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APPLICATION OF DENITRIFICATION TECHNOLOGY IN FLUE GAS TREATMENT OF COAL-FIRED BOILER

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Abstract. In recent years, people have paid more and more attention to environmental protection, and environmental protection standards have become increasingly stringent. The application of denitrification technology in coal-fired boilers is an effective way to reduce nitrogen oxides, and it has also received great attention. There are two main types of denitrification technology: SNCR (selective non-catalytic reduction technology) and SCR (selective catalytic reduction technology). This article focuses on the comparison and current status analysis of the denitrification principles, reductants, and catalysts of SNCR and SCR, and points out the current problems, in order to provide a reference for the future development of SNCR and SCR denitrification technology.

Keywords: coal-fired boiler, flue gases, nitrogen oxides, denitrification technology, catalyst, efficiency.

1. Introduction

With the continuous development of society, people are facing increasing pressure on environmental protection, and they are paying more and more attention to environmental protection. Energy conservation, consumption reduction, and environmental protection are inevitable requirements for achieving sustainable development. As far as the current environmental problems are concerned, nitrogen oxides are one of the important sources of pollution, and their emission limits are becoming more and more stringent. For the flue gas emissions of coal-fired boilers, the denitrification technology can be used to achieve the reduction of nitrogen oxides (NO_X) concentration (Jundong & Jie, 2019).

While extensive research has been conducted on denitrification technologies (SNCR and SCR) in coal-fired boilers, most studies focus on standalone applications or idealized laboratory conditions, with limited discussion on integrated solutions for real-world industrial challenges. This study aims to bridge this gap by providing a comprehensive comparative analysis of SNCR and SCR technologies, emphasizing their practical adaptability in addressing the unique constraints of high-ash flue gas, dynamic boiler loads, and stringent emission standards in China.

2. Materials and methods

In this study, we used literature analysis and other methods to explore SNCR (selective non-catalytic reduction technology) and SCR (selective catalytic reduction technology) in the flue gas denitrification treatment technology of coal-fired boilers, focusing on the comparison and current status analysis of SNCR and SCR denitrification principles, reductants, and catalysts, and pointed out the current problems. The purpose is to provide reference for the future application of denitrification technology in coal-fired boiler exhaust gas treatment.

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3. Traditional flue gas denitrification technology

Denitrification technology is the technology of NO_X reduction in flue gas. At present, with the increasing attention of society to environmental protection, denitrification technology is more and more widely used in many fields, especially in thermal power installations, steel, cement and other industries.

In general, the treatment of NO_X can be achieved through three channels: pre-combustion, during combustion and post-combustion. Pre-combustion NO_X removal technology converts usual fuel into fuel with low nitrogen content before combustion. This technology only exists in research at present, and there are many defects in practical application such as complicated process, difficult technology and high cost. The treatment technology during the combustion is mainly intended to effectively intervene in NO_X generation and control during the fuel combustion process. If you want to control NO_X generation, it is necessary to effectively control the combustion temperature, while reducing the oxygen concentration in the combustion area, and shorten the residence time of the fuel in the high temperature region as much as possible during the combustion process. Post-combustion NO_X removal technology mainly refers to the denitrification of flue gas (Hui et al., 2016).

Flue gas denitrification technology refers to the use of chemical, biological and other engineering technologies to convert NO_X (mainly NO and NO_2) into N_2, so as to achieve the purpose of NO_X emission reduction. At present, the technical measures to control NO_X emission are mainly divided into two categories: source control and tail control. Source control is mainly to control NO_2 generation reaction, such as low nitrogen combustion technology, flue gas recycling technology, etc. The tail control mainly relies on technical means to reduce NO_X due to converting it to N_2, such as SNCR and SCR methods in dry denitrification technology.

Dry flue gas denitrification technology (such as SNCR, SCR, SNCR+SCR combined denitrification technology) is relatively mature in commercialization. The abovementioned three denitrification technologies are widely used in coal and thermal power industries. This paper mainly compares and analyzes the denitrification principle, application status and future development trend.

