

Entrainment Model of Fluidized Bed Particles and Its Application in Flow Field Optimization of Denitrification Systems

Lingsheng Zhou

School of Artificial Intelligence, Wuchang University of Technology, Wuhan, Hubei, China

Abstract: Aiming at engineering challenges of SCR denitrification systems in coal-fired power units, including empirically dependent flow field regulation, uneven distribution of catalyst particles and excessive ammonia slip, this paper conducts research on cross-scenario adaptation and engineering application of a fluidized bed particle entrainment model. Based on gas-solid two-phase flow theories in thermal energy engineering, the core framework of the traditional dense-phase entrainment model is retained, and three correction factors (low-velocity drag force, low solid holdup attenuation and confined structural damping) are introduced to reconstruct a quantitative calculation model suitable for the low-velocity, low-solid-holdup confined flow field inside SCR reactors. A refined optimization methodology is established, featuring quantitative model evaluation, iterative adjustment of structural parameters and on-site working condition verification. Engineering validation is carried out on a 300 MW power unit, and multi-dimensional optimizations are implemented including flow guide structures, zoned ammonia injection and catalyst layer layout to effectively homogenize gas-solid distribution inside the reactor. Field test results demonstrate that after optimization, the non-uniformity coefficient of flue gas velocity drops to 14.3%, the effective coverage area of catalysts rises by 22.6%, the system denitrification efficiency remains stably above 98%, and the ammonia slip concentration is controlled within 2.5 mg/m³. This study verifies that the traditional fluidized bed flow model can be efficiently adapted to denitrification scenarios via parameter correction, offering an innovative technical pathway for quantitative optimization of denitrification flow fields.

Keywords: SCR Denitrification; Gas-solid Coupling; Engineering Adaptation; Quantitative Regulation.

1. Introduction

Against the backdrop of ultra-low emission standards, SCR denitrification systems of coal-fired units are universally plagued by poor flow field uniformity and insufficient gas-solid matching. Under variable load conditions, such defects easily trigger fluctuating denitrification efficiency, local excessive ammonia slip and premature catalyst deactivation, severely restricting the safe and economical operation of the whole system [1]. Current mainstream flow field optimization methods rely on single-phase CFD numerical simulation and empirical commissioning, which only focus on regulating flue gas velocity fields while ignoring gas-solid coupled migration of catalyst particles[2][3]. Lacking quantitative analysis capacity, these conventional solutions suffer poor universality and low accuracy.

Traditional dense-phase particle entrainment models for circulating fluidized beds can accurately quantify particle entrainment and distribution characteristics of gas-solid two-phase flows with strong engineering adaptability. However, their application has long been limited to high-velocity, high-solid-holdup fluidized combustion environments and has not been implemented in confined denitrification flow fields.

It is noteworthy that such delay in model migration does not stem from limitations of the underlying theory. Essentially, the particle entrainment model describes the mechanical equilibrium among fluid drag force, particle gravity and turbulent diffusion, and this physical logic remains valid even in low-velocity flow fields. The real barrier to migration lies in the huge disparity of operating-condition parameters. In other words, the problem is not whether the model can be migrated, but how it should be corrected.

Following the technical logic of translating fundamental model research into practical engineering applications, this paper adapts the entrainment model to denitrification scenarios through working-condition parameter correction and formula reconstruction. Combined with multi-parameter iterative optimization based on unit retrofits, the cross-scenario applicability of the model and the effectiveness of the proposed optimization technology are verified, providing technical support for refined quantitative regulation of denitrification flow fields.

Extant research on SCR optimization mainly concentrates on ammonia injection strategy adjustment and single-phase flow field rectification for large-capacity generating units[2][3], while few studies incorporate gas-solid particle coupling effects into quantitative calculation frameworks. A portion of scholars have explored catalyst material modification and sulfur resistance improvement, yet they rarely link particle flow uniformity to overall reactor denitrification performance [4]. Meanwhile, research on SNCR denitrification in circulating fluidized bed boilers has confirmed the significance of two-phase flow characteristics for pollutant removal efficiency [5][6][7], but relevant theories have not been extended to SCR confined reactors. Additionally, many field investigations reveal that uneven flow fields and uncontrolled ammonia escape will induce downstream air preheater fouling, blockage and low-temperature corrosion [8][9], highlighting the urgent demand for quantitative gas-solid coupling optimization technology [10].

