Academic Journal of Materials & Chemistry
ISSN 2616-5880 Vol. 3, Issue 2: 14-24, DOI: 10.25236/AJMC.2022.030203

A Review on Self-Preheating Combustion Technology for Reducing NO_x Emission in the Process of Carbon-Based Fuel Combustion

Dingyuan Jin[1,a], Hongliang Ding[2,b,*]

[1]*Second High School Attached to Beijing Normal University, Beijing, China*
[2]*Institute of Engineering Thermophysics, Chinese Academy of Science, Beijing, China*
[a]*rszjdy@163.com*, [b]*dinghongliang@iet.cn*
**Corresponding author*

Abstract: *Energy and environment are the two major themes of today's social development. Self-preheating combustion technology has opened a new path for the directional transformation of coal nitrogen, achieved the inhibition of NO_x generation in the combustion in-situ reaction, better realized the organic integration of efficient combustion of pulverized coal and low NO_x emission, and showed stronger advantages in the denitration efficiency, environmental compatibility and investment and operation cost. This study first introduces the basic principle of self-preheating combustion technology, including the principles of self-preheating, the principles of preheated fuel combustion and the NO_x formation mechanism. Subsequently, the research progress in reducing NO_x emission by self-preheating combustion technology in 30 kW bench scale text rigs and MW grade pilot-scale text rigs, and the industrial application of self-preheating combustion technology are respectively illustrated. Finally, the corresponding conclusions are given, and the future development direction of self-preheating combustion technology is prospected.*

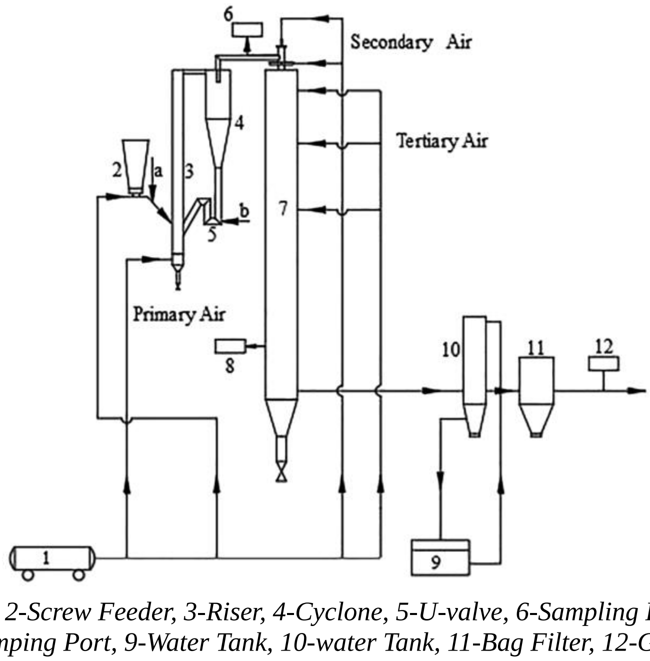
Keywords: *Self-preheating combustion; Clean and efficient; NO_x emission; Carbon-based fuel; Carbon neutral*

1. Introduction

Energy and environment are two major themes of social development today [1]. Under the goal of "double carbon", China is making efforts to optimize and improve the energy structure and energy utilization mode, and vigorously develop new energy technologies [2]. The proportion of non-fossil energy power generation in China's power structure has increased significantly. Nevertheless, renewable energy sources such as wind and solar power are intermittent and volatile. After its large-scale interconnection, it will bring severe challenges to the safe and stable operation of the power grid [3]. According to China's energy situation, using more clean and efficient flexible power sources such as coal-fired power generation as peak shaving power supply to stabilize power fluctuations is an effective measure to solve this difficulty. Therefore, coal is still the "ballast stone" of China's energy security [4]. It is estimated that after achieving carbon neutralization by 2060, the installed capacity of coal-fired power generation will still require maintaining 300~400 million kilowatts, and the annual coal consumption will be 390~640 million tons [5].

From the perspective of utilization mode, at present, the proportion of direct combustion of coal in China is as high as 80% [6]. In the process of coal combustion, a large number of NO_x (mainly composed of NO_2 and NO) will be produced, which seriously harms humankind health and damages the atmospheric environment [7]. Therefore, controlling NO_x emission from coal combustion has always been one of the important aspects of the clean coal combustion, the energy conservation and the environmental protection. In view of the NO_x generation characteristics of coal combustion, the existing technical means to control NO_x in the combustion process mainly include reasonably adjusting the combustion temperature, the oxygen concentration, the proportion, location, time and temperature of fuel and air input, etc., so as to suppress the generation of NO_x and reduce partial NO_x in the combustion process, thus achieving the purpose of NO_x emission inhibition, such as air-staged technology [8], fuel-staged technology [9], flue gas recirculation technology [10], low temperature and low oxygen combustion technology [11], etc. Nevertheless, the application of these mentioned technologies will inevitably sacrifice the combustion efficiency, and the degree of NO_x reduction is limited, which leads to the fact that the existing units have to use flue gas aftertreatment technologies such as selective catalytic reduction (SCR) or selective non catalytic reduction (SNCR) to reduce NO_x emissions [12]. While in the course of SCR and SNCR operation, there will also be quite a few issues such as high cost, catalyst poisoning, ammonia escape, narrow stable operation window and so on, which can not meet the demand of renewable energy peak shaving [13]. From this point of view, the development of revolutionary technologies for coal combustion, solely through the coal combustion process, without flue gas denitration equipment, will significantly reduced the investment and operating costs of coal-fired industrial boilers, making it possible to achieve ultra-low NO_x emissions. It is the ultimate goal of the research and application of clean and efficient coal combustion and utilization technology in China's industrial field to achieve breakthroughs in near-zero emission technology of efficient coal combustion with good economy and no scale restriction, so that coal can become a clean energy instead of the main factor of air contamination [14].