3.1. SNCR denitrification technology

SNCR denitrification technology utilizes urea, ammonia water, or liquid ammonia as reducing agents within a critical temperature range of 850–1100 °C. Temperatures below 850 °C may result in the release of ammonia, while exceeding 1100 °C promotes oxidation of ammonia to nitrogen oxides. The technology was first applied and patented by Exxon in the United States. In the 1970s, Japan was the first to apply it to oil and gas power plants. With the constant improvement of application experience and technical means, large-scale coal-fired power plants in the European Union began to be commercially put into operation in the late 1980s. China’s first use of SNCR denitrification technology is the new 600 MW supercritical turbine generator set in Xuzhou Kanshan Power Plant in Jiangsu Province, combined with low nitrogen combustion technology. In January 2015, SNCR denitrification technology, the largest generator set in China (2×330 MW), was successfully put into operation in Ordos Junzheng Energy and Chemical Company, which marked the further improvement of SNCR technology in the application scale of China’s generator sets. The relevant technical indicators are shown in in Table 1.

Table 1

Technical indicators of 2×330 MW generator set of Junzheng energy and chemical company

Index	Denitrification efficiency, %	Reductant	Ammonia escape rate, ppm	Ammonia spray rate, $t \cdot h^{-1}$
Numerical value	70	Ammonia liquor	<8	<1

Denitrification reducing agent

The main reducing agent of SNCR is NH_3, and its reaction principle is shown in equation (1)–(3). The source of NH_3 is mainly related to the boiler type, operating conditions and regional policies of the enterprise.

$$4NH_3+4NO+O_2 \rightarrow 4N_2+6H_2O \quad (1)$$

$$2NH_3+NO+NO_2 \rightarrow 2N_2+3H_2O \quad (2)$$

$$8NH_3+6NO_2 \rightarrow 7N_2+12H_2O \quad (3)$$

The denitrification system using ammonia water as reducing agent is mainly composed of ammonia discharge system, conveying system, diluted water system, compressed air system, spray gun system and so on. The operation process of the system is to mix the purchased ammonia water and diluted water into $W(NH_3)$ = 5–10 % dilute ammonia water, which is raised to the pre-furnace spray gun system through the conveying system, and the compressed air system is fully atomized into the furnace temperature area of about 600–900 °C, and react with NO and NO_2 in the flue gas to produce N_2 and H_2O.

The denitrification denitration system using urea as reducing agent is mainly composed of heating system, urea dissolving system, conveying system, diluted water system, compressed air system, metering system, spray gun system, etc. The operation process of the system is to lift solid granular urea to the urea dissolution tank by the crane, and mix the transfer pump with diluted water to generate 8–14 % urea solution, which is sent to the boiler by the conveying system, the compressed air system and the metering system are fully atomized and sprayed into the furnace temperature area of 600–900 °C, and react with NO and NO_2 in the flue gas to produce N_2 and H_2O.

The denitrification system using liquid ammonia as reducing agent mainly consists of liquid ammonia discharge system, liquid ammonia storage system, liquid ammonia evaporation system, gas ammonia dilution system (compressed air system), fire sprinkler system and ammonia area waste water discharge system. The operation process of the system is that the liquid ammonia discharge compressor will input the liquid ammonia into the ammonia storage tank by the tank truck, and the liquid ammonia in the ammonia storage tank will be transported to the liquid ammonia evaporation tank to evaporate into ammonia gas, and the ammonia pressure and flow rate will be controlled through the ammonia buffer tank (similar to the metering system), and then fully mixed with the compressed air system in the mixer, and then delivered to the SNCR denitrification system. To achieve the purpose of removing NO_X in flue gas.

The above three denitrification reducing agents can reduce the emission concentration of NO_X in the flue gas, and their commercialization is relatively mature, and they all need to fully atomize the NH_3 generation source through the spray gun, and then spray into the corresponding temperature area in the furnace. The difference lies in the NH_3 generation source and corresponding supporting facilities (Hui, 2016). Table 2 describes the quantity, efficiency, reliability and safety of the three denitrification reducing agents.