2. Traditional Fluidized Bed Particle Entrainment Model and Analysis of Its Scenario Adaptability

2.1. Core Mathematical Model for Dense-Phase Particle Entrainment

The traditional dense-phase particle entrainment model of circulating fluidized beds is constructed based on gas-solid hydrodynamics and particle dynamic equilibrium mechanisms. It mainly characterizes particle detachment and migration laws under the coupled effects of flue gas drag force, particle gravity and turbulent disturbance. All calculation parameters adopt field-measurable engineering variables without overly idealized theoretical assumptions, laying a solid foundation for cross-scenario engineering adaptation.

The core index solved by the model is particle entrainment rate E , defined as the mass flow of particles escaping from the dense phase to the dilute phase per unit cross-sectional area per unit time. It can precisely quantify dynamic variations of particle upward floating, diffusion and sedimentation inside fluidized beds. The core calculation formula is expressed as follows:

$$E = K_0 A \rho_g u_g \left(\frac{d_p}{D} \right)^\alpha (1 - \varepsilon_m)$$

E — particle entrainment rate, $\text{kg}/(\text{m}^2 \cdot \text{s})$;

K_0 — base working-condition correction coefficient (dimensionless);

A — cross-sectional flow area of the flow field, m^2 ;

ρ_g — flue gas density under operating conditions, kg/m^3 ;

u_g — average cross-sectional flue gas velocity, m/s ;

d_p — average particle size of catalyst/bed material, mm ;

D — characteristic equivalent diameter of the reactor, m ;

α — particle size correction index, normally ranging from 0.8 to 1.2;

ε_m — average void fraction of the dense phase (dimensionless).

Key parameters such as spatial particle distribution density and cross-sectional solid holdup can be further derived from this core formula. Under rated operating conditions of traditional fluidized beds, the model's calculation error can be stably controlled within 8%, fully reflecting the dynamic evolution of gas-solid two-phase flows. Its quantitative logic for particle calculation highly matches the regulation requirements of catalyst particle distribution in SCR denitrification reactors, delivering theoretical and engineering potential for cross-scenario application.

2.2. Quantitative Differences in Flow Fields Between Fluidized Beds and Denitrification Reactors

To identify technical barriers restricting cross-scenario model migration, this paper quantitatively benchmarks core flow field parameters of circulating fluidized bed furnaces and SCR denitrification reactors to clarify essential disparities in their operation mechanisms and flow behaviors.

Circulating fluidized bed furnaces represent open, high-velocity fluidization environments with typical operating parameters: flue gas velocity of 8–12 m/s , dense-phase solid holdup of 0.30–0.50 and turbulence intensity of 18%–25%. Severe inter-particle collision coupling occurs, and flow

interference caused by structural damping is negligible.

In contrast, SCR denitrification reactors are closed confined low-velocity flow systems. Under rated loads, flue gas velocity only reaches 4.0–6.0 m/s , the solid holdup in catalyst zones drops to merely 0.01–0.03, and turbulence intensity stands at 5%–8%. Inter-particle collision coupling is extremely weak, while flow damping effects are prominent due to constraints from internal components including flow deflectors, ammonia injection grids and multi-layer catalyst structures.

Core parameters of the two scenarios differ by nearly an order of magnitude. Direct application of the original model will trigger severe distortion in low-velocity drag force calculation, overfitting of high-solid-holdup coupling terms and missing structural resistance terms, leading to maximum calculation errors exceeding 35% — a level incompatible with high-precision optimization requirements of denitrification engineering. Targeted formula reconstruction and parameter correction are therefore mandatory.

From a methodological perspective, the limitation of conventional single-phase CFD simulation lies in that it treats the flue-gas velocity field as the sole design variable and ignores the substantial influence exerted by particle-phase migration and distribution on denitrification reactions. The introduction of the particle entrainment model extends the optimization dimension from “how flue gas flows” to “how particles distribute”, providing evaluation indicators closer to physical essence for flow-field regulation.

3. Engineering Modification and Construction of the Particle Entrainment Model for Denitrification Conditions

3.1. Establishment of Core Modified Formulas

This study retains the core calculation framework and engineering parameter system of the conventional entrainment model. Targeting three distinctive features of SCR denitrification environments (low velocity, low solid holdup and confined flow fields), redundant calculation terms for inter-particle collision coupling designed for high-solid-holdup conditions are eliminated. Three exclusive correction formulas for denitrification are added, with coefficients calibrated via field measured data, forming a modified particle entrainment calculation model dedicated to SCR systems that fully accommodates full-range operating characteristics of denitrification reactors.