At present, there is no mature low nitrogen combustion technology at home and abroad that can directly meet the requirements of ultra-low NO_x emission (≤50 mg/Nm^3) on the combustion side. Therefore, developing a new pulverized coal combustion technology to achieve ultra-low NO_x emission can significantly reduce the operation and maintenance costs of denitration and reduce equipment safety risks. Inspired by Japan's high-temperature air combustion technology, the Institute of Engineering Thermophysics, Chinese Academy of Sciences (IET, CAS) proposed a high-temperature combustion method of pulverized coal suitable for high-efficiency and low nitrogen combustion of solid fuels in 2007, and based on this, developed the coal self-preheating combustion technology [15], as shown in Fig. 1, that is, the fuel could be firstly modified, activated and denitrified in the preheating process, and then the staged combustion technology could be combined to further reduce nitrogen in the combustion process, so as to realize ultra-low NO_x emission of coal combustion. From 2007 to 2012, 30 kW bench-scale test rigs were established, and many experimental researches were carried out to master the mechanism of fuel modification, the combustion characteristics of the preheated fuel (high temperature coal gas + coal char) and the transformation law of fuel-N. Since 2013, IET has accelerated the scale-up and engineering demonstration research and development of coal self-preheating combustion technology, successively established 0.2 MW and 2 MW pilot scale test platforms, and carried out many experimental studies of bituminous coal, anthracite, pyrolysis semi-coke, gasification fly ash and other different grade fuels. Through the research and development of key technologies and system integration, in order to improve the share of preheating reaction, optimize the allocation of air equivalence ratio in the main combustion zone to form a reasonable range and atmosphere of the reduction zone, and develop ultra-low NO_x control strategies for optimizing the combustion organization, the preheated fuel characteristics and amplification laws of different carbon-based fuel have been mastered, and high efficiency combustion and low NO_x emission have been achieved.



1-Air compressor, 2-Screw Feeder, 3-Riser, 4-Cyclone, 5-U-valve, 6-Sampling Port, 7-Down-fired Combustor, 8-Samping Port, 9-Water Tank, 10-water Tank, 11-Bag Filter, 12-Gas Analyzer, a-the carrying coal air, b-returning air

Figure 1: Pulverized coal self-preheating combustion process

ISSN 2616-5880 Vol. 3, Issue 2: 14-24, DOI: 10.25236/AJMC.2022.030203

Showing stronger superiority in denitration efficiency, environmental compatibility, investment and operation costs, the coal self-preheating combustion technology opens up a new path of directional conversion of fuel-N, efficaciously inhibits the NO_x generation in the combustion in-situ reaction, and better realizes the organic integration of efficient coal combustion and low NO_x emission. In this study, the technical ideas and development of coal self-preheating combustion technology were specifically introduced, in order to provide a basis for the industrial application of the coal self-preheating combustion technology, and provide a reference for the next development direction.

2. Basic principles of self-preheating combustion technology

2.1 Principles of self-preheating

The common pulverized coal pretreatment technology is usually to heat the coal to a higher temperature by some means, so that the coal and the combustion air can react quickly, catch fire, and successfully achieve stable combustion. According to the difference of the reaction device and the components of the reduction product, it can be mainly divided into the gas fired pretreatment combustion technology [16-18] and burner pretreatment combustion technology [19-22].

The All-Russian Thermal Engineering Research Institute took the lead in conducting research on gas fired coal preheating (GFCP) in the 1980s [16]. The results revealed that when the coal was heated at 815 ℃, the NO_x generation could be reduced by 80%, and the denitrification efficiency increased with the heating temperature. Bryan B [17] carried out a series of experimental studies on a 0.88 MW pilot test platform, and the NO_x emission of high-volatile bituminous coal was finally controlled at about 300 mg/Nm^3 without air staged combustion. Liu C et al. [18] designed different burners for optimizing the combustion organization of heating products on a 35 kW one-dimensional tube furnace. Combined with the staged air distribution in the combustion chamber, the NO_x emission values of Shenmu bituminous coal, Huangling bituminous coal and Hejin lean coal could decrease by 74%, 67% and 48% respectively.

Niu Y [19] and Zhu G [20] designed preheating burners with different face configurations. The experimental results illustrated that NO_x emission could be controlled at 212~231 mg/Nm^3 within a reasonable air distribution range of the combustion system. Zhang H et al. [21] put forward a primary air enrichment and preheating (PRP) burner, which could realize stable combustion of anthracite (Vdaf=7.8%) without oil, and the NO_x emission was controlled at 306~490 mg/Nm^3. China Coal Research Institute proposed a double cone steady combustion chamber with central forced reflux [22]. Through the special design of the primary air return cap, it was conducive to fully preheat the pulverized coal and air before the mixing of primary and secondary air, which significantly prolonged the residence time of pulverized coal in the steady combustion chamber, and the NO_x emission could be controlled at 175~350 mg/Nm^3.

Different from the common pulverized coal pretreatment technology, the principle of coal self-preheating combustion technology is that the fuel is first partially burned and gasified in a circulating fluidized bed with a low air equivalence ratio. The heat generated in the course of this process is used to preheat the fuel itself to above 800 ℃. After preheating, the fuel is converted into high-temperature coal gas and coal char, and this part of high-quality fuel subsequently enters the combustion chamber to mix with the secondary air and burn. This technology makes use of the advantages of circulating fluidized bed such as wide fuel adaptability and good combustion stability. What's more, the same as GFCP technology, this technology is also staged combustion and high-temperature coal gas and coal char are produced in the first stage combustion. Nevertheless, the difference is that GFCP technology mainly uses combustible gas combustion to preheat pulverized coal, while this technology is self-preheating without external heat source. In addition, based on the characteristics of circulating fluidized bed, the residence time of pulverized coal particles in the self-preheating stage can be significantly longer, which is more conducive to the release of fuel-N and the conversion of fuel-N to N_2. Compared to preheating the air, the specific heat of pulverized coal is larger, the sensible heat of preheating to the same temperature is also greater, and the combustion stability becomes better. Furthermore, in addition to the temperature rise, the pulverized coal has also undergone significant physical and chemical changes during preheating, affecting the thermal migration of fuel-N, the characteristic of subsequent combustion and the NO_x formation, which is the most essential difference from high-temperature air combustion.