Table 2

Analysis and comparison of characteristics of three denitrification reducing agents

Reductant	Main equipment	Denitrification efficiency	System reliability	System security
1	2	3	4	5
Ammonia liquor	Ammonia discharge pump and other supporting facilities, centrifugal pump (ammonia supply pump), air compressor, compressed air tank, metering and distribution facilities, spray gun, etc	70–80 % denitrification efficiency is related to the ammonia spray point, in the temperature range of 800–900 °C, the reaction effect is the best, the flue gas residence time is above 0.5 s, to ensure the effective denitrification reaction time.	The system with ammonia water as reducing agent has fewer equipment, fewer control points and higher reliability	Ammonia has no explosive performance, the leaked ammonia is harmful to human body, and the safety is high
Urea	Lifts, centrifugal pumps (urea pumps), air compressors, compressed air tanks, heating motors, metering and distribution facilities, spray guns, etc	70–75 % urea solution is not a direct reactant, and some by-products will be generated during the pyrolysis process, which is less efficient than ammonia water	Urea as a reducing agent system equipment is the most, the control system is more complex, the reliability is poor	Urea is non-toxic and harmless, and does not have explosive properties, and the highest safety. It is often used in situations with high safety requirements, such as central heating boiler denitrification system

Continuation of Table 2

1	2	3	4	5
Liquid ammonia	Liquid ammonia discharge equipment, ammonia storage tanks, spray facilities, air compressors, compressed air tanks, metering and distribution facilities, spray guns, etc	More than 80 % liquid ammonia, as a high concentration of ammonia-free water, produces a relatively high concentration of NH_3, and its denitrification efficiency is higher than that of ammonia and urea	Compared with ammonia, the system of liquid ammonia as a reducing agent needs at least one more evaporator, spray system, and usually needs to be equipped with a fan that provides diluted air, and reliability is second	Liquid ammonia is dangerous goods, low concentration of ammonia has a stimulating effect on mucous membranes, high concentration of ammonia will cause damage to human tissues, the concentration of 16–25 %, in case of open fire will burn and explosive. Secondly, the transportation and storage of liquid ammonia have certain risks

Research and application status of SNCR denitrification technology

In recent years, with the improvement of atmospheric pollutant emission standards in various regions, some SNCR denitrification facilities set separately cannot guarantee the emission of flue gas to meet the standards, and technical transformation is needed to increase the efficiency of SNCR denitrification. Otherwise, the combination with other denitrifycation processes is needed: e. g., adjust combustion, improve urea dissolution and pyrolysis efficiency, and select the appropriate ammonia-nitrogen ratio. Denitrification is combined with low nitrogen combustion technology and flue gas recirculation technology. The following case studies can increase the denitrification efficiency to some extent, and can provide reference for some enterprises' denitrification transformation and actual operation.

When the combustion load of the boiler increases and the denitrification efficiency decreases, the flue gas temperature in the upper screen area of the furnace can be increased by 12 °C by adjusting the combustion, so as to eliminate the adverse effects on the steam temperature caused by the operation of the SNCR denitrification device (Ruijing, 2024). Meng Hongjun et al. made the urea solution enter the reaction chamber reciprocally by increasing the transmission actions such as stirring rod, transmission belt, belt pulley and push rod, and at the same time, the cooling equipment was equipped to cycle the device and reduce the reaction heat. This improved method not only reduced the input of urea solution, but also reduced the occurrence of ammonia escape (Hongjun et al., 2021). Anichkov S. N. the possibility of improving the technical and economic indicators of SNCR devices by multi-zone injection of reducing mixtures into the gas to be purified at less than stoichiometric flow rates has been demonstrated, which makes it possible to achieve high technical efficiency (Anichkov et al., 2021). Through CKM&CFD simulation, Chen Haijie concluded that high-efficiency SNCR technology has low overall investment cost and denitrification efficiency of 38–75 %, which can not only be successfully applied to W-type flame furnaces of large units, but also serve as the best joint means of ultra-low emission for large units of other furnace types (Haijie, 2016).

