

Key Technologies and Application Practices of High-Temperature and High-Dust SCR Denitrification for Cement Kilns

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Abstract

Under increasingly stringent national environmental protection policies, ultra-low emission renovation has become an inevitable trend for nitrogen reduction and pollution control in the cement industry. SCR denitrification technology features high efficiency and can achieve ultra-low NO_x emission (≤ 50 mg/m³). However, cement kiln flue gas with high temperature, high dust and high alkali metals brings severe challenges to the stable operation of SCR systems. This paper discusses key technologies and engineering practices of high-temperature and high-dust SCR denitrification for cement kilns. It analyzes core problems including catalyst clogging, abrasion, poisoning and flow field imbalance, and proposes targeted solutions such as customized catalyst design, CFD simulation optimization, combined soot blowing and intelligent control. A 5000 t/d cement production line case shows that after renovation, NO_x emission is stably below 35 mg/m³, ammonia slip is less than 2.5 ppm, and system resistance is below 800 Pa, realizing long-term stable and economic ultra-low emission operation.

Keywords

cement kiln, SCR denitrification, ultra-low emission, high temperature and high dust, CFD simulation

1. Introduction

Global atmospheric pollution has always been a key concern internationally. Since the Industrial Revolution, the burning of fossil fuels, industrial emissions, and vehicle exhaust have led to a continuous increase in the concentration of pollutants such as nitrogen oxides (NO_x) and sulfur dioxide in the atmosphere, causing acid rain, photochemical smog, and fine particulate matter (PM_{2.5}) pollution. This results in millions of premature deaths worldwide every year, with the pollution situation being particularly severe in developing countries due to their biased industrial structure and weak governance capabilities.

In recent years, China has made remarkable achievements in air pollution control. As an important precursor of PM_{2.5} and ozone formation, nitrogen oxides (NO_x) still face huge pressure for emission reduction. The cement industry is the third largest NO_x emission source after power and steel industries, with annual emissions exceeding one million tons [1]. The Ministry of Ecology and Environment and relevant authorities have issued the Emission Standard of Air Pollutants for Cement Industry (GB 4915) and stricter

local standards, driving NO_x emission concentration in the cement industry to drop gradually from 800 mg/m³ and 400 mg/m³ to below 100 mg/m³, and finally toward the ultra-low emission target (≤ 50 mg/m³) [2].

At present, mainstream denitrification technologies for cement kilns include low NO_x burner (LNB), staged combustion (SC), selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR). SNCR is widely used due to low investment and operation costs, but its efficiency is only 40%–60% with high ammonia slip, making it difficult to meet ultra-low emission standards independently [3]. SCR technology reduces NO_x to N₂ and H₂O with ammonia as the reducing agent under catalyst action, with efficiency over 90%, which is the most effective route for ultra-low NO_x emission.

Flue gas at the outlet of cement kiln preheaters shows typical characteristics of “three highs and one fluctuation”: high temperature (300–380°C), high dust concentration (up to 100 g/Nm³), high NO_x concentration (300–1300 mg/m³) and large working condition fluctuation [5, 6]. These features make the application of SCR in cement kilns face unprecedented difficulties. The design and renovation of high-temperature and high-dust SCR systems require all-round customization and key technical breakthroughs.

2. Challenges in Implementing SCR in Cement Kilns

2.1 Catalyst Clogging and Abrasion

High-concentration and high-hardness dust at the kiln tail physically covers the catalyst surface and blocks pores, resulting in activity failure and rapid increase of system resistance [7]. High-speed airflow scouring also causes severe mechanical abrasion.

2.2 Catalyst Poisoning and Deactivation

Alkali metals (K, Na), alkaline earth metals (Ca) and heavy metals (As) in flue gas react with active components of the catalyst (V₂O₅-WO₃/TiO₂), covering active sites and permanently reducing catalytic activity.