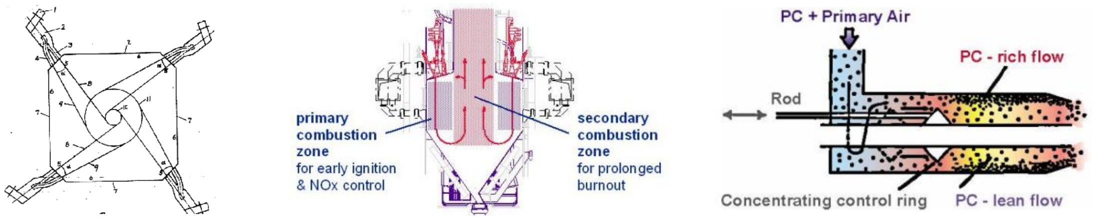
2.2 Principles of preheated fuel combustion

Combustion stability and burnout are the two most important issues in the process of coal combustion.

ISSN 2616-5880 Vol. 3, Issue 2: 14-24, DOI: 10.25236/AJMC.2022.030203

For the stable combustion of pulverized coal, it is mainly divided into three directions: 1) increasing the concentration of pulverized coal in the furnace to reduce the ignition heat of pulverized coal-air flow [23]. The physical basis of this technology is that different pulverized coal concentration correspond to different ignition temperatures; 2) Strengthening the ignition and stable combustion of pulverized coal by entraining high-temperature flue gas [24]. The physical basis of this technology is that the high-temperature flue gas flows back to the root of pulverized coal flow and mixes with it, which strengthens the ignition and combustion of pulverized coal. 3) High temperature air combustion technology [25]. The physical basis of this technology is that the preheating temperature of high-temperature air exceeds the ignition temperature of pulverized coal, and the physical heat carried by high-temperature air is higher than the ignition heat of pulverized coal.

For the burnout of pulverized coal, the commonly used methods to improve the burnout of pulverized coal are mainly to prolong the residence time of pulverized coal in the high temperature zone of the furnace and control the particle size distribution of pulverized coal within a reasonable range [26]. To name only a few, the tangentially fired combustion mode [27] as shown in Fig. 2a, and the "W" flame combustion mode [28] as shown in Fig. 2b. These two combustion modes can effectively improve the burnout rate of pulverized coal, but there also exist some difficulties such as large investment, complicated installation and high NO_x emission. Japan IHI Company has developed CI-αWR burner [29] as shown in Figure 2c, which can realize the separation of pulverized coal concentration and dilution to improve the burnout rate. Nevertheless, it is necessary to burn extremely fine pulverized coal whose fineness R_{90} is less than 5%, hence the operation cost increases and the safety must also be considered.



a. Corner tangential [27] *b. W-boiler [28]* *c. CI-αWR burner [29]*

Figure 2: Common burning method of pulverized coal

In comparison with the above technologies, coal self-preheating combustion technology has more prominent advantages in stable combustion and burnout. Since the fuel is firstly preheated in the circulating fluidized bed before entering the combustion chamber, the combustion time is greatly prolonged and the final combustion efficiency is improved. What' more, the fuel will be modified and upgraded in the preheating process, such as the development of specific surface area, the decrease of graphitization degree, and the increase of active sites in the carbon structure, which is more conducive to the contact and mixing of the fuel with O_2 in the combustion chamber. With the wide fuel adaptability of circulating fluidized bed, it is also proved that coal self-preheating combustion technology can be applied to many carbon-based fuels, from bituminous coal with high volatile matter to anthracite with extremely low volatile matter, even semi-coke and gasification fly ash. Moreover, coal self-preheating combustion technology can also be combined with air-staged combustion, oxygen-enriched combustion, MILD combustion and other technologies, so as to achieve stable combustion and burnout of fuel and further reduce the generation of NO_x.

3. Research progress in reducing NOx emission by self-preheating combustion technology

3.1 kW grade bench-scale text rigs

The research team of IET realized the stable combustion of various fuels with coal self-preheating technology in 30 kW bench scale text rigs, and obtained the influence of preheating conditions and air distribution conditions on combustion characteristic and NO_x emission.

For non-flammable anthracite,, Wang J et al. [30] studied the effects of excess air coefficient (λ) and air equivalence ratio (λ_{Re}) in the reduction zone on combustion characteristics and NO_x emission, discovering that when λ was 1.26~1.67, the NO_x emission concentration was less than 371 mg/Nm^3 (@6%O_2), and when λ_{Re} was 0.12, the NO_x concentration was 221 mg/Nm^3 (@6%O_2). The results of NO_x emission obtained in the course of experiments were much lower than those produced by other conventional boilers. Later, Ouyang Z et al. [31,32] studied the characteristics of the preheated fuel and NO_x emission of anthracite. The results illustrated that the average particle size of preheated anthracite became smaller, and the specific surface area was larger. Additionally, the axial temperature distribution of the combustion chamber was uniform, and the combustion efficiency could exceed 96.5% with low NO_x emission (256 mg/Nm^3, @6%O_2). Further experimental studies [33] revealed that adding limestone to the self-preheating burner could reduce SO_2 emission and achieve desulfurization at the same time without affecting NO_x emission. Subsequently, Ouyang Z [34] proposed a stable flameless combustion method of pulverized coal based on coal preheating. The temperature of the combustion chamber was observed to be homogeneous, and the colour of the entire combustion chamber presented pale yellow with no manifest flame front surface observed. Fuel preheating was effective for improving the combustion efficiency, with values of 98.3% and 97.9 % achieved for two different anthracite coals, and NO_x emission was determined to be 187 mg/Nm^3 (@6%O_2) and 165 mg/Nm^3 (@6%O_2).