3.2. SCR denitrification technology

SCR denitration technology is to use urea, ammonia water, liquid ammonia as reducing agents, supplemented by catalysts, at the reaction temperature of 290–400 °C, NOx is reduced to N_2. In 1950, American Eegelhard Company first proposed SCR and applied for invention patent in 1959. SCR denitrification technology was first applied in Japan and Western Europe, with the maturity of technology, Japan took the lead in 1979 to realize the commercial operation of SCR denitrification technology, Germany, the United States also began the industrial development of SCR denitrification technology in 1984 and 1993. In 1999, China introduced SCR denitrification technology for the first time, mainly used in thermal power industry flue gas treatment, followed by 10 years of continuous promotion and popularization, from the power, thermal industry gradually shifted to non-power industries, such as cement, steel, etc., SCR catalyst from high temperature to low temperature, ultra-low temperature research.

SCR denitrification catalyst

In order to ensure the NO_X emission concentration reaches the standard, SCR denitrifycation technology is often combined with SNCR denitrification technology. The difference between SCR and SNCR is that the denitrification catalyst is increased and the reaction temperature is reduced. As the core component of SCR system, catalyst should be arranged separately in the reactor. The catalyst can be divided into honeycomb, plate and corrugated plate according to the type. This paper mainly introduces the catalyst with V_2O_5 as the active component and TiO_2 as the carrier.

The honeycomb catalysts are generally homogeneous catalysts, with a market share of more than 60 %, and are widely used, especially in the coal power industry. The molding method is mainly extrusion type and coating type, and the catalyst module size can be adjusted according to the needs of the owner. During the molding process, the active component of the catalyst (V_2O_5) is dispersed in the whole carrier (matrix WO_3/TiO_2), so the honeycomb catalyst has a long service cycle and good wear resistance.

The plate catalyst is generally made of stainless steel metal mesh as the substrate, the active components (WO_3, V_2O_5) are uniformly adhered to the stainless steel mesh, and the catalyst module is assembled after pressing, forging and other forming processes. The market share is about 30 %. Because the plate catalyst is made of stainless steel mesh as the structural skeleton, it has a certain mechanical strength, and will not cause the overall or partial collapse of the catalyst, ensuring the safety and stability of the denitrification catalyst operation.

The corrugated plate catalyst generally uses TiO_2 (including glass fiber) as the substrate, and the active ingredients such as WO_3 and V_2O_5 are uniformly impregnated onto the catalyst surface to improve the catalyst activity and reduce the oxidation rate of SO_2. Due to the use of new carrier materials, its overall density is lower than the honeycomb, plate catalyst, for the flue gas with a large amount of fly ash, it is easy to cause blockage, which is not conducive to safe and stable operation, so the market share is less than 10 %.

The above three types of catalysts can meet the requirements of flue gas SCR denitrification, and their commercial applications are different due to the difference in forming method, application scope and structure. The characteristics and application range of the three catalysts are compared in Table 3.

Table 3

Comparison of the characteristics of three catalysts

Catalyst type	Formed structure	Process characteristics		Applicable flue gas condition	Optimum temperature range	Denitrification efficiency	Market share
		Advantage	Shortcoming				
Honeycomb catalyst	Extrusion, coating molding, honeycomb carrier, circulation area of about 80 %	Large contact surface, long life, wear resistance, easy regeneration	High density, not easy to disassemble	Suitable for various flue gas conditions	300–400 °C	90–95 %	> 60 %
Plate catalyst	The stainless steel mesh is used as the catalyst module carrier, the surface is coated with the carrier and active components, and the flow area is about 85 %	Stainless steel net, easy to disassemble, easy to regenerate	Low life, poor wear resistance	Clean flue gas	280–400 °C	88–94 %	About 30 %
Corrugated plate catalyst	The corrugated ceramic / fiberglass board is the carrier, the surface is loaded with active components, and the flow area is about 85 %	The density is small and the contact surface is medium	Easy to accumulate dust and clog	Clean (low dust content) smoke	250–400 °C	85–92 %	< 10 %

