gas analyzer manufactured by Germany and an Stype platinum-rhodium thermocouple. Each operating condition was measured three times and averaged to ensure the accuracy of the experimental results. The temperature was measured under different conditions after the thermocouple corrected for radiation and conduction losses, the measurement results were shown in Figure 2. The postflame temperature near HAB = 5 mm was close to 1500 K, indicating that the actual combustion conditions were consistent with the theoretical setting and the design of gas flow rates were reasonable. At different coal concentrations, as the HAB increased, the flue gas temperature showed a trend of increasing and then decreasing. With the increase of the coal concentration, the flue gas temperature decreased, which illustrated that the addition of ammonia was beneficial to the coal and ammonia gas-solid fuel combustion.



Figure 2. Postflame temperature change curve with HAB

3. RESULTS AND DISCUSSION

3.1. Ignition of Pulverized Coal. The ignition of pulverized coal gas flow is the basis of coal and ammonia gas-solid fuel combustion, and first, the ignition process will be clarified by the jet diffusion flame generated by coal and ammonia gas-solid fuel combustion. Then, the ignition delay time of pulverized coal under different pulverized coal concentrations will be investigated, and meanwhile, the relationship between ignition delay time of pulverized coal gas flow and the combustion stability of coal and ammonia gas solid fuel will be elaborated. It will provide theoretical support for

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finding the optimal pulverized coal concentration of coal and ammonia gas-solid fuel and realizing its stable combustion.

3.1.1. Ignition Process. Based on the coal ammonia jet flame under different pulverized coal concentrations captured by the camera, the combustion mechanism of laminar flow of premix gas was referred in order to clarify the ignition process of coal,¹⁹ the ignition of coal was divided into four regions: cold reactant zone, preheating zone, reaction zone and product zone. The coal and ammonia jet flame and schematic diagram are shown in Figure 3.

Below the flat flame burner was the cold reactant zone, where coal and ammonia gas/solid fuel were thoroughly mixed. The initial temperature and concentration of the coal and ammonia gas-solid fuel were denoted as T_0 and C_0 . The area between the flat flame burner plane and the beginning of the ignition of pulverized coal was defined as the high-temperature preheating zone which is generated by gas fuel and ammonia combustion. According to the "intense mixing model", the coal and ammonia gas-solid fuel strongly and uniformly mixed with the surrounding airflow when inflowed a combustion region formed by a glass cover. The flue gas temperature was preheated and elevated to T_{i} , under the effect of the high-temperature preheating zone on the burner plane. The coal particle was heated by the flame and high-temperature flue gas, which caused the volatile components of coal to begin to evaporate and crack, producing small molecular combustible gases. Therefore, a few intermediate products were generated in the preheating zone, and the concentration of coal and ammonia gas-solid fuel decreased to C_i . In the reaction zone, with the temperature around the coal particles exceeding their ignition temperature, the fuel and oxygen began to burn at the temperature and concentration of fuel were T_i and C_i , respectively. At this time, the visible flames were produced. The flame of ammonia combustion appeared to orange, while the flame of coal combustion appeared to yellow. The bright yellow flame in the midlate stage of combustion was produced by the combustion of coke, with the concentration of coal decreased, the brightness of the flame increased, it illustrated that the pulverized coal burned more vigorously. The reason for this was that ammonia rapidly burned under the effect of hightemperature preheating, so the coal particles were preheated by the heat released by ammonia combustion. The release rate of volatile components in the coal was accelerated and the local gas equivalence ratio around the coal particles was also increased.²⁰

The coal particles burned while being preheated, and they were enveloped by the free radicals and volatile gas which formed by pulverized coal cracking and ammonia decomposition, so the flue gas around the coal particles quickly reached the coal ignition temperature. When the concentration of coal was lower, each individual coal particle received more heat which was released by ammonia combustion, and the heating rate of coal particles was higher. Consequently, the combustion of coal was more thorough and the flame became brighter. These results also corresponded to the results of postflame temperature.

3.1.2. Ignition Delay Time. The Camera Measure was employed to measure the ignition distance of coal (L_c) , which was denoted as the distance from the flat flame burner plane to the position where the initial flash point of coal appeared. Each operating condition was measured five times to ensure the measurement error within a reasonable range. The gas flow velocity in the central feed pipe was calculated at different coal concentrations (c, kgc/kga), the curve of the relationship between coal concentration (c, kgc/kga) with ignition delay time ($T_{c'}$ ms) and flue gas temperature was obtained when HAB = 100 mm, as shown in Figure 4.