For bituminous coal with good reactivity, In Zhu J's research [35], NO_x emission decreased with the increase of pulverized coal particle size (d_{50}) and the primary air equivalent ratio (λ_P). While with the increase of preheating temperature (T_P), NO_x emissions first decreased and then increased, and could be controlled below 368 mg/Nm^3 (@6%O_2). Subsequently, Ouyang Z et al. [34] realized the stable flameless combustion of bituminous coal based on coal preheating, controlling NO_x at 232 mg/Nm^3 (@6%O_2). Additionally, Zhu S et al. [36,37] studied the influence of the secondary air nozzle structure and the position of the tertiary air on NO_x emission, and found that the circular secondary air nozzle structure could make high temperature fuel and air mix evenly, and prolong the length of the high temperature reduction zone, which was more conducive to reduce NO_x emission, while reasonable arrangement of the tertiary air position and adjustment of the reduction zone length could further restrain NO_x generation, and the minimum NO_x emission could be controlled at 193.72 mg/Nm^3 (@6%O_2). Liu W et al. [38,39] have done further research on the flameless combustion behavior of preheated fuel and found that NO_x was generated near the fuel nozzle, and then further reduced in the main combustion zone. Through reasonable air distribution, NO_x emission was controlled at 67 mg/Nm^3 (@6%O_2). In order to further tap the low nitrogen potential of the coal self-preheating combustion technology, Zhang Y et al. [40,41] reasonably converted λ_P. T_P, combustion temperature, λ_{Re} and other operating parameters, realized ultra-low NO_x combustion of pulverized coal for the first time at home and abroad. The average value of NO_x original emission reached 31 mg/Nm^3 (@6%O_2).

For ultra-low volatile carbon based fuels such as semi-coke and coal gasification fly ash (CGFA), Yao Y et al. [42,43] studied the influence of secondary air distribution and tertiary air position on NO_x emission, discovering that lower and uniformly distributed O_2 concentration was conducive to the initial NO_x reduction, while the staged tertiary air promoted the conversion of NH_3 generated by fuel-N into N_2 in a complete combustion process, and the lowest NO_x emission was 60 mg/Nm^3 (@6%O_2). Liu W et al. [39,44] discussed the preheated fuel characteristics, combustion behavior and the generation mechanism of NO_x of semi-coke, finding that the lower the initial amount of NO_x generation near the secondary air nozzle, the lower the NO_x emission. By reducing the inner secondary air, increasing the external secondary air and adding CO_2 to the secondary air, the generation of initial NO_x could be effectively suppressed and finally controlled. Furthermore, the influence of secondary air jet velocity on NO_x emission was studied [45], and the flameless combustion of semi-coke and CGFA were also realized [46]. It was found that the secondary air jet velocity would affect the average temperature and root mean square temperature, thus affecting NO_x emission. In addition, Liu W et al. [47] also discussed the impact of single-stage and multi-stage tertiary air on NO_x emission in the flameless mode. The results revealed that for single-stage tertiary air, there was a nozzle position that minimized NO_x emission, while for multi-stage tertiary air, the introduction of the appropriate amount of tertiary air in the reduction zone could be beneficial to NO_x emission reduction, while the introduction of more tertiary air in the burnout zone was disadvantageous. Whereafter, Ouyang Z and Ding H [48,49] studied the effects of λ_P, secondary air distribution and d_{50} on flameless combustion characteristics and NO_x emissions, discovering that the increase of λ_P could improve the pre-denitrification effect in the self-preheating burner, while too high T_P would affect the heterogeneous reduction of NO_x on the coal char surface. The preheated fuel was easy to achieve flameless combustion in the coaxial three-channel nozzle. By adjusting the ratio of internal and external secondary air, the lowest NO_x emission was 50.8 mg/Nm^3 (@6%O_2). In Ding H's research [50], there existed a critical value of d_{50} of Shenmu semi-coke (d_{50}=198.54 μm). When the particle size was less than or higher than this critical value, the NO_x generated by combustion would be reduced. When d_{50} was 35.34 μm, the NO_x emission was the lowest, which was 89.46 mg/Nm^3 (@6%O_2).

The above studies prove the advantages of coal self-preheating combustion technology in reducing NO_x generation in the process of coal combustion. With the help of the wide fuel adaptability of the circulating fluidized bed, it is also confirmed that self-preheating can be applied to quite a few kinds of coal, from bituminous coal with high volatile to anthracite with extremely low volatile and even semi-coke and CGFA. Moreover, self-preheating can also be combined with air-staged combustion, flameless combustion, and other technologies to further reduce the generation of NO_x, thus possessing a broad application prospect.

3.2 MW grade pilot-scale text rigs

Through the research and development of key technologies and system integration, the research team of IET has realized the stable self-preheating combustion of many kinds of fuels on the pilot platform of 0.2 MW, 0.4 MW and 2 MW, mastered the preheated fuel characteristics and amplification rules of different fuels, realizing high efficiency combustion and low NO_x emission of carbon-based fuels.