Research and application status of SCR denitrification technology

With the continuous advancement of the national ecological civilization construction, the emission standards of atmospheric pollutants are becoming more and more stringent. NO_X, as one of the binding indicators, undoubtedly puts forward higher requirements for the existing out-of-stock technology. SCR technology has the advantages of high denitrification efficiency, no secondary pollution, and wide application range, and is an important technology to control NO_X content in the future. SCR denitrification catalyst is the core of SCR system, which not only influences the denitrification efficiency, but also controls the construction cost of SCR system. Therefore, the research of universities and scientific research institutes mainly focuses on the development of new catalysts, the improvement of existing catalysts, such as catalyst deactivation research, catalyst additive research and so on. Table 4 lists the modification or experimental improvements of catalysts with V_2O_5 as the active component and TiO_2 as the carrier conducted by experts and scholars in recent years. This provides theoretical basis and laboratory data support for improving the denitrification efficiency of SCR, and also provides reference for the commercial application of the improved catalyst.

Table 4

List of experimental studies on improvement of vanadium and titanium catalysts

Catalyst	Active ingredient carrier	Additive	Catalyst forming method	Results		References
				Advantages	Disadvantages	
1	2	3	4	5	6	7
V-Mo	TiO_2	Fe_2O_3	Impreg nation method	Improve the reduction performance and acidity of the catalyst	Poisoning the catalyst	(Li et al., 2021)
		Cr_2O_3	Impreg-nation method	The pore structure of catalyst has little effect	With more surface acid content, reducing denitrification efficiency	(Li et al., 2021)
		Sn	Blending pyrolysis method	It has higher reducing performance, acidic energy, denitrification activity, mercury oxidation efficiency and more chemisorbed oxygen content	/	(Yuhao et al., 2021)
		Zn	Impreg-nation method	A suitable H_2SO_4 solution can remove the loaded Zn	The catalyst performance of denitrification catalyst is reduced	(Yuhao et al., 2020)
		Nb	Impreg-nation method	It can effectively inhibit the acidity and reducibility of catalyst caused by Na poisoning, and improve the denitrification performance	/	(Li et al., 2020)
		Silica sol	Impreg-nation method	Improve the wear resistance of the catalyst, increase the specific surface area of the catalyst, and promote the dispersion of active components	The reducing and acidic properties of the catalyst were reduced	(Li et al., 2020)
V_2O_5	TiO_2	Br	Sol-gel method, impreg nation method	At the reaction temperature of 120–240 °C, VTiBr2.0 catalyst has the best activity and has anti-sulfur activity	/	(Yupeng et al., 2021)

Continuation of Table 4

1	2	3	4	5	6	7
V_2O_5/ WO_3	TiO_2	NiO $NiTiO_3$	Coprecipitation	/	Ni component infiltrates into V_2O_5–WO_3/TiO_2 catalyst in an improper way and has toxic effect on it	(Chunlin et al., 2018)
		CuO	Sol-gel method and impregnation method	Improve the performance of denitrification catalyst	/	(Haiyan et al., 2020)
		Ce	Coating method	The denitrification activity is significantly increased at the medium and low temperature of 180–260 °C, and the active temperature window is obviously widened	/	(Mengmeng et al., 2019)
		K and As	Vapor deposition and wet impregnation	When potassium and arsenic coexist, the degree of deactivation of the catalyst shows an "enhanced effect"	When potassium ion exists alone, the denitrification activity of catalyst decreases	(Ming, 2018)
V_2O_5	TiO_2-SiO_2	NH_4VO_3 and HPMC	Drip glue coating method	The catalyst performance of denitrification catalyst was improved and the consumption of vanadium was reduced	/	(Chunhui et al., 2021)

4. Problems in boiler flue gas denitrification technology

SNCR and SCR denitrification technologies have become the most mature and reliable clean production technologies in the coal-fired power industry. As China continues to improve its NO_X emission targets, investment in denitrification equipment will reach a peak. However, in China, there are still few denitrification technologies with independent intellecttual property rights, and most research results are still in the laboratory stage. This is the biggest challenge facing the development of China's denitrification technology.