2.3 Uneven Flow Field and Concentration Field

Fluctuating kiln conditions lead to uneven velocity distribution and mismatched NO_x/NH₃ concentration at the reactor inlet, causing local abrasion, ash accumulation, increased ammonia slip and reduced denitrification efficiency.

2.4 Ammonia Slip and Secondary Pollution

Excessive ammonia slip causes waste of reducing agent and generates ammonium bisulfate, which blocks and corrodes downstream equipment and shortens the service life of bag filters.

3. Key Technologies for Ultra-Low Emission Transformation

3.1 Selection of SCR Reactor Layout Scheme

There are three main layout schemes of SCR reactors in the cement process system:

- 1) High-temperature and high-dust layout (the key point of this paper): The SCR reactor is arranged between the preheater outlet and the waste heat boiler. It has the advantages of small floor area, only considering SCR occupation, no need for additional heating, relatively low investment and operation costs, and the flue gas temperature (300~380°C) is the most suitable activity window for standard vanadium-titanium catalysts [8]. The disadvantage is high dust content, which has high requirements for catalysts, soot blowers and anti-clogging design. This scheme is the mainstream option for current cement SCR transformation (See Figure 1).
- 2) High-temperature and medium-dust layout: On the basis of high-temperature and high-dust layout, a set of high-temperature electrostatic precipitator is added to reduce the dust concentration in flue gas to below 30 g/Nm³. Its advantage is reduced dust content, which is friendly to catalyst clogging and

abrasion and can prolong its service life. The disadvantages are large floor area, high cost, the body resistance of electrostatic precipitator is about 250 Pa, increasing system resistance, the power consumption of electrostatic precipitator is about 80 kW·h, and there are requirements for CO concentration in flue gas; the flue gas flow rate of electrostatic precipitator is low with temperature loss, which will cause power generation loss to waste heat power generation and high operation costs (See Figure 2).

- 3) High-temperature and low-dust layout: On the basis of high-temperature and high-dust layout, a set of high-temperature metal bag filter is added before SCR. After dust treatment by metal filter bags, the dust concentration is reduced to 10 mg/Nm³, and the temperature is still maintained above 300°C. The advantage is that it completely solves the problems of catalyst abrasion, clogging and poisoning, prolongs the service life, reduces the catalyst filling volume and the energy consumption of soot blowers. The disadvantage is extremely high construction investment, large area and large temperature loss, reducing power generation (See Figure 3).