On the 0.2 MW pilot platform, Man C et al. [51] found that T_P could be widely adjusted in the range of 800~950 ℃, and λ_P could be reduced to 0.15. With the increase of the secondary air equivalence ratio (λ_2), more air was provided to the high temperature preheated fuel, promoting the release of fuel-N and the generation of NO_x. The lower injection position of tertiary air would form a longer reduction zone, thus inhibiting the conversion of fuel-N to NO_x, but reducing the combustion efficiency. Ouyang Z et al. [52] studied the effects of T_P, λ_2 and tertiary air nozzle positions on the combustion characteristics and NO_x emissions of bituminous coal. The results illuminated that the increase of T_P and λ_2 would lead to the increase of NO_x emission. With the increase of the distance between the tertiary air nozzle and the preheated fuel nozzle, the NO_x emission decreased, which was consistent with the results of Man's research. Since the stable low NO_x combustion of coarse pulverized coal could improve the energy efficiency of the combustion system, Zhu S et al. [53] further studied the coarse coal (0~1 mm) and found that the NO_x concentration in the high temperature coal gas and the strong reduction zone were almost 0 ppm. As the reaction atmosphere on the combustion path gradually altered from reduction to oxidation, fuel-N was mainly oxidized to NO, with 114 mg/Nm^3 (@6%O_2). Subsequently, Zhu S et al. [54] tried to further realize the stable, efficient, and low NO_x combustion of weakly caking coal. The results revealed that higher T_P and higher fluidization gas velocity were beneficial to alleviate or even solve the preheating instability of weak caking coal. Without affecting the combustion effect, the reduction zone was separated from the oxidation zone by arranging the burnout air level, which broadened the reduction zone and further reduced NO_x emission.

On the 0.4 MW pilot test platform, Ouyang Z et al. [55] studied the combustion of CGFA. The results demonstrated that the self-preheating combustion system could operate smoothly, and the combustion efficiency reached 98.6%. The NO_x emission was 155 mg/Nm^3 (@6%O_2), which realized the efficient and clean combustion of CGFA. It was also found that NO_x emission increased with the increase of λ_P and the decrease of λ_2. The position of the tertiary air nozzle had a significant impact on combustion characteristics of CGFA. When the position of the tertiary air nozzle was far away from the bottom of the combustion chamber, NO_x emission could be effectually reduced.

On the 2 MW pilot test platform, Liu J et al. [56] applied coal self-preheating combustion technology to evaluate and study the deep staged gasification and combustion of bituminous coal. The representative factors such as λ_2, internal and external momentum ratio of secondary air, graded tertiary air and swirl number of secondary air were compared and discussed. It was found that the lowest NO_x emission of bituminous coal could reach 49.6 mg/Nm^3 (@6%O_2), and the combustion efficiency was as high as 98.8%, achieving efficient and clean combustion. In the process of further reducing NO_x emission, the deep control of preheated fuel injection mode, the construction of flame structure and propagation, and the organization of stoichiometric ratio of multi-stage air were helpful to reconstruct the type of diffusion flame and realize the visualization of flameless structure and type. Ouyang Z [57,58] adopted a novel fluidized bed combustor (IFBC) with an internal separator, and thereafter carried out a series of experiments combined with air-staged method. The effects of λ_2, the degree of air-staged combustion and the tertiary air position on NO_x emission were investigated. The results represented that when λ_2 decreased from 0.50 to 0.40, the NO_x emission decreased due to the enhancement of reduction atmosphere in the reduction zone. In addition, the deep air-staged combustion would help to form low oxygen and strong reduction zone in the early stage of staged combustion, thereby inhibiting the generation of NO_x. Strong mixing and long residence time were the key to reduce NO_x emission, and the multi-layer arrangement and delayed supply of tertiary air could also significantly reduce NO_x emission which could be reduced to a minimum of 67 mg/Nm^3 (@6%O_2) with the combustion efficiency of 99.2%.

The in-depth study on the MW pilot plant illustrates that the coal self-preheating combustion technology opens up a new path for the directional conversion of fuel-N and realizes the inhibition of NO_x generation in the in-situ combustion reaction. If the coal self-preheating combustion technology is further popularized and applied, it will bring significant social and economic benefits.

ISSN 2616-5880 Vol. 3, Issue 2: 14-24, DOI: 10.25236/AJMC.2022.030203

3.3 Industrial application of preheating combustion technology

When it comes to the industrial application of coal self-preheating combustion technology, researchers of IET have designed, developed, and established a 40 t/h pulverized coal boiler with a self-preheating burner on the bottom based on experimental studies. As shown in Fig. 3a, stable operation has been achieved and industrial verification of the self-preheating combustion system has been accomplished [59]. The test NO_x emission was lower than 100 mg/Nm^3 at 100% load, which realized the efficient and clean combustion of the pulverized coal. With the enlargement of boiler capacity, the coupling scheme of the self-preheating burner and furnace gradually transformed. The 60 t/h pulverized coal boiler with hedging arrangement of self-preheating burner sidewall was designed, developed and applied, as shown in Fig.3b. Through the demonstration of the furnace type engineering, the capacity scale expansion of self-preheating combustion industrial boiler and the demonstration application of power station boiler were supported. Furthermore, on the basis of 60 t/h pulverized coal self-preheating combustion boiler, a 90 t/h pulverized coal self-preheating combustion boiler was designed and developed, equipped with two 40 MW self-preheating burners. Two cyclone separators and return feeders were arranged on the left and right sides of the riser to form a double circulation loop. The 90 t/h pulverized coal self-preheating combustion boiler under construction is shown in Fig. 3c. The successful demonstration of pulverized coal self-preheating combustion boiler is of great significance to promote the development and technological progress of coal-fired boilers.

a. 40 t/h boiler *b. 60 t/h boiler* *c. 90 t/h boiler*

Figure 3: Industrial application of coal self-preheating combustion technology

In addition to pulverized coal boilers, IET has also developed a 35t/h self-preheating combustion boilers for pure combustion of ultra-low volatile fuel [60] and a 100 t/d self-preheating combustion boilers for CGFA [61], which can provide key equipment and technical demonstration for efficient and clean combustion and resource utilization of pyrolysis semi-coke and CGFA, promote the development of coal quality classification technology, improve the comprehensive utilization efficiency of coal, and realize the clean consumption of coal resources.