The efficiency of SNCR denitrification technology is related to the generation of NH_3 and the atomization effect of flue gas. The control process has a low degree of automation, many interference factors, and is limited by technical and operating conditions. There are few boiler temperature measurement points. When adjusting the boiler load, it is impossible to obtain the changes in the temperature field inside the boiler, which will reduce the denitrification efficiency. The most common reasons of NO_X exceeding the standard are the following. One is that the urea solution concentration, spray gun air pressure and flow rate are all adjusted based on experience, resulting in an instantaneous excess of NO_X concentration. The second is that local high temperature may occur (Ling, 2015), resulting in high NO_X concentration. In the denitrification system using urea as the reducing agent, the boiler spray gun air pressure and flow rate need to be manually adjusted, and the system composition is complex, with many control points, which reduces reliability. The spray gun nozzles produced in China still lag behind those of other countries in structure, high temperature resistance, and injection effect.

The efficiency of SCR denitrification technology is closely related to the catalyst. At present, China still does not have the property rights of vanadium-titanium catalysts that are widely used in the coal-fired power industry. This not only increases the investment costs of enterprises, but also makes it unclear whether their applicability meets the needs of the Chinese industry. Secondly, some scholars have developed SCR denitrification catalysts with independent intellectual property rights, such as Shanghai's domestically produced Yakilong plate catalysts. However, in the face of the sharply increasing market demand for denitrification catalysts, the gap is still large (Yingli, et al., 2019). Waste vanadium-titanium catalysts are hazardous wastes that are toxic to the environment and human body. They should be scientifically handled and disposed of in accordance with relevant laws and regulations, which invisibly increases the production costs of enterprises.

5. Conclusions

The application of denitrification technology in coal-fired boiler flue gas treatment remains a critical pathway for reducing NO_X emissions, especially as environmental regulations become increasingly stringent worldwide. This study systematically compared SNCR and SCR technologies, focusing on their principles, reductants, catalysts, and operational challenges. The main findings are summarized as follows: (1) SNCR Technology operates within a narrow temperature range (850–1100 °C) and achieves 70–80 % efficiency under optimal conditions (e. g., ammonia spray rate control, residence time >0.5 s). SCR Technology demonstrates higher efficiency at lower temperatures (290–400 °C) but relies heavily on catalyst performance.

As the control standards for gaseous pollutants in various countries around the world will become increasingly stringent, in response to the needs of clean production of coal-fired boilers, the development of flue gas denitrification technology for coal-fired boilers in the future will still be dominated by SNCR and SCR technologies, and innovations need to be made in the following aspects:

SNCR denitrification technology cannot meet the increasingly stringent emission standards. In addition to low-nitrogen combustion technology and flue gas recirculation technology, other combined denitrification technologies should be developed;

SCR denitrification technology has the advantages of high efficiency and wide application range. Denitrification catalysts with independent intellectual property rights should be gradually developed to break the monopoly technology. At the same time, it is necessary to accelerate the research on catalyst regeneration technology to reduce the production costs;

Experts and researchers have conducted a lot of research on the catalysts improvement, but most of them are in the laboratory stage and cannot meet the needs of the denitrification catalyst market. The transformation of experimental results should be accelerated to allow highly efficient improved catalysts to go out of the laboratory and realize comercial operation;

The development of non-toxic and non-polluting catalysts can not only avoid secondary environmental pollution, but also save the expenses for waste vanadium and titanium catalysts disposing.

In conclusion, while SNCR and SCR technologies are mature, their sustainable application requires addressing technical limitations (e. g., temperature sensitivity, catalyst lifespan) and aligning with circular economy principles (e. g., waste catalyst recycling).

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