Technical White Paper on Industrial Exhaust Gas Purification Catalysts

Industrial exhaust gas purification catalysts are core materials in VOCs treatment, nitrogen oxide (NO_x) reduction, carbon monoxide (CO) purification, and other environmental protection fields. By lowering the reaction activation energy, they efficiently convert pollutants into harmless substances (CO$\square$, H$\square$O, N$\square$) at low temperatures, serving as a key technological foundation for compliant industrial exhaust emission, energy saving, carbon reduction, and green production. As the “dual carbon” goals advance, the Law on Prevention and Control of Atmospheric Pollution is strictly enforced, and industrial VOCs treatment undergoes comprehensive upgrading; catalyst performance directly determines treatment efficiency, operating costs, and environmental compliance.

This white paper systematically presents the catalytic principles, material systems, core performance indicators, preparation processes, product forms, selection logic, application scenarios, operation & maintenance standards, and technology trends of industrial exhaust gas purification catalysts. It incorporates national standards such as GB/T 34701-2017 Engineering Technical Specifications for Industrial Organic Exhaust Treatment by Catalytic Combustion and HJ 1091-2020 Determination of Volatile Organic Compounds in Fixed Pollution Source Exhaust Gas, providing professional, accurate, and practical technical references for enterprises in catalyst selection, system design, environmental compliance, and cost optimization, helping enterprises achieve efficient treatment, stable operation, and cost reduction.

I. Catalytic Principles and Core Value

1. Catalytic Reaction Mechanism

Industrial exhaust gas purification catalysts achieve efficient pollutant purification through three core mechanisms: adsorption – activation – oxidation (reduction):

Adsorption Activation: Active sites on the catalyst surface adsorb pollutant molecules such as VOCs, NO_x, and CO from the exhaust gas, weakening their chemical bonds and reducing the reaction activation energy;

Catalytic Reaction: In the presence of oxygen, pollutants undergo deep oxidation (VOCs→CO$_2$+H$_2$O, CO→CO$_2$) or selective catalytic reduction (NO_x→N$_2$+H$_2$O) on the catalyst surface;

Product Desorption: Harmless reaction products desorb from the catalyst surface; the catalyst regains its activity and continues to participate in the reaction.

Compared with traditional direct combustion (600–800°C) and adsorption concentration (prone to saturation and secondary pollution), the core advantages of catalytic purification are low-temperature high-efficiency, energy-saving, zero secondary pollution, and long-term stability.

2. Core Value

Low-Temperature High-Efficiency: Ignition temperature 200–350°C; saves 40%–60% energy vs. direct combustion; VOCs removal rate ≥95%;Environmental Safety: No open flame; no secondary pollutants such as NO_x or dioxins; compliant with GB 16297-1996 emission standards; Cost-Effective & Long-Lasting: Service life 8,000–20,000 hours; regenerable and reusable; reduces O&M costs; Wide Applicability: Suitable for low-concentration, high-airflow, multi-component exhaust gases, covering coating, printing, chemical, pharmaceutical, and other industries.

II. Material Systems and Classification

Industrial exhaust gas purification catalysts consist of three components: active component, support, and promoter. They are classified into three major types based on the active component:

1. Precious Metal Catalysts (High-Efficiency Low-Temperature Type)

Active Components: Platinum (Pt), palladium (Pd), rhodium (Rh), gold (Au), and other precious metals. Core Advantages: Extremely high low-temperature activity (ignition temperature 200–300°C); catalytic efficiency ≥99%; high selectivity; good thermal stability; long service life. Application Scenarios: Low-concentration, high-airflow VOCs treatment including aromatics, alkanes, alkenes, and esters, e.g., coating, printing, electronics, and pharmaceutical industries. Typical Products: Pt-Pd alloy catalyst; honeycomb ceramic-supported precious metal catalyst.

2. Non-Precious Metal Catalysts (Cost-Effective General-Purpose Type)

Active Components: Transition metal oxides of manganese (Mn), cobalt (Co), copper (Cu), nickel (Ni), chromium (Cr), etc. Core Advantages: Low cost (1/5–1/10 of precious metals); strong poison resistance; high-temperature tolerance; suitable for medium-to-high-concentration complex exhaust gases. Application Scenarios: Chemical, pharmaceutical, rubber, and dyeing industries with sulfur-containing, chlorine-containing, and high-concentration VOCs exhaust gases.
Typical Products: MnO_x, CuO, Co$_{3}$O$_{4}$, CuMn$_{2}$O$_{4}$ spinel-type catalysts.

3. Composite Oxide Catalysts (High-Performance Custom Type)

Active Components: Perovskite-type (ABO$_{3}$, A=La/Ce, B=Mn/Co), spinel-type, rare-earth composite oxides.