Figure 1: Layout under high temperature and high dust conditions

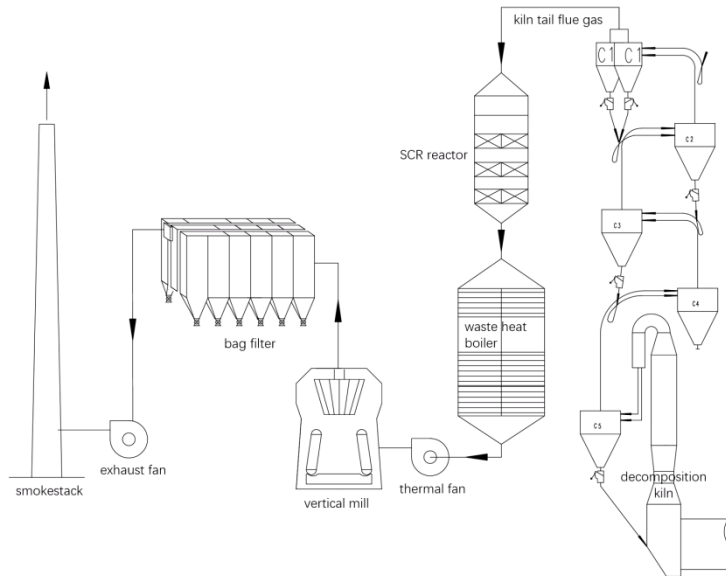


Figure 2: High-temperature dust layout

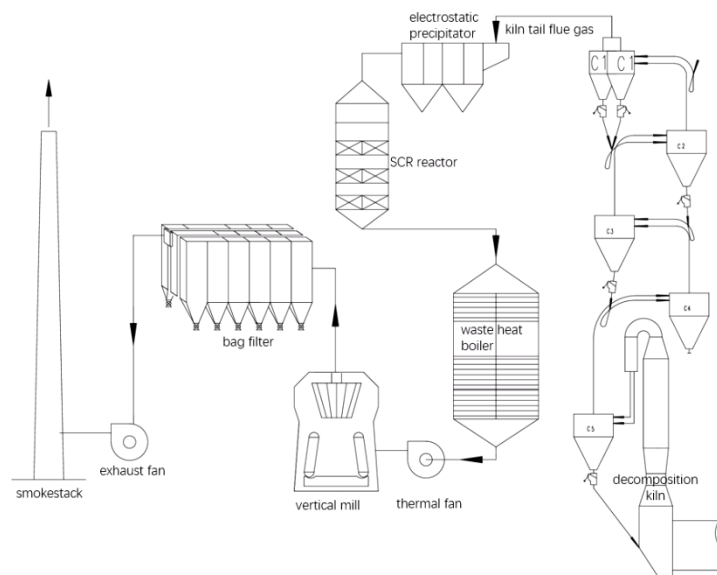
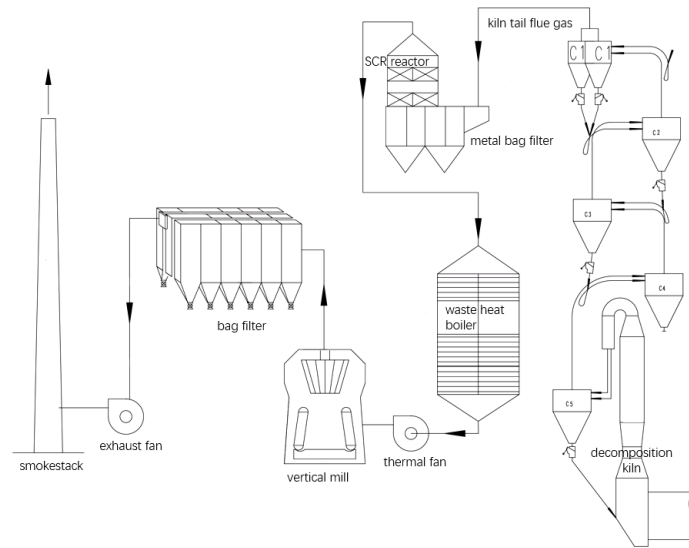


Figure 3: Layout under High Temperature and Low Dust Conditions



Comprehensive comparison shows that its economic and technical feasibility makes it the first choice after engineering implementation. Although the high-temperature and high-dust scheme faces great challenges, the core of transformation is how to solve the problems caused by high dust. Detailed data are shown in Table 1.

Table 1: Comparison of Technical Scheme Indicators

| Description | Scheme 1 | Scheme 2 | Scheme 3 |
|---------------------------------------|---|--|--|
| Process Route | High-temperature and high-dust | High-temperature electrostatic precipitator + SCR | Metal bag filter + SCR |
| Treatment Method | SCR | High-temperature electrostatic precipitator + SCR | Metal bag filter + SCR |
| Layout Location | C1 outlet | C1 outlet | C1 outlet |
| Dust concentration at C1 outlet | 80~120 g/Nm ³ | 80~120 g/Nm ³ | 80~120 g/Nm ³ |
| Dust received by catalyst | 80~120 g/Nm ³ | 50 g/Nm ³ | 10 mg/Nm ³ |
| Flue gas temperature | 290 ~310°C | 290 ~310°C | 290 ~310°C |
| Denitrification efficiency | About 95% | About 95% | About 95% |
| Catalyst service life | 2 years, add the fourth layer after 2 years of operation, then replace one layer every 1 year | 2 years | >3 years |
| Catalyst usage | ~250 m ³ | ~230 m ³ | ~90 m ³ |
| SCR system floor area | 12×12 m | 19×16 m | 20×10 m |
| Increased system resistance of SCR | 800 Pa | 1500 Pa | 1600 Pa |
| Temperature drop of SCR system | 7 ~10°C | 10 ~15°C | 7 ~10°C |
| Impact on waste heat power generation | -200 kW·h | -270 kW·h | -230 kW·h |
| Installed power of SCR system | 410 kW | About 510 kW | 130 kW |
| Substances affecting catalyst | Dust, alkali metals | Dust | Dust |
| Impact on system fan | Transform high-temperature fan, increase 1000 Pa wind pressure | Transform high-temperature fan, increase 1700 Pa wind pressure | Transform high-temperature fan, increase 1800 Pa wind pressure |
| Investment cost (ten thousand yuan) | About 2100 | About 2500 | About 3300 |