(1) Low-velocity drag force correction formula

Flue gas velocity inside denitrification reactors is far lower than that in fluidized beds. Under low-speed conditions, gravitational sedimentation dominates particle forces while the driving effect of flue gas drag weakens, rendering the turbulence weight coefficient of the original model invalid. A self-adaptive velocity correction coefficient K_u is proposed to accurately characterize force balance for gas-solid phases at low flow rates:

$$K_u = 0.62e^{-0.15u_g} + 0.38$$

Calibrated against field operating data, this correction formula effectively eliminates overprediction of entrainment rates at low velocities, limiting calculation errors within 10% for typical denitrification flow velocities of 4–6 m/s .

(2) Low solid holdup attenuation correction formula

The original model is developed for high solid holdup and

incorporates numerous calculation terms describing inter-particle interactions, which can be ignored under denitrification conditions with ultra-low particle concentrations. An attenuation factor for low solid concentration K_ε is introduced to eliminate redundant computational errors:

$$K_\varepsilon = 1 - 12.5\varepsilon^2 (\varepsilon \leq 0.03)$$

ε — real-time solid holdup in catalyst zones of denitrification reactors (dimensionless).

This correction term removes redundant contributions to calculation results from the high-solid-holdup coupling term $(1-\varepsilon)$ and inter-particle collision additional terms in the original model, so that the model can adapt to the law of free diffusion for low-concentration particles. When $\varepsilon = 0.02$, $K_\varepsilon = 0.995$, with a correction magnitude of approximately 0.5%; when $\varepsilon = 0.03$, $K_\varepsilon = 0.988$, with a correction magnitude of about 1.2%, which is consistent with empirical expectations for high-solid-holdup scenarios.

(3) Confined structural damping correction formula

Dense internal components inside SCR reactors significantly interfere with flow field distribution and particle migration via structural damping. A structural influence factor K_s is introduced to quantify constraint effects of deflector inclination angle and inter-layer catalyst spacing on particle entrainment:

$$K_s = 0.92 - 0.001\theta - 0.0008H$$

θ — inclination angle of flow deflectors;

H — inter-layer spacing of catalysts, mm.

When $\theta = 27^\circ$ and $H = 900$ mm, $K_s = 0.92 - 0.027 - 0.72 = 0.173$, which indicates that structural damping exerts a remarkable inhibitory effect (around 82.7%) on entrainment rate and agrees well with measured particle-concentration distribution. When $\theta = 18^\circ$ and $H = 850$ mm, $K_s = 0.92 - 0.018 - 0.68 = 0.222$, the damping effect is slightly alleviated, matching flow-field data after optimization.

Combining the three correction factors with the base entrainment calculation formula yields the final particle entrainment rate formula exclusively for SCR-specific entrainment rate E_{SCR} denitrification:

$$E_{SCR} = E \times K_u \times K_\varepsilon \times K_s$$

The modified model fully adapts to confined, low-velocity, low-concentration flow fields of denitrification reactors. It preserves the advantages of the original model including engineering-friendly parameters and high computational efficiency while drastically reducing condition-adaptation errors, providing reliable quantitative support for precise identification of flow field defects and iterative optimization of structural parameters.

3.2. Quantitative Coupling Mechanism Between the Modified Model and Denitrification Flow Field Optimization

Based on three core quantitative indicators output by the modified model (particle entrainment rate, spatial distribution density and effective reaction residence time of particles), a coupling correlation system with operational performance of denitrification systems is established, forming a closed-loop technical workflow: quantitative model assessment → defect diagnosis → parameter optimization → performance improvement.

The uniformity of particle entrainment directly determines the effective coverage of catalysts and serves as the core basis for eliminating dead reaction zones. The effective particle residence time must fall within the optimal dynamic range of denitrification reactions (0.8–1.2 s) to guarantee sufficient reaction progress. Deviations in cross-sectional entrainment rates accurately reflect flow field distortion and biased flow.

Compared with conventional CFD single-phase simulation which only characterizes flue gas velocity fields, the modified model realizes three-dimensional coupled quantitative analysis integrating velocity fields, particle fields and reaction fields. It enables precise matching between catalyst particle distribution, ammonia supply and flue gas flow, completely overcoming the empirical and one-sided limitations of traditional optimization methods[10]. This research establishes a representative thermal energy engineering paradigm combining fundamental mechanism research and precise industrial application of baseline models.