To summarize, coal self-preheating combustion technology has the advantages of wide fuel adaptability, good combustion stability, high combustion efficiency and low pollutant emission. The self-preheating burner can operate stably for a long period without external heat source. At present, self-preheating combustion boilers burning different characteristic fuels such as coal, semi-coke and CGFA have been developed and applied, and the engineering demonstration and application of self-preheating combustion boilers have been accomplished, which will certainly promote the development and progress of high efficiency pulverized coal industrial boilers.

4. Conclusion and prospect

As a novel type of low NO_x combustion technology, coal self-preheating combustion technology ensures the release of volatile-N before fuel combustion and the conversion in oxygen-poor and strong reducing atmosphere can effectively reduce the formation of NO_x. With the help of the wide fuel adaptability of circulating fluidized bed, it is also confirmed that this technology can be applied to many kinds of coal, from bituminous coal with high volatile to anthracite with extremely low volatile and even semi-coke and CGFA. And it can also be combined with air-staged combustion, flameless combustion and other technologies to further reduce NO_x emissions. Summarizing the existing literature, the realization of low NO_x emission from coal combustion by self-preheating combustion technology mainly depends on two key points: first, during the self-preheating process, the gaseous fuel-N released in the environment of high concentration coal char particles and strong reduction atmosphere only exist in the form of nitrogen-containing intermediates (NH_i, HCN, etc.) and N_2; Second, the residual nitrogen-containing intermediate products in the dispersion reduction zone at the intlet of the combustion chamber are reduced to N_2, and the more flexible configuration of reduction zone and oxidation zone further restrains the conversion of char-N to NO_x. In conclusion, coal self-preheating combustion technology realizes the organic integration of high efficient coal combustion and low NO_x emission, and can show strong advantages in the denitration efficiency, environmental compatibility and investment and operation costs. If the technology is popularized and applied, it will bring significant social and economic benefits.

Based on the inherent requirements of promoting sustainable development and the responsibility of building a community with a shared future for mankind, China has announced the goal vision of "double carbon" goals. However, the existing technical means still mainly rely on tail gas purification to achieve ultra-low NO_x emission from coal combustion, which is close to the theoretical limit and still does not meet the requirements of cleanliness. The construction of near-zero emission theory of coal combustion is of strategic significance to the smooth implementation of carbon neutralization. Based on the coal self-preheating combustion technology, putting forward the new concept of coal purification combustion with near zero emission, overcoming major scientific problems in the key core technology in the near zero emission key technology of coal combustion, and forming a new process of near zero emission of coal-fired pollutants are the important development directions of coal self-preheating combustion in the future.

What's more, in order to meet the needs of power security, coal-fired generating units must achieve rapid and flexible peak shaving. However, at present, the variable load rate of coal-fired power units in China is basically lower than 1.5%/min, which cannot meet the peak regulation needs of power grid. The difficulty of realizing rapid load change in pulverized coal combustion is that the combustion rate of heterogeneous reaction cannot match the fuel change rate, which can easily cause problems such as powder accumulation, fire extinguishing, deflagration, low combustion efficiency and high pollutant emission in the furnace when the load changes rapidly, seriously affect the stability and safety of boiler operation. The application of coal self-preheating combustion technology can realize the transformation from heterogeneous reaction to homogeneous reaction, so as to realize the rapid load change of coal combustion. Therefore, putting forward the technical route of pulverized coal gasification-combustion, obtaining the dynamic characteristics and automatic control characteristics of rapid load change of coal combustion, and providing experimental and theoretical guidance for the research and development of flexible peak shaving coal-fired power generation technology will be another important development direction of coal self-preheating combustion technology.

References

[1] Hrvoje M, Jakov B, Jiří J. Sustainability through combined development of energy, water and environment systems [J]. Journal of Cleaner Production 2020; 251: 119727.
[2] Wang J, Huo J, Zhang S, Teng Y, Li L, Han T. Flexibility transformation decision-making evaluation of coal-fired thermal power units deep peak shaving in China [J]. Sustainability 2021; 13(4): 1882.
[3] Krautz H, Lisk A, Posselt J, Katzer C. Impact of renewable energies on the operation and economic situation of coal fired power stations: Actual situation of coal fired power stations in Germany [J]. Frontiers in Energy 2017; 11(2): 119-125.
[4] Zhang X, Cui X, Li B, Hidalgo G, Kammen D, Zou J, et al. Immediate actions on coal phaseout enable a just low-carbon transition in China's power sector [J]. Applied Energy 2022; 308: 118401.
[5] Zhang Q, Zhou Q. Research on the development path of China's thermal power generation technology based on the goal of "Carbon Peak and Carbon Neutralization" [J]. Power Generation Technology 2022; 1-15.
[6] Zhao L, Liu Z, Cheng L. How will China's coal industry develop in the future? A quantitative analysis with policy implications [J]. Energy 2021; 235: 121406.
[7] Song G, Xiao Y, Yang Z, Yang X, Lyu Q, Zhang X, et al. Operating characteristics and ultra-low NO_x emission of 75 t/h coal slime circulating fluidized bed boiler with post-combustion technology [J]. Fuel 2021; 292: 120-276.
[8] Wang Y, Zhou Y, Bai N, Han J. Experimental investigation of the characteristics of NO_x emissions with multiple deep air-staged combustion of lean coal [J]. Fuel 2020; 280: 118416.
[9] Fan W, Chen J, Feng Z, Wu X, Liu S. Effects of reburning fuel characteristics on NO_x emission during pulverized coal combustion and comparison with air-staged combustion [J]. Fuel 2020; 265: 117007.
[10] Pan D, Zhu T, Ji C, Ke E. Effects of flue gas recirculation on self-excited combustion instability and NO_x emission of a premixed flame [J]. Thermal Science and Engineering Progress 2022; 30: 101252.

[11] Xu M, Tu Y, Zeng G, Yang W. Evaluation of ignition process and NO_x reduction of coal under moderate and intensive low-oxygen dilution combustion by implementing fuel-rich/lean technology [J]. Fuel 2021; 296: 120657.