It was observed that the ignition delay time of the coal increased as the coal concentration increased. However, after adding ammonia, the variation trend of coal concentration with



Figure 4. Relationship curve between the pulverized coal concentration and ignition delay time.

coal ignition delay time was opposite that of pure coal combustion.²¹ It indicated that ammonia promoted the ignition of coal, which was consistent with the research findings of Ma.¹¹ However, when $c \leq 0.67$ kgc/kga, the decreasing trend of coal ignition delay time became slower, demonstrating that lower coal concentrations were not necessarily better. The reason for this was that coal particles were easily flammable, which were enveloped by volatile gases and ammonia before ignited. The heating rate of coal particles was influenced by convective heat transfer and radiative heat transfer from the environment. When c = 1.08 kgc/kga, the more radiative heat transferred from the high-temperature gas and less convective heat transferred to the coal particles because of the higher coal concentration. Simultaneously, heating rate of coal particles were reduced because of the preheating effect of ammonia combustion on coal decreases. The concentration effect of volatile components released by coal particles was not enough to offset the decrease of the heating rate, which leading to a significant increase of coal ignition delay time.²² When $c \le 0.67$ kgc/kga, the concentration of volatile components around the coal particles decreased and the temperature in the preheating zone increased, which caused the surrounding flue gas temperature around the coal to rise and the amount of heat absorbed per unit mass of coal particles increase. Some studies had indicated that convective heating of coal particles by high-temperature flue gas was 23 times faster than pure radiative heating,²³ hence higher ammonia fuel concentrations led to shorter coal ignition delay time. However, more oxygen and heat were consumed in the surrounding environment of pulverized coal with the higher ammonia concentration, which resulted in a slight decrease of coal ignition time.

Figure 4 illustrates that with the ignition delay time of coal increased, the flue gas temperature of coal and ammonia gassolid fuel decreased. Moreover, the increase rate of ignition delay time corresponded to the decrease rate of flue gas temperature at different coal concentrations, which indicating that the pulverized coal ignition of coal and ammonia gas-solid fuel had a good correspondence with combustion stability. The ignition of pulverized coal was crucial for combustion, and combustion or ignition characteristics of pulverized coal can be predicted according to the ignition delay time of pulverized coal or the flue gas temperature of coal and ammonia gas-solid fuel.

3.1.3. Ignition and Combustion Stability. Based on the heat balance theory,²⁴ the relationship between coal ignition and combustion stability of coal and ammonia gas-solid fuel will be elucidated from a theoretical point of view. When the heat production per unit mass of coal was equal to the heat dissipation, the corresponding temperature was the ignition temperature of coal (T_i) . The coal ignited and burned steadily when the heat production of coal exceeded heat dissipation. Conversely, the coal extinguished and could not sustain combustion stably when the heat production of coal was less than the heat dissipation. It was assumed that the volume of the combustion region formed by the glass cover was V, the mass flow rate of coal in the central feed pipe was Q_0 m/s, the calorific value of coal was Q_i the density of the airflow was ρ_i and the specific heat was $C_{\rm P}$, then the heat production of coal in the combustion region formed by the glass cover could be expressed as follows

$$Q_1 = k_0 C_0 V Q \, \exp\left(-\frac{E}{RT}\right)$$

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The consumption rate of combustible components of coal was

$$Q_1 = Q_0 (C_0 - C) Q$$
 (2)

After simplification, that was

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$$Q_1 = \frac{C_0 Q}{\frac{1}{Q_0} + \frac{\exp\left(\frac{E}{RT}\right)}{k_0 V}}$$
(3)

The residence time of coal in the combustion region was

$$\tau_0 = \frac{V}{Q_0} \tag{4}$$

Therefore, the heat production rate per unit volume of coal was

$$q_1 = \frac{C_0 Q}{1 + \frac{\exp\left(\frac{E}{RT}\right)}{k_0 \tau_0}}$$
(5)

Assuming that the glass cover wall was adiabatic, the radiative heat dissipation of the airflow to the glass cover wall was neglected, and only the heat carried away by the airflow was considered. Therefore, the heat dissipation of the airflow was

$$Q_2 = Q_0 \rho C_p (T - T_0)$$
(6)

The heat dissipation per unit volume of the gas was

$$q_{2} = \frac{Q_{2}}{Q_{0}} = \rho C_{p} (T - T_{0})$$
⁽⁷⁾

The relationship between the heat production and heat dissipation per unit volume of coal and the temperature was shown in Figure 5,²⁵ where the intersection point "a" of curves q_1



Figure 5. Relationship curve of fuel heat production and heat dissipation with temperature.

and q_2 represented the normal combustion state, "b" indicated an unbalanced state, and "c" denoted extinguishment. The temperature corresponding to point "a" was the ignition temperature of coal (T_i) . The coal particles were preheated with ammonia and ignited during the early stages of combustion. Therefore, as the coal concentration decreased, the preheating effect on coal particles became more pronounced, which led to combustion becoming more thorough. The residual combustible components in the furnace decreased, so the outflowing gas from the glass cover carried fewer combustible components, which led to a decrease of incomplete combustion loss and increase of heat production per unit fuel. So the curve q'_1 moved upward, and the intersection of q'_1 and q_2 corresponded to the coal ignition temperature T'_i . Additionally, ammonia combustion was considered to cause an increase of the initial temperature during the early stages of combustion, so the heat release curve q'_2 shifted to the right. The intersection point "e" between q'_1 and q'_2 corresponded to the ignition temperature T''_i , and at this time, there was no unstable operating point like point "b". The safe combustion zone expanded (from point b to c), which reducing the possibility of extinguishment and improving combustion stability.