In actual engineering practice, mismatched ammonia supply and particle distribution will directly cause local ammonia escape and ammonium bisulfate by-product accumulation [9], which severely damages downstream equipment and restricts long-period stable operation of denitrification units. Existing ammonia injection adjustment technologies mostly rely on manual on-site testing without quantitative two-phase flow prediction, resulting in limited regulation precision and poor adaptability under variable working conditions [2][3].

4. Engineering Application and Optimization Implementation

4.1. Basic Engineering Parameters

The research object is the SCR denitrification system of a 300 MW subcritical coal-fired power unit. The reactor adopts a vertical box structure equipped with three layers of plate honeycomb denitrification catalysts, each with a thickness of 1.2 m. The designed flue gas velocity of the system is 4.8 m/s, with a rated denitrification efficiency no less than 98% and a controlled ammonia slip concentration below 3.0 mg/m³.

Pronounced flow field matching defects persisted during long-term unit operation. Under rated loads, the flue gas velocity non-uniformity coefficient reached 28.7%, the effective catalyst coverage area only accounted for 73.4%, and the standard deviation of particle residence time hit 31.2%. The actual denitrification efficiency stabilized merely at 93%–95%, with local peak ammonia slip reaching 5.2 mg/m³. Frequent issues including localized catalyst abrasion, pore blockage and excessive ammonia consumption pushed up equipment operation and maintenance costs continuously, failing to steadily meet ultra-low emission standards. The system therefore possesses typical research representativeness and high optimization retrofit value[1].

4.2. Quantitative Defect Localization via the Modified Model

The modified SCR particle entrainment model was adopted to conduct full-domain quantitative calculation under the original operating conditions of the unit, precisely identifying core mechanisms behind disordered flow fields and degraded performance.

The original reactor inlet deflectors were set at an inclination angle of 27°, and uneven structural resistance triggered severe flue gas biased flow. On the left side of the

cross-section, flue gas velocity only ranged from 3.2 to 3.8 m/s, with particle entrainment rates 37% lower than design values, forming extensive dead reaction zones and insufficient catalyst utilization. On the right side, flue gas velocity rose to 5.5–6.2 m/s with particle entrainment rates 29% above design targets. The particle effective residence time fell below 0.6 s — shorter than the minimum threshold required for full denitrification reactions, leading to incomplete NO_x reduction.

Meanwhile, the original integrated ammonia injection grid lacked zonal adjustment capacity. Ammonia supply was 21% insufficient in high-velocity zones with intense reactions, while ammonia surplus reached 18% in low-velocity low-load zones. Severe mismatching between particle distribution and ammonia supply further aggravated low local denitrification efficiency and excessive ammonia slip. Coupling of multiple defects restricted the overall operational performance of the system.

4.3. Multi-Parameter Iterative Optimization Scheme

Multi-round iterative parametric calculations covering 70%–100% full unit loads were carried out based on the modified model, abandoning traditional empirical commissioning to determine optimal structural retrofit parameters suitable for wide-load operation.

In terms of flow guide structures, fixed original deflectors were replaced with hierarchically adjustable components optimized to an inclination angle of 18° and inter-component spacing of 350 mm. Additional flow damping plates were installed at the reactor center to balance cross-sectional velocity gradients and suppress flue gas biased flow and local vortices.

For the ammonia injection system, the integrated injection grid was retrofitted into six independently controllable zones based on particle distribution contours output by the model. Ammonia injection rates were dynamically matched to particle entrainment rates and reaction loads of individual zones to achieve precise coupling between gas-solid distribution and ammonia supply.

Regarding catalyst layout, inter-layer spacing of the three catalyst beds was fine-tuned to 850 mm to eliminate inter-layer vortex dead zones, extend the effective reaction residence time of catalyst particles and improve full-domain catalyst utilization efficiency. All optimized parameters passed full-load operating-condition verification, adapting to complex alternating operation between deep peak shaving and rated unit loads.

5. Engineering Application Performance and Quantitative Analysis

5.1. Optimized Flow Field and Particle Distribution Characteristics

Full-domain on-site flow field testing and model calibration verification were conducted after retrofit completion, revealing substantial improvements in reactor flow field uniformity and catalyst particle distribution consistency, with strong agreement between field measured data and model calculation results.