3.2 Selection and Design of High-Performance Catalysts

The catalyst is the “heart” of the SCR system. For cement kiln working conditions, special catalysts must be customized and developed.

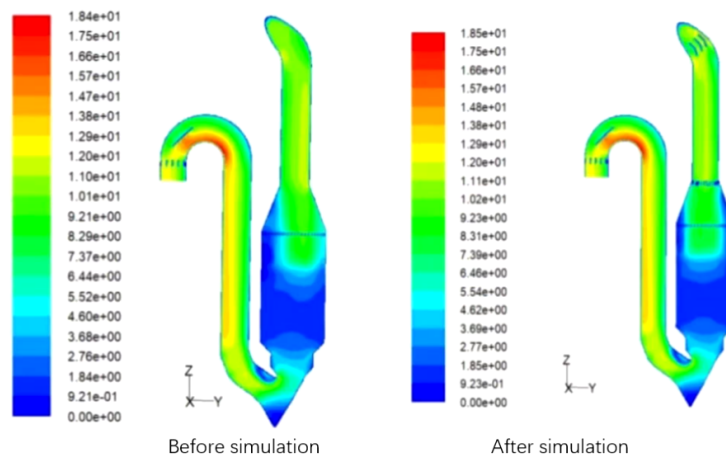
- 1) Measures can be taken to increase the spacing to effectively reduce the risk of ash clogging. Specifically, select catalysts with larger pore sizes, increase the plate spacing, and ensure the pitch is not less than 7 mm. A variety of pitch structures such as large top and small bottom can also be innovatively designed.
- 2) Adjust the catalyst type: compared with honeycomb catalysts, the selection of plate catalysts can more effectively reduce the risk of ash clogging.
- 3) To enhance wear resistance, various effective measures can be taken, such as thickening the catalyst wall thickness, or coating wear-resistant coatings on the windward side, such as ceramics, silicon carbide and other materials, which can greatly improve its mechanical strength and erosion resistance.
- 4) Optimize the active formula: adjust the proportion of active components such as V_2O_5 , WO_3 , MoO_3 to enhance the catalyst's resistance to alkali metal poisoning (alkali/calcium resistance) and prolong the chemical service life.
- 5) Modular design: adopt “building block” modular installation, which is convenient for layered hoisting and replacement in the future, and can configure different characteristics of catalysts in different areas of the reactor (such as upper and lower layers, windward and leeward sides) to achieve optimal configuration under working conditions.

3.3 Optimal Design Based on CFD Numerical Simulation

In the engineering design stage, to ensure system performance, CFD numerical simulation technology should be adopted to conduct a comprehensive and accurate simulation analysis of the flow field from the flue inlet to the SCR reactor outlet, and carry out optimal design accordingly [9] (See Figure 4).