[12] Caneghem J, Greef J, Block C, Vandecasteele C. NO_x reduction in waste incinerators by selective catalytic reduction (SCR) instead of selective non catalytic reduction (SNCR) compared from a life cycle perspective: a case study [J]. Journal of Cleaner Production 2016; 112: 4452-4460.

[13] Zhang S, Zhao Y, Yang J, Zhang Y, Sun P, Yu X, et al. Simultaneous NO and mercury removal over MnO_x/TiO_2 catalyst in different atmospheres [J]. Fuel Processing Technology 2017; 166: 282-290.

[14] Lyu Q, Li S, Huang C. Current situation and development suggestions of coal clean and efficient combustion technology in industry field [J]. Bulletin of Chinese Academy of Sciences 2019; 34(04): 392-400.

[15] Lyu Q, Zhu J, Niu T, Song G, Na Y. Pulverized coal combustion and NO_x emissions in high temperature air from circulating fluidized bed [J]. Fuel Processing Technology 2008; 89: 1186-1192.

[16] Rabovitser J, Bryan B, Knight R, Nester S, Wohadlo S, Tumanovsky A, et al. Development and testing of a novel coal preheating technology for NO_x reduction from pulverized coal-fired boilers [J]. Gas 2003; 1(2): 4.

[17] Rabovitser J. Methane de-NO_x for utility PC boilers [R]. Office of Scientific & Technical Information Technical Reports, 2000.

[18] Liu C, Hui S, Pan S, Wang D, Shang T, Liang L. The influence of air distribution on gas-fired coal preheating method for NO emissions reduction [J]. Fuel 2015; 139:206-212.

[19] Niu Y, Xue X, Zhang H. Cold experiment research of Multistage air-regulating pre-combustion cyclone burner [J]. Clean Coal Technology 2021; 27(05): 1-9.

[20] Zhu G, Gong Y, Niu Y, Wang S, Lei Y, Hui S. Study on NO_x emissions during the coupling process of preheating-combustion of pulverized coal with multi-air staging [J]. Journal of Cleaner Production 2021; 292: 126012.

[21] Zhang H, Jia Z, Mao J, Lyu J, Liu Q. Research on high temperature air combustion technology via primary air enrichment and preheating burner [J]. Journal of Power Engineering 2008; 01: 36-39.

[22] Wang J, Wang N. Demonstration project of high efficiency pulverized coal fired industrial boiler for bulk coal clean utilization [J]. Coal Engineering 2016; 48(9): 1-5.

[23] Zhou C, Wang Y, Jin Q, Chen Q, Zhou Y. Mechanism analysis on the pulverized coal combustion flame stability and NO_x emission in a swirl burner with deep air staging [J]. Journal of the Energy Institute 2019; 92: 298-310.

[24] Xu Q, Shen M, Shi K, Liu Z, Feng J, Xiong Y, et al. Influence of jet angle on diffusion combustion characteristics and NO_x emissions in a self-reflux burner [J]. Case Studies in Thermal Engineering 2021; 25: 100953.

[25] Pei P, Wang Q, Wu D. Application and research on regenerative high temperature air combustion technology on low-rank coal pyrolysis [J]. Applied Energy 2015; 156: 762-766.

[26] Su S, Pohl J, Holcombe D, Hart J. A proposed maceral index to predict combustion behavior of coal [J]. Fuel 2001; 80(5): 699-706.

[27] Qin M, Wu S, Chen J, Kong C, Chen L. An experimental comparison of the airflow characteristics of four-walls tangential firing and four-corners tangential firing [J]. Experimental Thermal and Fluid Science 2015; 62: 21-28.

[28] Wang J, Kuang M, Zhao X, Wu H, Ti S, Chen C, et al. Trends of the low-NO_x and high-burnout combustion characteristics in a cascade-arch, W-shaped flame furnace regarding with the staged-air angle [J]. Energy 2020; 212: 118768.

[29] Makino K. Technologies for NO_x reduction in PC fired utility boilers-A manufacturers perspective [J]. IFRF Combustion Journal, 2000.

[30] Ouyang Z, Song W, Liu J, Zhu J, Man C, Zhu S, et al. Experimental study on combustion characteristics and NO_x emissions of pulverized anthracite preheated by circulating fluidized bed [J]. Fuel 2021; 294: 120538.

[31] Ouyang Z, Zhu J, Lyu Q. Experimental study on preheating and combustion characteristics of pulverized anthracite coal [J]. Fuel 2013; 113: 122-127.

[32] Ouyang Z, Zhu J, Lyu Q, Wang J, Hou H. Particle characteristics of anthracite powder preheated quickly in circulating fluidized bed. Proceedings of 2013 International Conference on Materials for Renewable Energy and Environment, BeiJing, China 2013: 6.

[33] Ouyang Z, Zhu J, Lyu Q, Yao Y, Liu J. The effect of limestone on SO_2 and NO_x emissions of pulverized coal combustion preheated by circulating fluidized bed [J]. Fuel 2014; 120: 116-121.

[34] Ouyang Z, Liu Wen, Zhu J. Flameless combustion behaviour of preheated pulverized coal [J]. The Canadian Journal of Chemical Engineering 2018; 96(5): 1062-1070.