3.2. Gas-Phase Components. The combustion characteristics can be directly reflected by the variation of gas-phase components along the height above the burner of coal and ammonia gas-solid fuel. The following will investigate the changes of the O_2 , CO, and NO_x concentrations at different coal concentrations to elucidate the influence of coal concentration on gas emission characteristics. The research findings will lay the theoretical foundation for identifying the optimal coal concentration and proposing measures for low-nitrogen combustion of coal and ammonia gas-solid fuel.

3.2.1. O_2 Concentration. Oxygen content is a crucial parameter during the combustion process. When the oxygen content is low, the combustion reaction occurs in a reducing atmosphere, which leads to an increase in chemical and mechanical incomplete combustion heat losses and a risk of coking and slagging. When the oxygen content is high, excessive air takes away a significant amount of heat and ash, resulting in a decrease of combustion temperature and potential increase in pollutant emission concentrations and raising pollutant control costs. Therefore, exploring the variations of the oxygen content during the combustion process at different coal concentrations of coal and ammonia gas-solid fuel is essential to find the optimal operating oxygen content. Three sets of repeated experiments were conducted for the condition with c = 1.08 kgc/kga, and the experimental results were within a reasonable range of error, confirming the reliability and repeatability of the data. The curves depicting the changed in O₂ concentration at different coal concentrations along the height above the flat flame burner were shown in Figure 6.

According to Figure 6, at different coal concentrations, the oxygen content showed a trend of initially decreasing and then increasing as HAB increased, and when HAB = 60 mm, the oxygen content reached minimum (except for c = 0.23 kgc/kga). At the starting point of combustion (HAB = 5 mm), the oxygen content was lower than that of pure coal combustion, and when c \leq 0.41 kgc/kga, the oxygen content was even lower. The reason for this was ammonia competed with coal for oxygen during combustion, and the complete combustion of ammonia required more oxygen consumption.²⁶ This reflected the inhibitory effect of ammonia addition on the cocombustion of coal and ammonia. When $c \leq 0.23$ kgc/kga, the low oxygen region was larger, and when c = 0.10, 0.23 kgc/kga, the oxygen content was lower than that of pure ammonia combustion. At the same time, after addition of ammonia, the combustion mode changed from oxygen-enriched combustion to oxygen-poor combustion, which indicated the oxygen competition mechanism between ammonia and coal combustion. As a result, the oxygen



Figure 6. O₂ concentration change curve with HAB.

consumption of coal and ammonia gas-solid fuel at a lower pulverized coal concentration was greater than that of pure ammonia combustion.

3.2.2. CO Concentration. During the coal combustion process, the CO concentration reflects the degree of incomplete combustion of fuel. Investigating the generation pattern of CO at different coal concentrations provided theoretical support for better organizing the combustion of coal and ammonia gas–solid fuel. The curves depicting the changes of CO concentration at different coal concentrations along the height above the flat flame burner were shown in Figure 7.



Figure 7. CO concentration change curve with HAB.

At different coal concentrations, the CO concentration first reached highest value and then decreased as HAB increased, which was opposite to the trend of oxygen concentration change with HAB. When HAB = 60 mm, the CO generation increased significantly at lower coal concentrations ($c \le 0.10$ kgc/kga), reaching a maximum of 19773.05 mg/Nm³, and much higher than pure coal combustion. One reason for this was that ammonia has higher reactivity than coal and preferentially reacted with O₂, as shown in reaction eq 8. According to the variation in oxygen concentration in Figure 6, the combustion reaction occurred under a low oxygen atmosphere at this time, leading to a significant amount of incomplete combustion of carbon.

$$C + CO_2 \rightarrow 2CO$$

(8)

When the oxygen concentration reached its lowest, it corresponded to the peak of the CO concentration, which was consistent with the variation pattern of coal combustion in terms of oxygen and CO concentrations. However, when c = 0.23 kgc/kga and HAB = 20 mm, the oxygen concentration reached minimum, while the peak of the CO concentration reached at HAB = 40 mm. This phenomenon indicated a delayed peak of CO concentration, which occurred because the combustion reaction was progressed at lower coal concentrations, and the concentration of water vapor in the flue gas was increased by ammonia combustion, which coal gasification reaction was further promoted,²⁷ as shown in reaction eq 9. When HAB ≥ 60 mm, the CO concentration started to decrease, and the CO oxidation reaction became dominant. When c = 0.1 kgc/kga and HAB = 60 mm, the CO concentration reached peak and then rapidly decreased. When HAB = 100 mm, the CO concentration was lower than that in pure coal combustion. The reason for this was when HAB \geq 60 mm, the oxygen concentration was relatively high, and CO began to react with oxygen to undergo oxidation. CO also reacted with OH radicals formed by water vapor in the flue gas, as shown in reaction eq 10. Additionally, more intense gasification reactions occurred in char at low coal concentrations. Previous research had also found that the probability of fragmentation during the volatile combustion stage of coal increased when adding ammonia.²⁸ These two factors altered the pore structure of char, leading to the specific surface area and the diffusion rate of oxygen within the char increasing, resulting in the accelerated CO oxidation rate was accelerated.

$$C + H_2 O \to CO + H_2 \tag{9}$$

$$\rm CO + OH^* \to \rm CO_2 + H^* \tag{10}$$

In conclusion, a significant amount of CO was generated during the combustion process at lower coal concentrations. However, the combustion reaction rate was accelerated because the pore structure of char was altered, and the combustion process of coal ammonia gas—solid fuel was shortened.

