Thesis Booklet

Applied Innovative Engineering and Chemical Approaches for Flue Gas Emission Reductions

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1. Abstract

This thesis presents advanced research in emission control technology focused on achieving near-zero emissions from internal combustion engines. It tackles critical challenges posed by conventional catalysts, notably high cost, flow restriction, and regeneration difficulties. The study employs innovative engineering and chemical methodologies to investigate the relationship between catalyst support geometry, reaction chamber design, and catalytic performance. Extensive evaluation using a Real Driving Emission (RDE) setup allowed for the systematic exploration of multiple variables. A central finding is the optimized system configuration: a six-channel reaction chamber coupled with a bimetallic (5wt% Co + 0.1wt% Pd) catalyst supported on pelletized γ-Aluminum Oxide, demonstrating 98% emission conversion efficiency. This research significantly advances emission control, offering practical and economically viable solutions for stringent regulatory compliance through novel design and cost-effective promoter strategies.

2. Introduction & Aims

Air pollution remains a critical global challenge with far reaching implications for human health and environmental sustainability. While debates persist about its origins and extent, the urgent need for clean air is universally acknowledged. Non-road mobile Machinery (NRMM) has emerged as a significant yet often overlooked emission source, encompassing equipment in construction, agriculture, and industry. The environmental and health impacts are profound: respiratory diseases, cardiovascular problems, and accelerated global warming are direct consequences of air pollution. Despite stringent controls on-road vehicles, air quality improvements have fallen short of expectations. This project introduces an innovative high-efficiency flue gas conversion system through a dual-innovation approach: a novel catalyst design and an optimized catalytic converter chamber. The research presents several groundbreaking findings most notably a breakthrough emission control technology: a six-way reactor utilizing an innovative catalyst design. By combining optimized geometry with minimal noble metal usage specifically, a catalyst containing 70 grams with 5wt% Co and 0.1wt% Pd on pelletized gamma-Al_2O_3 support we achieved an unprecedented 98% stable flue gas conversion. This approach advanced three critical aspects of emission control: innovative support design, revolutionary reaction chamber configuration, and optimal metal-promoter synergy, ultimately demonstrating that intelligent engineering can dramatically reduce emissions from internal combustion engines. And during my research, the questions we aimed to answer were:

1. How does support shape impact flue gas emission conversion efficiency?
2. What is the role of support properties in conversion performance?
3. How does reaction chamber shape affect catalytic converter efficiency?
4. How does the reaction chamber design promote the catalyst's performance inside?
5. Identification of ideal promoters for noble metals

6. Influence of metal loading combinations on ceramic supports

From the set goals mentioned above the objectives were as follows:

- Development of advanced catalytic converters overcoming current limitations
- Optimization of catalyst composition and support geometry
- Design of innovative reaction chamber configurations
- Cost reduction through bimetallic catalyst systems
- Achievement of near-zero emissions performance

3. Experimental Methods & Materials

The research details the development of a sophisticated catalyst system. Preparation involved wet impregnation of palladium acetate, alumina supports, and Ni, Cu, Co promoter metals, culminating in precise thermal treatment. The experimental setup featured a fixed-bed reactor with gas chromatography and a HONDA GX390-based Real Driving Emission (RDE) system. Comprehensive catalyst characterization was performed using techniques such as X-ray Diffraction and Transmission Electron Microscopy. A key aspect was the evaluation of three progressive reactor designs (A, B, C) for flue-gas conversion, exploring configurations from basic vertical flow to a complex six-channel distribution system to optimize gas flow and catalytic performance. Finite Element Method simulations and fuel consumption measurements provided a holistic analysis.

4. Summary of New Scientific Results

1. The geometric characteristics of catalyst supports, particularly spherical and pellet shapes, significantly influence conversion efficiency, with amorphous structure and higher BET surface area being the key contributing factors to enhanced performance.

the geometric features and the composition of the ceramic support have a huge effect on the conversion of flue gas. By exploring alternatives to traditional honeycomb structures, we developed adaptable catalyst shapes suitable for various applications, This novel approach enables modular, application-specific solutions for both irregular and conventional catalytic converters, and the conclusion indicated that pelletized and spherical gamma aluminum oxide supports loaded with 0.2%wt Pd achieved an impressive 95^{+}% reduction of NO_X and CO as their amorphous nature and the order of magnitude larger BET surface area synergized with the conversion process and further promoted the activity.

2. The addition of transition metal promoters (Cu, Ni, Co) to palladium catalysts improves both performance and cost-effectiveness, with 5wt% Co + 0.1wt% Pd achieving a 38% improvement in conversion performance while reducing costs by 61.7% compared to pure Pd catalysts.