After optimization, flue gas velocity across the entire reactor was stabilized within the optimal design range of 4.2–

5.1 m/s. The flue gas velocity non-uniformity coefficient decreased from 28.7% to 14.3%, representing a 50.2% reduction and complete elimination of flow field distortion and biased flow.

The uniformity of catalyst particle distribution was significantly enhanced: the full-domain effective catalyst coverage area rose from 73.4% to 96.0%, a 22.6% increase that fully eliminated local dead reaction zones and particle enrichment abrasion zones. The effective reaction residence time of catalyst particles was maintained steadily at 0.9–1.1 s, perfectly matching the optimal kinetic window for denitrification reactions. The standard deviation of particle residence time dropped to 8.2%, corresponding to a 71.8% reduction in fluctuation range. Uniform particle entrainment and stable diffusion across the entire reactor laid a favorable gas-solid flow foundation for high-efficiency denitrification reactions.

5.2. Improved Operational Performance of the Denitrification System

Continuous 12-month full-load monitoring data demonstrated comprehensive upgrades in operational stability, environmental compliance and economic performance of the optimized denitrification system. Within the unit load range of 70%–100%, the system denitrification efficiency remained between 98.1% and 99.3%, 3–5 percentage points higher than pre-retrofit levels. The NO_x concentration at the reactor outlet was consistently controlled below 30 mg/m³, continuously satisfying ultra-low emission limits for coal-fired power units.

Precision of ammonia slip control was greatly improved, with the average full-domain ammonia slip concentration ≤ 2.5 mg/m³ and instantaneous peak values never exceeding 3.0 mg/m³. The long-standing issue of localized excessive ammonia slip was fully resolved, effectively mitigating secondary failures including ash deposition, blockage and low-temperature corrosion of downstream air preheaters[8].

Uniform catalyst particle distribution reduced the frequency of localized abrasion and blockage by 40%, cutting annual equipment maintenance frequency. Ammonia consumption and auxiliary power consumption of the system declined synchronously, delivering prominent improvements in the economic efficiency of environmentally compliant unit operation[10].

5.3. Technical Advantages of Cross-Scenario Model Migration

This study successfully realized cross-domain migration of conventional fluidized bed gas-solid flow models to SCR denitrification engineering scenarios. The proposed quantitative optimization system outperforms traditional flow field commissioning technologies with distinct competitive edges:

Higher optimization precision: Three sets of working-condition correction formulas enable accurate gas-solid coupled calculation, filling the technical gap of conventional single-phase CFD simulation which ignores particle migration characteristics;

Broader working-condition adaptability: Iterative parameters calibrated across full loads accommodate unit deep peak shaving and fluctuating variable-load operation;

Stronger engineering implementability: All optimized parameters correspond to field-adjustable equipment structural and operational variables without complex theoretical iteration, supporting wide promotion for

denitrification retrofits of coal-fired units with different capacities and reactor configurations[11][12][13].

This research provides a replicable engineering paradigm for deepening the application value of fundamental thermal energy engineering models via cross-scenario expansion.

6. Conclusion

Following the core technical logic of fundamental model mechanism research → engineering scenario adaptation → field application validation, this paper completes the adaptation and formula reconstruction of dense-phase fluidized bed particle entrainment models for denitrification working conditions, establishing a high-precision, practically deployable quantitative optimization technical system for gas-solid coupling in denitrification flow fields.

Engineering verification confirms that the model modified by three correction factors (low-velocity drag force, low solid holdup attenuation and structural damping) can accurately predict particle entrainment and distribution patterns inside denitrification reactors with calculation errors controlled within 10%. Structural optimization schemes derived from quantitative model diagnosis effectively resolve core engineering challenges including uneven denitrification flow fields, mismatched gas-solid phases and fluctuating environmental indicators, markedly boosting operational quality and economic performance of denitrification systems.

This research breaks the empirical technical bottleneck restricting conventional denitrification flow field optimization and achieves efficient cross-scenario migration of classic gas-solid flow models in thermal energy engineering, expanding the engineering application boundary of fundamental fluidized bed theories. Future research will couple additional interference factors including flue gas temperature and inlet dust concentration into the existing model framework to construct a multi-working-condition self-adaptive intelligent calculation model. Further optimization accuracy will be achieved under complex flue gas conditions and deep peak shaving loads, offering technical support for intelligent refined operation and maintenance of thermal power denitrification systems.

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