Core Advantages: Combines advantages of precious and non-precious metals; high activity; strong stability; poison resistance; high-temperature tolerance; long service life.Application Scenarios: High-concentration, high-temperature, easily poisoned exhaust gases containing sulfur/chlorine/phosphorus, e.g., metallurgy, petrochemical, and waste incineration. Typical Products: La$_{0.6}$Ce$_{0.4}$MnO$_{3}$ perovskite catalyst; CeO$_{2}$-ZrO$_{2}$ solid solution support catalyst.

Supports and Promoters

Supports: Honeycomb ceramics (cordierite), alumina (Al$_{2}$O$_{3}$), molecular sieves (ZSM-5, Beta), titanium dioxide (TiO$_{2}$).
Promoters: Rare-earth oxides such as CeO$_{2}$, ZrO$_{2}$, La$_{2}$O$_{3}$ — enhancing activity, poison resistance, and thermal stability.

III. Core Performance Indicators

1. Ignition Temperature (T50 / T90)

Definition: Minimum temperature at which VOC conversion rate reaches 50%/90%. Specification: Precious metal T90 ≤250°C; non-precious metal T90 ≤350°C.

2. Catalytic Activity (Conversion Rate)

Definition: Pollutant removal rate at target temperature.

Specification: VOCs conversion rate ≥95% and CO conversion rate ≥98% at 300°C.

3. Thermal Stability

Definition: Activity decay rate after prolonged high-temperature operation.

Specification: Activity decline ≤10% after 1,000 hours; temperature resistance 600–800°C.

4. Space Velocity (SV)

Definition: Exhaust gas flow rate treated per unit volume of catalyst (h^{-1}).

Specification: Precious metal 10,000–30,000 h^{-1}; non-precious metal 5,000–15,000 h^{-1}.

5. Poison Resistance

Definition: Tolerance to impurities such as S, Cl, P, Si.

Specification: Activity retention ≥90% when sulfur ≤50 ppm and chlorine ≤10 ppm.

6. Mechanical Strength and Service Life

Strength: Compressive strength ≥10 MPa; wear rate ≤5%.

Service Life: Precious metal ≥15,000 hours; non-precious metal ≥8,000 hours.

IV. Product Forms and Application Scenarios

1. Honeycomb Ceramic Catalyst (Industrial Mainstream)

Form: Honeycomb structure; pore diameter 2–5 mm; cell density 200–400 cpsi.

Advantages: Low airflow resistance (<500 Pa); large specific surface area; high mechanical strength; temperature-resistant; long service life.

Applications: High-airflow, low-concentration VOCs; coating, printing, electronics, chemical industries.

2. Pellet / Cylindrical Catalyst (High-Concentration Dedicated)

Form: Spherical or cylindrical (3–5 mm).

Advantages: High packing density; large contact area; suitable for medium-to-high-concentration exhaust gases.

Applications: Chemical, pharmaceutical, rubber industries with high-concentration VOCs.

3. Metal Support Catalyst (High-Temperature / Thermally Conductive)

Form: Metal mesh, metal honeycomb.

Advantages: Good thermal conductivity; high-temperature resistant; thermal shock resistant; suitable for high-temperature applications.

Applications: Metallurgy, petrochemical, high-temperature exhaust gases.

4. Powder Catalyst (R&D / Custom)

Form: Powder.

Advantages: Large specific surface area; high activity; suitable for laboratory and small-batch custom applications.

V. Selection Logic and Adaptation Principles

1. Selection by Pollutant Type

VOCs (aromatics, esters, ketones): Select precious metal (Pt-Pd); ignition temperature 200–300°C;

Sulfur/Chlorine/Phosphorus-Containing Exhaust: Select composite oxide (perovskite); strong poison resistance;

High-Concentration VOCs (>1,000 mg/m³): Select non-precious metal (MnO_x, CuO); lower cost; NO_x (SCR): Select vanadium-titanium or molecular sieve catalyst.

2. Selection by Operating Parameters

Temperature: ≤300°C → precious metal; 300–450°C → non-precious metal; >450°C →composite oxide;

Concentration: Low (<500 mg/m³) → honeycomb precious metal; medium-to-high → pellet non-precious metal;

Airflow: High (>10,000 m³/h) → honeycomb; medium-to-low → pellet;
Space Velocity: Precious metal 15,000–30,000 h^{-1}; non-precious metal 5,000–15,000 h^{-1}.

3. Selection by Cost and Service Life

Long-Term Stability, Low Maintenance: Select precious metal; long service life; simple maintenance;
Cost-Sensitive, Short-to-Medium Term: Select non-precious metal; lower price; good cost-performance ratio;
Complex Conditions, High Requirements: Select composite oxide; comprehensive performance; strong poison resistance.