3.2.3. NO_x Concentration. The ammonia, which is a high fuel-N fuel adding in coal and ammonia gas-solid fuel, makes the generation characteristics of NO_x during combustion an important concern. Below, we separately investigate the production of NO, the conversion rate of nitrogen per unit of fuel, and the proportions of NO_x . The NO_x generation and the conversion mechanism of fuel-N in the process of combustion will be expounded, which lays a theoretical foundation for the proposal of low nitrogen combustion measures for coal and ammonia gas-solid fuel.

3.2.3.1. NO Concentration. The instantaneous NO concentration during the combustion process of coal and ammonia gas—solid fuel at different proportions were detected by the flue gas analyzer, was depicted in the following curve, shown in Figure 8:

According to Figure 8, the addition of ammonia in coal and ammonia gas—solid fuel led to a linear increase in NO emission. On the one hand, ammonia replaced equal calorific value of coal, and the nitrogen content in unit mass of ammonia fuel was much higher than coal. On the other hand, based on the analysis results mentioned, the release and conversion of N elements into gaseous components was accelerated by the behaviors like the fragmentation of char led to the breakdown of N-containing



Figure 8. Amount of NO generated per unit mass of fuel change curve with HAB.

rings which further increased NO emission. When HAB = 100 mm, the generation of NO per unit fuel initially increased and then decreased with the increase of coal concentration, which was consistent with the research findings of Ishihara.²⁹ When HAB = 100 mm and c = 0.10 kgc/kga, the emission of NO was 3290.41 mg/Nm³, whereas the emission of NO was 2474.52 mg/Nm³ when c = 0 kgc/kga, indicating the decrease in NO production. One reason for this was the competition between NH₃-O₂ reaction and char-O₂ reaction increased which elevated the concentration of O and OH radicals and reduced the concentration of NH₂, NH, and NNH intermediates. As a result, NO production during the cocombustion of char and NH₃ was higher than in pure ammonia combustion, which also weakened the homogeneous reduction of NO. Another reason was based on the previous research results,³⁰ suggesting that unburned ammonia may exist in flue gas during pure ammonia combustion, and it had a more significant reduction effect on NO, as shown in reaction eqs 11-13. As a result, the generation of NO was reduced.

$$4NH_3 + 6NO \rightarrow 5N_2 + 6H_2O$$
 (11)

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$$
 (12)

$$4NH_3 + 2NO + 2O_2 \rightarrow 3N_2 + 6H_2O$$
 (13)

When HAB \geq 80 mm, the generation of NO started to show a decreasing trend, and the rate of NO concentration reduction was faster when the coal concentration was lower ($c \le 0.23 \text{ kgc}/$ kga). This also indicated that appropriately extending the residence time of coal and ammonia gas-solid fuel combustion can effectively reduce the production of NO. The reason for this was that CO and ammonia radicals had a synergistic effect on NO reduction. According to the emission results of CO concentration in Figure 7, the CO emission was higher when c \leq 0.23 kgc/kga, which improved the NO reduction efficiency in the NH₃/char system. Meanwhile, the reduction effect of char on the NO could not be ignored. When c = 0.23 kgc/kga, the reduction in NO was the most significant, indicating that the presence of the synergistic reduction of char was enhanced and NH on NO and NH₃ reduction of NO was promoted by a certain amount of char,³¹ while the heterogeneous reduction of NO and NH on the char surface was weakened, ultimately leading to a reduction in NO concentration.

When HAB changed in the range of 20-100 mm, the peak of NO generation position shifted forward when coal concentration decreased. For pure coal combustion and pure ammonia combustion, the peaks of NO concentration were reached at HAB = 100 mm and HAB = 40 mm, respectively. The reason for this was that the generation of NO was based on the oxidation of fuel-N (ammonia-N/coal-N) to NO and the cooperative reduction of NO by unburned ammonia and char. According to the experimental results, the temperature and unburned ammonia concentration increased as the coal concentration decreased, both of which promoted the reduction of NO by ammonia-based reducing agents and char.³² Therefore, the peak of the NO concentration was reached earlier at lower coal concentrations.