The article "Enhanced Performance and Cost-Effectiveness of Pd-Based Catalysts with Cu, Ni, and Co

Promoters for CO and NOx Conversion in Flue Gas Emission" presents new scientific results demonstrating that palladium (Pd) catalysts, when enhanced with copper (Cu), nickel (Ni), and cobalt (Co) promoters on pelletized aluminium oxide supports, significantly improve the conversion of carbon monoxide (CO) and nitrogen oxides (NOx) in flue gas emissions from internal combustion engines. The standout finding is that the 5 wt.% Co + 0.1 wt.% Pd catalyst achieved a 38% increase in CO conversion at 0.5 kW and a 27% improvement at 1.0 kW, while reducing conversion costs by 61% compared to pure Pd catalysts. For NOx conversion, Ni/Pd catalysts excelled, showing a 14% improvement at 0.5 kW and 36% at 1.0 kW. These results highlight the potential of using cost-effective transition metal promoters to enhance catalytic performance and reduce reliance on expensive noble metals, offering a more sustainable and economical solution for emission control.

3. Reaction chamber design is a critical factor in catalytic converter performance, with the six-way

reactor configuration demonstrating superior results compared to traditional designs, particularly under Real Driving Emission (RDE) testing conditions.

This study presents new scientific results demonstrating that reaction chamber design significantly enhances the efficiency of flue gas treatment in catalytic converters. We manufactured and tested three reactor designs—Reactor A (simple cylindrical), Reactor B (tube-dispersed), and Reactor C (multi-cylinder dispersed)—each loaded with a 0.1wt% Pd on spherical Al_2O_3 catalyst. Compared to the baseline Reactor A, Reactor B achieved a 5-fold increase in CO conversion, while Reactor C showed a 3-fold increase in CO conversion and a 225% increase in NO reduction at higher power output (1.0 kW). Additionally, both Reactors B and C reduced fuel consumption by 20% under the same conditions. These findings, supported by Finite Element Method (FEM) analysis, underscore the potential of optimized reactor designs to improve emission control and fuel efficiency, addressing stringent environmental regulations effectively.

4. The integration of a six-way reaction chamber design with bimetallic catalysts (5wt% Co + 0.1wt% Pd) on pelletized γ-Aluminum Oxide support achieves 98% conversion efficiency of flue gas emissions, demonstrating a superior approach to emission control while reducing costs.

In summary, three major projects were carried out to develop an effective system that can convert flue gas emissions. In a combined effort, we utilized the best-performing sample of each project, meaning from the support design effect project we chose the pelletized Al_2O_3 sample as our primary catalyst support, and from the reaction chamber design effect project we chose Reactor C (the six-way reactor) as our primary reaction chamber, and finally from the promoter addition effect project we chose the 5wt.% Co + 0.1 wt. % Pd combination loading as our primary wash coat of the support, afterward an extensive flue gas conversion experiment was held under RDE setup at three conditions 1500rpm, 2500rpm, and 3500rpm, the conversion process was consistent and stable as we were able to convert 98% of the flue gas emissions produced by gasoline engine.

5. Publications and Conferences

Hungarian Scientific Bibliography MTMT Identifier: 10080733

Publications

1. **Al-Aqtash, O.,** Farkas, F., Sápi, A., Szenti, I., Boldizsár, T., Ábrahámné, K.B., Kukovecz, Á. and Kónya, Z., 2023. Differently shaped Al2O3-based Pd catalysts loaded catalytic converter for novel non-road mobile machinery exhaust systems.

   Reaction Kinetics, Mechanisms and Catalysis, *136*(1), pp.149-161.

   (IF = 1.7, Independent Citations = 2)

2. **Al-Aqtash, O.,** Sápi, A., Farkas, F., Basheer, H.S., Kukovecz, Á. and Kónya, Z., 2025. Enhanced Performance and Cost-Effectiveness of Pd-Based

Catalysts with Cu, Ni, and Co Promoters for CO and NOx Conversion in Flue Gas Emission.

Atmospheric Pollution Research, p.102579.

(IF = 3.9, Independent Citations = 0)

3. **Al-Aqtash, O.,** Sápi, A., Multi-cylindrical packed catalyst-type reactor for efficient flue gas treatment

   Under review in **Catalysts**

   IF = 4

∑IF = 9.6

Conference Presentations

1. "Ceramics-Based catalyst characterization" - 14th ECerS Conference for Young Scientists in Ceramics, Novi Sad, Serbia (October 20-23, 2021)
2. "Ceramics-Based Catalyst for Treating Exhaust Gases of SI Engine" - 27th International Symposium on Analytical and Environmental Problems, Szeged, Hungary (November 22-23, 2021)
3. "Differently shaped Al_2O_3 based Pd catalysts loaded catalytic converter for novel non road mobile machinery exhaust systems" - Hungarian

Society for Microscopy Conference 2023, Siofok, Hungary (May 1-4, 2023)

4. "Differently shaped ceramic-based Pd catalysts for flue gas conversion" - 12th Virtual Nanotechnology Poster Conference (April 24, 2023)
5. "Differently shaped Al_2O_3 based Pd catalysts for exhaust systems after treatment" - 18th Carpathian Basin Conference for Environmental Science, Szeged, Hungary (September 8-10, 2023)
6. "Reactor chamber design effect on flue gas conversion" - ICOSTEE 2024, Szeged, Hungary (May 31, 2024)