[35] Zhu J, Ouyang Z, Lyu Q. An experimental study on NO_x emissions in combustion of pulverized coal

ISSN 2616-5880 Vol. 3, Issue 2: 14-24, DOI: 10.25236/AJMC.2022.030203
preheated in a circulating fluidized bed [J]. Energy & Fuels 2013; 27: 7724-7729.
[36] Zhu S, Lyu Q, Zhu J, Wu H, Wu G. Effect of air distribution on NO_x emissions of pulverized coal and char combustion preheated by a circulating fluidized bed [J]. Energy & Fuels 2018; 32(7): 7909-7915.
[37] Zhu S, Lyu Q, Zhu J, Liang C. Experimental study on NO_x emissions of pulverized bituminous coal combustion preheated by a circulating fluidized bed [J]. Journal of the Energy Institute 2019; 92(2): 247-256.
[38] Liu W, Ouyang Z, Cao X, Na Y. Experimental research on flameless combustion with coal preheating technology [J]. Energy & Fuels 2018; 32(6): 7132-7141.
[39] Liu W, Ouyang Z, Song W, Zhu S, Li S. Experimental research on combustion characteristics and NO_x emission of three kinds of solid fuels preheated by a self-preheating burner [J]. Energy & Fuels 2019; 33(9): 8483-8490.
[40] Zhang Y, Zhu J, Lyu Q, Liu J, Pan F. Experimental study on ultra-low NO_x emissions from pulverized coal preheating combustion [J]. Asia-Pacific Journal of Chemical Engineering 2021; 16(1).
[41] Zhang Y, Zhu J, Lyu Q, Liu J, Pan F, Zhang J. The ultra-low NO_x emission characteristics of pulverized coal combustion after high temperature preheating [J]. Fuel 2020; 277: 118050.
[42] Yao Y, Zhu J, Ouyang Z, Lyu Q. Experimental study on nitrogen transformation in combustion of pulverized semi-coke preheated in a circulating fluidized bed [J]. Proceedings of the CSEE 2016; 36(08): 2188-2194.
[43] Yao Y, Zhu J, Lyu Q, Zhou Z. Experimental study on preheated combustion of pulverized semi-coke [J]. Journal of Thermal Science 2015; 24: 370-377.
[44] Liu W, Ouyang Z, Na Y, Cao X, Zhu S. Experimental research on NO emission with coal preheating combustion technology [J]. Asia-Pacific Journal of Chemical Engineering 2020, 15(4).
[45] Liu W, Ouyang Z, Cao X, Na Y, Liu D, Zhu S. Effects of secondary air velocity on NO emission with coal preheating technology [J]. Fuel 2019; 256: 115898.
[46] Liu W, Ouyang Z, Cao X, Na Y. The influence of air-stage method on flameless combustion of coal gasification fly ash with coal self-preheating technology [J]. Fuel 2019; 235: 1368-1376.
[47] Liu W, Ouyang Z, Na Y, Cao X, Liu D, Zhu S. Effects of the tertiary air injection port on semi-coke flameless combustion with coal self-preheating technology [J]. Fuel 2020; 271: 117640.
[48] Ouyang Z, Ding H, Liu W, Cao X, Zhu S. Effect of the primary air ratio on combustion of the fuel preheated in a self-preheating burner [J]. Combustion Science and Technology 2020; 194(6).
[49] Ouyang Z, Ding H, Liu W, Li S, Cao X. Effect of the staged secondary air on NO_x emission of pulverized semi-coke flameless combustion with coal preheating technology [J]. Fuel 2021; 291: 120137.
[50] Ding H, Ouyang Z, Zhang X, Zhu S. The effects of particle size on flameless combustion characteristics and NO_x emissions of semi-coke with coal preheating technology [J]. Fuel 2021; 297: 120758.
[51] Man C, Zhu J, Ouyang Z, Liu J, Lyu Q. Experimental study on combustion characteristics of pulverized coal preheated in a circulating fluidized bed [J]. Fuel Processing Technology 2018; 172: 72-78.
[52] Ouyang Z, Liu W, Man C, Zhu J, Liu J. Experimental study on combustion, flame and NO_x emission of pulverized coal preheated by a preheating burner [J]. Fuel Processing Technology 2018; 179: 197-202.
[53] Zhu S, Zhu J, Lyu Q, Liu J, Ouyang Z. Pilot-scale study on NO emissions from coarse coal combustion preheated by circulating fluidized bed [J]. Fuel 2020; 280: 118563.
[54] Zhu S, Zhu J, Lyu Q, Man C, Ouyang Z, Liu J, et al. Experimental study on weakly caking coal combustion preheated by circulating fluidized bed [J]. Fuel 2021; 295: 120592.
[55] Ouyang Z, Liu W, Zhu J, Liu J, Man C. Experimental research on combustion characteristics of coal gasification fly ash in a combustion chamber with a self-preheating burner [J]. Fuel 2018; 215: 378-385.
[56] Liu J, Liu Y, Zhu J, Ouyang Z, Man C, Zhu S, et al. Bituminous coal deep regulated ultra-low NO_x flameless combustion with fluidized self-preheating fuel: A 2 MWth experimental study [J]. Fuel 2021; 294: 120549.
[57] Ouyang Z, Song W, Li S, Liu J, Ding H. Experiment study on NO_x emission characteristics of the ultra-low volatile fuel in a 2 MW novel pulverized fuel self-sustained preheating combustor [J]. Energy 2020; 209: 118448.
[58] Ouyang Z, Song W, Liu J, Zhu J, Man C, Zhu S, et al. Experimental study on NO_x emissions of pulverized coal combustion preheated by a 2 MW novel self-sustained preheating combustor [J]. Fuel 2021; 294: 120538.
[59] Man C, Gao C, Ouyang Z, Pan Q, Tian J, Liu J, et al. Operation and low NO_x experimental research of a 40 t/h preheating combustion pulverized coal boiler [J].Thermal Power Generation 2021; 50(09):

ISSN 2616-5880 Vol. 3, Issue 2: 14-24, DOI: 10.25236/AJMC.2022.030203

160-166.
[60] Ouyang Z, Man C, Li Z, Li S, Pang Q, Zhu J, et al. Study on operation characteristics of a 35 t/h preheating combustion boiler with pure ultra-low volatile carbon-based fuels [J].Integrated Intelligent Energy 2020; 42(07): 50-56.
[61] Man C, Zhu J, Lyu Q, Ouyang Z, Liu J. Design and operation of a 100 t/d gasification fly ash boiler [J].Clean Coal Technolog 2021; 27(03): 88-93.