- 1) Scientifically plan and install guide plates, rectifying grids and other facilities in the flue to homogenize the flow field, which can be realized by simulation. In this way, the air speed at the inlet section of the reactor can be effectively controlled, so that its relative standard deviation does not exceed 15%, and as close as possible to the target value of 10%.
- 2) Concentration field homogenization and AIG optimization: establish sufficient mixing distance upstream of AIG, optimize the ammonia injection distribution of each nozzle of AIG through simulation, so that the ammonia-nitrogen ratio distribution reaches a relative standard deviation of 5%, and control ammonia slip from the source.
- 3) Optimize the internal structure of the flue and reactor to avoid dead zones and low flow velocity areas of flue gas, and prevent ash accumulation in ash hoppers, catalyst module tops, reactor corners and other parts.

Figure 4: Comparison of Flow Field Before and After Simulation

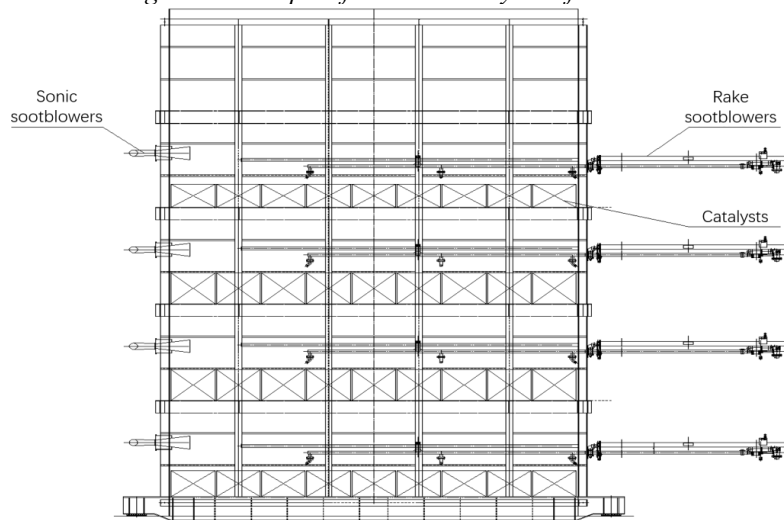


3.4 High-Efficiency Ash Cleaning System

A strong and reliable soot blowing system is a necessary condition for the long-term stable operation of the SCR system. For high-dust working conditions, a combination of rake soot blowing and sonic soot blowing is generally adopted (See Figure 5).

- 1) Rake soot blowing: low-pressure and high-flow ash cleaning with strong purging force, achieving thorough ash removal effect, especially for the dense ash layer accumulated on the catalyst surface. In this case, a heated air source needs to be configured, and improper operation may cause thermal shock or physical damage to the catalyst.
- 2) Sonic soot blowing: use sound wave energy to vibrate and break dust particles that are difficult to adhere to the surface, achieving a “precautionary” ash cleaning effect. Its advantages are wide action range, no dead ends in soot blowing, no damage to the catalyst, and low energy consumption. The disadvantage is limited ash removal capacity for hardened hard ash. In actual operation, sonic soot blowing should operate continuously or at high frequency to prevent ash accumulation.

Figure 5: Example of Combined Layout of Soot Blowers



3.5 Intelligent Control System

Aiming at kiln condition fluctuations, an advanced intelligent control system needs to be designed.

- 1) Predict the change trend of NO_x concentration according to the data of high-temperature analyzer at the kiln tail, such as flow rate, NO_x concentration and O_2 content, adjust the ammonia injection amount in advance, and then conduct precise fine-tuning according to the feedback signal of NO_x concentration at the reactor outlet to improve the response speed and accuracy of ammonia injection control [10].
- 2) Closed-loop control of ammonia slip: install an on-line ammonia slip monitor at the reactor outlet, introduce its signal into the control system as a constraint condition for ammonia injection amount, and prioritize controlling ammonia slip within a safe range.
- 3) Ammonia injection optimization system: dynamically adjust the valve opening of each zone of AIG according to the multi-point NO_x and NH_3 concentration distribution at the reactor outlet section, realizing refined and balanced control of ammonia injection.