3.2.3.2. Fuel-N Transformation Rate. In order to provide a more intuitive comparison of the influence of coal concentration on the conversion rate of fuel-N and fuel-N to NO_x in coal and ammonia gas—solid fuel were calculated based on the measured instantaneous NO_x concentration. The calculation process was described by eq 14

$$m_{\rm NO} = \int \frac{Q_0 \frac{273.15}{273.15 + t} \Phi_{\rm NO} 10^{-3}}{m_{\rm coal} + m_{\rm NH_3}} dt$$
(14)

This paragraph explained the variables used in the equation for calculating the nitrogen conversion rate of fuel-N to NO_x in coal and ammonia gas—solid fuel. The variables were as follows: " m_{NO_x} " represented the amount of NO_x generated per unit mass of coal and ammonia gas—solid fuel, measured in milligrams per gram (mg/g), "Q₀" stand for the total flue gas flow rate, measured in liters per second (L/s), " Q_{NO} " referred m_{NO_x} to the instantaneous concentration of NO_x, measured in milligrams per cubic meter (mg/Nm³), " denoted the relative molar mass of NO_x, measured in grams per mole (g/mol), " m_{coal} " and " m_{NH_3} " respectively represented the initial mass of coal and ammonia in the coal and ammonia gas—solid fuel, measured in grams (g), "t" was the measurement time, expressed in seconds (s).

According to eq 15, the nitrogen conversion rate of fuel-N to NO_x in coal and ammonia gas—solid fuel was calculated

$$\eta = \frac{m_{\rm NO-N}}{m_{\rm coal-N} + m_{\rm NH_3-N}} \times 100\%$$
(15)

The symbol η represented the nitrogen conversion rate of fuel N to NO_x, expressed as a percentage (%), and $m_{\text{coal}-N}$ was the mass of nitrogen in the pulverized coal of coal and ammonia gas—solid fuel, measured in milligrams per gram (mg/g). $m_{\text{NH}_3\text{-N}}$ $m_{\text{NH}_3\text{-N}}$ was the mass of nitrogen in ammonia, also measured in milligrams per gram (mg/g). $m_{\text{NH}_3\text{-N}}$ was the nitrogen content in NO_x generated from the unit mass of coal and ammonia gas—solid fuel, measured in milligrams per gram (mg/g). Based on the above equations, the nitrogen conversion rates of fuel-N to NO_x in coal and ammonia gas—solid fuel for different coal concentrations were calculated and are shown in Figure 9.

As we can see in Figure 9, the nitrogen conversion rate of fuel-N to NO_x in unit mass of coal and ammonia gas—solid fuel fell between that of pure coal combustion and pure ammonia combustion. When HAB = 100 mm (except for c = 0.10 kgc/ kga), the nitrogen conversion rate of fuel N per unit mass decreased as the coal concentration decreased. Moreover, the nitrogen conversion rate tended to stabilize in the late stages of combustion. This indicated that the addition of ammonia in coal



Figure 9. Conversion curve of fuel-N to NO_x per unit mass of fuel change with HAB.

and ammonia gas-solid fuel promoted the conversion of fuel nitrogen to N2.33 The reason for this was ammonia burned before coal combustion under the effect of a high-temperature preheating zone produced by the flat flame burner plane and conditions of excess oxygen, which promote the complete combustion of ammonia to form N2. On the other hand, incompleted combustion of coal was more likely to occur when the coal concentration was higher, leading to the conversion of nitrogen in coal to NO_x. However, the NO_x emissions of coal and ammonia gas-solid fuel combustion remain higher than pure coal combustion because the nitrogen content in the ammonia was much higher than that in coal. When c = 0.10 kgc/kga, the nitrogen conversion rate of fuel-N per unit mass increased. This reason was that ammonia absorbed more heat and consumed more oxygen in the preheating zone during the early stages of combustion because of the high ammonia concentration; this ultimately led to an increase of the conversion rate of fuel-N. The high generation of CO under this condition was also found in Figure 7, which validated this hypothesis.

3.2.3.3. NO_x Composition. Coal and ammonia gas-solid fuel exhibited increased complexity of the generation of NO_x particularly the production characteristics of N_2O and NO_2 due to the high nitrogen in ammonia, which remained unclear. Investigating the influence of coal concentration on the types and proportions of nitrogen oxides was crucial for finding corresponding low nitrogen measures. The different concentrations of pulverized coal detected and the composition of NO_x under HAB were shown in Figure 10.