VI. Installation, Operation & Maintenance, and Regeneration Standards

1. Installation Standards

Honeycomb Catalyst: Vertical installation; inter-layer sealing; avoid air leakage; uniform loading; Pellet Catalyst: Loading height 300–500 mm; moderate compaction; prevent channeling; Pre-Filter: Install paint mist filter cotton and primary filter to prevent dust and paint residue clogging;
Temperature Control: Inlet temperature 250–350°C; avoid overheating (>600°C).

2. Replacement Cycle Determination

Precious Metal: 12–24 months; service life 15,000–20,000 hours;
Non-Precious Metal: 6–12 months; service life 8,000–12,000 hours;
Saturation Signals: Outlet concentration exceeds standard; abnormal temperature; airflow resistance increases 2–3x.

3. Routine Operation & Maintenance

Weekly: Check temperature, airflow resistance, concentration, dust clogging;

Monthly: Clean pre-filter; inspect catalyst bed; prevent channeling;
Prohibitions: Overheating, water ingress, dust accumulation, strong acid/alkali corrosion.

4. Regeneration Technology (Cost Reduction & Efficiency Improvement)

Thermal Regeneration: High-temperature desorption at 500–600°C; activity restoration; regeneration rate ≥80%;

Chemical Regeneration: Acid/alkali or solvent washing; applicable to poisoned catalysts;

Microwave Regeneration: Fast and efficient; low energy consumption; regeneration rate ≥85%.

VII. Typical Industry Application Solutions

1. Coating / Paint Booth Exhaust (VOCs + Paint Mist)

Solution: Paint mist filter cotton → honeycomb precious metal catalyst (Pt-Pd).

Performance: VOCs removal rate ≥95%; ignition temperature 250°C; service life 18 months.

2. Printing / Electronics Industry (Low-Concentration, High-Airflow)

Solution: Honeycomb precious metal catalyst (Pd).

Performance: Treated airflow 5,000–30,000 m³/h; space velocity 20,000 h^{-1}; conversion rate≥98%.

3. Chemical / Pharmaceutical Industry (High-Concentration, Sulfur/Chlorine-Containing)

Solution: Pellet composite oxide catalyst (perovskite).

Performance: Sulfur/chlorine resistant; conversion rate ≥90%; service life 12 months.

4. Metallurgy / Petrochemical Industry (High-Temperature, High-Concentration)

Solution: Metal support composite catalyst.

Performance: Temperature resistance 600°C; thermal shock resistant; high stability.

VIII. Technology Development Trends

1. High-Efficiency & Low-Energy Consumption

Ultra-High Activity: Precious metal loading reduced by 30%; activity increased by 20%; Ultra-Low Ignition: Ignition temperature reduced to 180–220°C; energy saving 50%;

High Stability: Service life extended to 30,000 hours; regeneration rate ≥90%.

2. Green & Eco-Friendly

Precious-Metal-Free: High-activity non-precious metals replace precious metals; cost reduced by 70%;

Regeneration & Recycling: Catalyst regeneration technology becomes widespread; regeneration rate ≥85%;

Low-Pollution Preparation: Cyanide-free, heavy-metal-free preparation processe

environmentally compliant.

3. Intelligence & Digitalization

Online Monitoring: Real-time monitoring of temperature, concentration, airflow resistance, and activity;

AI Optimization: Automatic adjustment of temperature and space velocity; extended service life; Remote O&M: Fault early warning; predictive maintenance; reduced operation & maintenance costs.

4. Multi-Functional Integration

Adsorption-Catalysis Integration: Activated carbon + catalyst; adsorption + catalysis; efficiency improved by 30%;

Multi-Pollutant Synergistic Treatment: Integrated VOCs+NO_x+CO purification; one catalyst, multiple uses;

Nanotechnology: Nano-catalysts; specific surface area increased by 50%; activity increased by 40%.

IX. Conclusion

As core materials for environmental protection and treatment, industrial exhaust gas purification catalysts directly determine treatment effectiveness, operating costs, and environmental compliance. With the accelerated green and intelligent transformation of industry, high-efficiency, low-consumption, stable, eco-friendly, and intelligent catalysts have become the inevitable choice for the industry, serving as a key support for achieving the “dual carbon” goals and promoting high-quality industrial development.

This white paper systematically presents the technical principles, performance indicators, selection logic, operation & maintenance standards, and industry applications of industrial exhaust gas purification catalysts, combining the latest national standards and industry trends to provide enterprises with comprehensive technical references throughout the entire process.