4. Engineering Practice Case

4.1 Project Overview

Taking the ultra-low emission transformation project of a 5000 t/d new dry-process cement production line in China as an example. The original SNCR denitrification was adopted, with NO_x emission

concentration of about 180-250 mg/m³. To meet the ultra-low emission requirement of ≤ 50 mg/m³, it was decided to add a high-temperature and high-dust SCR denitrification system after the C1 outlet of the preheater (See Table 2).

Table 2: Production Line Data Sheet

| No. | Name | Parameter | Unit |
|-----|---|------------|--------------------|
| 1 | Output | 5000 | t/d |
| 2 | Flue gas volume | 450000 | Nm ³ /h |
| 3 | O ₂ content at C1 outlet | 2~3 | % |
| 4 | Temperature at C1 outlet | 300~320 | °C |
| 5 | Flue gas temperature at waste heat boiler outlet | 230~240 | °C |
| 6 | Dust concentration | 100 | g/Nm ³ |
| 7 | Initial NO _x concentration | 250 | mg/Nm ³ |
| 8 | Ammonia water concentration | 20 | % |
| 9 | NO _x emission concentration at kiln tail chimney | ≤ 50 | mg/Nm ³ |
| 10 | Ammonia slip at kiln tail chimney | ≤ 3 | mg/Nm ³ |
| 11 | 20% ammonia water consumption | ≤ 3.5 | Kg/t.cl |

4.2 Main Technical Transformation Contents

- 1) Process flow: flue gas from C1 preheater outlet → newly added SCR reactor (including ammonia injection grid, CFD optimized diversion system) → SP boiler and original subsequent system.
- 2) Catalyst: adopt 3+1 layer layout, the upper layer is anti-clogging and wear-resistant catalyst with a pitch of 8.0 mm, the middle and lower layers are high-activity anti-poisoning catalysts with a pitch of 7.0 mm. The designed chemical service life of the catalyst is ≥ 24000 hours.
- 3) Soot blowing system: 6 sonic soot blowers are densely arranged above each layer of catalyst, and rake soot blowers are also installed.
- 4) Control system: adopt DCS integrated control technology, integrate PID algorithm optimization control, and plan in advance to reserve relevant interfaces for ammonia slip meter and precise ammonia injection system.

4.3 Operation Effect Analysis

Since the system was put into operation in 2023, it has operated stably with excellent performance (See Figure 6):

- 1) Emission indicators: under normal operating conditions of the kiln system, the NO_x concentration at the SCR outlet is stably controlled at 20-35 mg/m³, far lower than the committed value of 50 mg/m³, and the ammonia leakage concentration is stable at 1.5-2.5 ppm.
- 2) System resistance: through CFD optimization and effective soot blowing, the overall pressure drop of the system is stable at 650-750 Pa without obvious increase.
- 3) Economy: although the power consumption and soot blowing energy consumption have increased, compared with the SNCR stage, the ammonia water consumption per ton of clinker has been reduced by about 35%, and the overall operation cost increase is within a controllable range.

5. Conclusion

Combining theoretical analysis and engineering practice, this paper discusses the key technical paths of implementing cement kiln SCR ultra-low emission transformation under high-temperature and high-dust conditions. Practice proves that:

- 1) The high-temperature and high-dust layout scheme is the practical optimal choice under current technical and economic conditions, and its successful implementation depends on the systematic solution of the “high-dust” problem.

- 2) Customized high-performance catalysts, precise CFD flow field design and efficient and reliable soot blowing system are the three core technical pillars to ensure the long-term, stable and efficient operation of the SCR system.
- 3) Facing working condition fluctuations, the intelligent control strategy plays a key role, which can achieve the coordination of ultra-low emission and low ammonia slip, and effectively reduce the overall operation cost.

Looking forward, cement SCR technology will still develop towards a more intelligent direction. SCR technology has broad application prospects. New low-temperature catalysts, catalysts with stronger performance, and the application of artificial intelligence and big data analysis in operation optimization and fault prediction and maintenance will be the focus of future technology research and development.

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Conflicts of Interest

The authors declare no conflict of interest.

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