At high coal concentrations (c = 0.41-1.08 kgc/kga), The proportions of different NO_x species showed little variation with HAB, and the proportion of NO was relatively small. However, the proportion of NO in NO_x significantly increased at low coal concentrations (c = 0-0.23 kgc/kga), reaching a maximum proportion of 97%. It suggested that compared to coal combustion, the addition of ammonia led to a more dominant presence of NO_x species. Additionally, more N₂O and NO₂ were generated during combustion at low coal concentrations, which indicating that the production of ammonia radicals promoted the formation of N₂O and NO₂. The generation of N₂O was related to NH₂ radicals, which can form through the direct reaction of NH₃ with NO or NH₃ being attacked by active



Figure 10. Proportion of different nitrogen oxides.

radicals (H, OH, or O) during combustion. N_2O was rapidly oxidized to NO in the later stages of combustion and then reacted with NH₂ to form N₂ by reaction 13. Therefore, the generation of N₂O decreased in the later stages of combustion. The production of N₂O during coal combustion was positively correlated with the combustion temperature and NH₃ content.³⁴ However, after the addition of ammonia, the influence of unburned ammonia on N₂O generation needed to be considered. According to experimental results, the production of N₂O rapidly decreased in the later stages of combustion. The amount of N₂O production was low at high temperature when the temperature distribution in Figure 2 was combined, so it could be concluded that unburned ammonia was the main influencing factor affecting N₂O production.

$$NO + NH_2 \rightarrow N_2 + H_2O \tag{16}$$

At low coal concentrations ($\leq 0.41 \text{ kgc/kga}$), there was a higher generation of NO₂ in the early stages of combustion, but the NO₂ production rapidly decreased in the later stages due to the intense combustion of coke in a reducing atmosphere. According to eqs 14–16, it could be found that when the oxygen concentration was high, it was more likely to form NO and NO₂. In this experiment, the relative oxygen content increased as the coal concentration decreased. Comparing with Figure 6, it was observed that there was a good correlation between the oxygen volume fraction and the generation of NO₂ in the early stages of combustion, so the oxygen content in flue gas was the main factor affecting the NO₂ production.³⁵ Simultaneously, ammonia radicals began to decompose in the early stages of combustion, so there were more ammonia radical decompositions when the coal concentration was lower, which facilitated the generation of NO₂. The OH radicals were produced by the decomposition of water vapor in the flue gas after ammonia combustion also promoted the conversion of N₂O to NO₂,³⁶ as shown in eq 17. When HAB = 100 mm, the nitrogen in the fuel was mainly converted to NO and the content of NO₂ was relatively low. Overall, lower coal concentrations tended to generate more NO₂, and creating a reducing atmosphere could effectively suppress the generation of NO₂.

$$2\mathrm{NH}_3 + 3\mathrm{O}_2 \to \mathrm{N}_2 + 3\mathrm{H}_2\mathrm{O} \tag{17}$$

$$2NH_3 + 5O_2 \rightarrow 2NO + 3H_2O \tag{18}$$

$$2NH_3 + 7O_2 \to 2NO_2 + 3H_2O$$
(19)

$$N_2O + OH \rightarrow NH + NO_2$$
⁽²⁰⁾

In conclusion, reducing the amount of unburned ammonia and creating a reducing atmosphere could effectively suppress the generation of N₂O and NO₂. When $c \le 0.23$ kgc/kga, the proportion of NO was higher, and the types of NO_x tend to be more singular, which reduced the difficulty of achieving lownitrogen combustion of coal and ammonia gas—solid fuel.

4. CONCLUSIONS

The experimental study on coal and ammonia solid fuel combustion in a flat flame burner led to the following significant conclusions:

(1) Ignition of the coal was the key to the combustion of coal and ammonia solid fuel, and it was subject to the high temperature preheating zone formed by the combustion of gas fuel and ammonia fuel on the burner plane. The ignition characteristics of pulverized coal were changed by ammonia concentration, which leading to the ignition delay time of pulverized coal was proportional to the concentration of pulverized coal. With the increase of pulverized coal concentration, the downward trend of pulverized coal ignition delay time was consistent with the upward trend of flue gas temperature, which illustrated that the combustion stability of coal and ammonia gas solid fuel was improved. Therefore, self-sustaining preheating combustion, plasma assisted combustion and other combustion technologies can be used to strengthen the ignition of coal and ammonia gas—solid fuel was an effective method to achieve low-nitrogen and stable combustion.

- (2) The convection and radiation heat transfer during combustion changed when the composition of coal and ammonia gas—solid fuel was different. Higher coal concentration enhanced radiation heat transfer, while lower concentrations led to the consumption of oxygen increased due to ammonia and oxygen competition with coal ignition combustion. Hence, when coal concentration was low, an appropriate increase of excess air coefficient was required to promote combustion reaction.
- (3) At lower coal concentrations, there was a higher propensity to generate N₂O and NO₂. Reducing the content of unburned ammonia and creating a reducing atmosphere will effectively reduced the production of N_2O and NO_2 . The proportion of NO in NO_x exceeded 94% when $c \le 0.23 \text{ kgc/kga}$, indicating a tendency toward singular NO_x species, which mitigated the challenges of achieving low-nitrogen combustion of coal and ammonia gas-solid fuel. The composition of coal ammonia gassolid fuel changed the heat transfer path and share in the combustion process. When the concentration of pulverized coal increased, the radiation heat transfer effect was enhanced, and the concentration of pulverized coal decreased, ammonia absorbed heat as it ignited and competed with pulverized coal for oxygen combustion, the oxygen consumption of the coal ammonia gas-solid fuel combustion under the low pulverized coal concentration may be higher than that of pure ammonia combustion, which was not conducive to the combustion reaction, but the strong reducing atmosphere was conducive to reducing the generation of NO_{x} , so that the NO_x generation increased first and then decreased with the concentration of pulverized coal. Reducing the content of unburned ammonia and creating a reducing atmosphere can effectively inhibit the formation of N2O and NO₂. When the $c \leq was 0.23 \text{ kgc/kga}$, the NO_x type tended to be single, and the proportion of NO_x in NO exceeded 94%, which reduced the difficulty of controlling the generation of NO_x in coal-ammonia gas-solid fuel.
- (4) Overall, the addition of ammonia resulted in decreased O_2 concentration, elevated flue gas temperature, increased NO_x and CO production. The optimum coal concentration was found to be 0.41 kgc/kga. The effect of water vapor concentration on the combustion of coal ammonia gas—solid fuel and the change of fly ash pore structure is not clear, and it will be the future research direction.

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Notes

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REFERENCES

(1) Aziz, M.; Wijayanta, A. T.; Nandiyanto, A. B. D. Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization. *Energies* **2020**, *13* (12), 3062.

(2) Li, J.; Lai, S.; Chen, D.; Wu, R.; Kobayashi, N.; Deng, L.; Huang, H. A Review on Combustion Characteristics of Ammonia as a Carbon-Free Fuel. *Front. Energy Res.* **2021**, *9*, 760356.

(3) Yapicioglu, A.; Dincer, I. A review on clean ammonia as a potential fuel for power generators. *Renew. Sustain. Energy Rev.* **2019**, *103*, 96–108.

(4) Ozturk, M.; Dincer, I. An integrated system for ammonia production from renewable hydrogen: A case study[J]. *Int. J. Hydrogen Energy* **2021**, *46* (8), 5918–5925.

(5) Lide, D. R. CRC Handbook of Chemistry and Physics, 72nd ed.; CRC Press: Boca Raton, FL, 1991.

(6) Kobayashi, H.; Hayakawa, A.; Somarathne, K. K. A.; Okafor, E. C. Science and Technology of Carbon-free Ammonia Combustion(1)-Carbon-free Ammonia Combustion[J]. *J. Combust. Soc. Jpn.* **2016**, *58*, 41.

(7) Xia, Y.; Hadi, K.; Hashimoto, G.; Hashimoto, N.; Fujita, O. Effect of ammonia/oxygen/nitrogen equivalence ratio on spherical turbulent flame propagation of pulverized coal/ammonia co-combustion. *Proc. Combust. Inst.* **2021**, 38 (3), 4043–4052.

(8) Hiraoka, K.; Fujimura, Y.; Watanabe, Y.; et al. Cost Evaluation Study on CO2-Free Ammonia and Coal Co-Fired Power Generation Integrated with Cost of CCS[C]//2018 AIChE Annual Meeting; AIChE, 2018.

(9) Lee, E. S.; Keel, S. I.; Kim, M. S.; Jegal, H.; Yun, J. H.; Chi, J. H.; Baek, S.; Lee, J.; Jeon, M. Behavior of nitrogen oxides in a lab-scale coal ammonia co-firing system. *J. Energy Inst.* **2023**, *107*, 101174.

(10) Chen, C.; Wang, Z.; Zhu, R.; Tan, J.; He, Y.; Cen, K. Co-firing characteristics and fuel-N transformation of ammonia/pulverized coal binary fuel. *Fuel* **2023**, *337*, 126857.

(11) Cardoso, J. S.; Silva, V.; Chavando, J. A. M.; Eusébio, D.; Hall, M. J. Numerical modelling of the coal phase-out through ammonia and biomass co-firing in a pilot-scale fluidized bed reactor. *Fuel Commun.* **2022**, *10*, 100055.

(12) Hadi, K.; Ichimura, R.; Hashimoto, G.; Xia, Y.; Hashimoto, N.; Fujita, O. Effect of fuel ratio of coal on the turbulent flame speed of ammonia/coal particle cloud co-combustion at atmospheric pressure. *Proc. Combust. Inst.* **2021**, 38 (3), 4131–4139.

(13) Ma, P.; Huang, Q.; Si, T.; et al. Experimental investigation of NO_x emission and ash-related issues in ammonia/coal/biomass cocombustion in a 25-kW down-fired furnace[J]. *Proc. Combust. Inst.* **2023**, 39 (49), 3467.

(14) Zhang, J.; Ito, T.; Ishii, H.; Ishihara, S.; Fujimori, T. Numerical investigation on ammonia co-firing in a pulverized coal combustion facility: Effect of ammonia co-firing ratio. *Fuel* **2020**, *267*, 117166.

(15) Ma, P.; Huang, Q.; Wu, Z. Q.; Lyu, J.; Li, S. Optical diagnostics on coal ignition and gas-phase combustion in co-firing ammonia with pulverized coal on a two-stage flat flame burner. *Proc. Combust. Inst.* **2023**, *39*, 3457–3466.

(16) Zhu, J. J.; Xu, Y. S.; Xu, J. Y.; et al. Effect of Co-firing Ammonia on Coal Volatile Flame Characteristics and Particulate Matter Formation Behaviours[J]. *Power Gener. Technol.* **2022**, *43* (6), 908.

(17) Niu, T.; Zhang, W. Z.; Liu, X.; et al. Industrial-scale experimental investigation of ammonia-coal cofiring in coal-fired boiler[J]. *Clean Coal Technol.* **2022**, *28* (3), 193–200.

(18) Mei, B.; Zhang, J.; Shi, X.; et al. Enhancement of ammonia combustion with partial fuel cracking strategy: Laminar flame propagation and kinetic modeling investigation of $NH_3/H_2/N_2/air$ mixtures up to 10 atm[J]. *Combust. Flame* **2021**, 231, 111472.

(19) Zhang, Q.; Huang, X. Q. Aircraft engine combustion; Defense Industry Press: Beijing, 2015.

(20) Tan, J.; He, Y.; Zhu, R.; Zhu, Y.; Wang, Z. Experimental study on co-firing characteristics of ammonia with pulverized coal in a staged combustion drop tube furnace. *Proc. Combust. Inst.* **2023**, *39*, 3217–3225.

(21) Yu, W. W. Experimental Study on Ignition Characteristics of Pulverized Coal Jet; Tsinghua University: Beijing, 2013.

(22) Sheng, C.; Yuan, J.; Xu, M.; et al. Ignition Model of Pulverized-Coal Cloud Heated by Radiation[J]. *J. Combust. Sci. Technol.* **1996**, *2*, 38.

(23) Yuan, Y.; Li, S. Q.; Li, G. D.; Wu, N.; Yao, Q. The transition of heterogeneous-homogeneous ignitions of dispersed coal particle streams. *Combust. Flame* **2014**, *161* (9), 2458–2468.

(24) Yang, S. M.; Tao, W. S. *Heat Transfer*; Higher Education Press, 1988.

(25) Han, C. Y. Coal Combustion; Science Press: Beijing, 2001.

(26) Hong, D.; Yuan, L.; Wang, C.; Wang, H. Insight into the Competitive and Synergistic Effects during Coal/NH₃ Cofiring via Reactive Molecular Dynamics Simulations[J]. *Energy Fuels* **2023**, *37* (4), 3071–3082.

(27) Wang, X.; Fan, W. D.; Chen, J.; Feng, G.; Zhang, X. Experimental study and kinetic analysis of the impact of ammonia co-firing ratio on products formation characteristics in ammonia/coal co-firing process. *Fuel* **2022**, *329*, 125496.

(28) Wu, Z. Q.; Huang, Q.; Ma, P. Single-coal-particle ignition in cofiring ammonia with coal[J]. *Clean Coal Technol.* **2023**, *29* (10), 1–8.

(29) Ishihara, S.; Zhang, J. W.; Ito, T. Numerical calculation with detailed chemistry on ammonia co-firing in a coal-fired boiler: Effect of ammonia co-firing ratio on NO emissions. *Fuel* **2020**, *274*, 117742.

(30) Hong, D.; Yuan, L.; Wang, C. Competition between NH_3 - O_2 reaction and char- O_2 reaction and its influence on NO generation and

reduction during char/ NH_3 co-combustion: Reactive molecular dynamic simulations[J]. *Fuel* **2022**, 324, 124666.

(31) Chen, P.; Hua, C. H.; Wang, P. P. Study on NO formation mechanism of ammonia-coal co-combustion[J]. *Coal Convers.* **2023**, *46* (04), 51–58.

(32) Chen, P.; Wang, Y.; Wang, H. C.; et al. Molecular mechanism of N oxidation in ammonia-coal co-firing[J]. *J. China Coal Soc.* **2023**, *48* (2), 1037–1046.

(33) Chen, C.; Wang, Z.; Zhu, R.; Tan, J.; He, Y.; Cen, K. Co-firing characteristics and fuel-N transformation of ammonia/pulverized coal binary fuel. *Fuel* **2023**, *337*, 126857.

(34) Hou, X.; Zhang, H.; Pilawska, M.; Lu, J.; Yue, G. The formation of N_2O during the reduction of NO by $NH_3[J]$. *Fuel* **2008**, 87 (15–16), 3271–3277.

(35) Chen, P.; Gong, C.; Hua, C.; Gu, M.; Jiang, B.; Fan, J.; Wang, Y. Mechanism analysis of fuel-N oxidation during ammonia-coal cocombustion: Influence of $H_2O[J]$. *Fuel* **2023**, *342*, 127747.

(36) Jeon, M.; Lee, E.; Kim, M.; et al. Nitric oxide (NO) and nitrous oxide (N₂O) emissions during selective non-catalytic reduction and selective catalytic reduction processes in a pulverized coal/Ammonia Co-fired boiler[J]. *J. Environ. Chem. Eng.* **2023**, *11* (2), 109398.