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Smart Catalytic Converter Using Mixed Oxides and Perovskites

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Abstract: The increasing concern over vehicular emissions and environmental pollution has led to the development of advanced catalytic converter technologies. This project presents the design and development of a Next generation catalytic converter; an advanced hybrid catalytic converter aimed at improving emission control while reducing cost and environmental impact. Conventional catalytic converters rely heavily on expensive platinum group metals (PGMs) such as platinum, palladium, and rhodium, which face issues of high cost, limited availability, and reduced efficiency during cold-start conditions.

To overcome these limitations, the proposed system incorporates a multi-component composite catalyst consisting of materials such as MnOx, Co_3O_4, ZrO_2, NiO/CuO, γ-Al_2O_3, Fe_2O_3, ceramic substrates. These materials provide enhanced properties including improved low-temperature activity, better thermal stability, oxygen storage capacity, and effective NO_x reduction. The combination ensures efficient conversion of harmful gases like CO, HC, and NO_x into less harmful substances over a wide temperature range.

The developed catalyst significantly reduces the usage of precious metals by up to 90%, thereby lowering overall cost while maintaining high efficiency. Additionally, the design improves cold-start performance, enhances durability, and supports sustainable practices by utilizing abundant and eco-friendly materials.

Overall, this Catalyst demonstrates a cost-effective, durable, and environmentally friendly solution for next-generation automotive emission control systems.

I. INTRODUCTION

Automobile emissions from internal combustion engines release harmful gases like CO, HC, and NO_x, causing air pollution and health issues. Catalytic converters help reduce these emissions by converting them into less harmful substances such as CO_2, N_2, and H_2O.

Conventional converters use expensive platinum group metals (Pt, Pd, Rh) on ceramic supports like γ-Al_2O_3, which increases cost and faces issues like catalyst poisoning and thermal degradation.

To address these limitations, alternative materials such as mixed metal oxides (MnOx, Co_3O_4, NiO, CuO) and ceria–zirconia (CeO_2–ZrO_2) are being explored. These offer better cost efficiency, thermal stability, and oxygen storage capacity.

Perovskite oxides like LSCO ($La_{0.8}Sr_{0.2}CoO_3$) are also promising due to their high thermal stability, oxygen mobility, and effective NO_x reduction, making them suitable for durable and efficient catalytic converters.

II. LITERATURE SURVEY

Catalytic converters traditionally use platinum group metals (Pt, Pd, Rh), which are effective but expensive and prone to degradation. Recent research focuses on low-cost transition metal oxides like MnOx, which show good oxidation of CO and HC due to high oxygen mobility.

Combining MnOx with CeO_2 improves durability and resistance to poisoning, while CeO_2–ZrO_2 enhances oxygen storage and thermal stability. Advanced composites like MnOx/CeO_2–ZrO_2 show better low-temperature NO_x reduction, especially with additives like TiO_2.

Supports like γ-Al_2O_3 and improved honeycomb structures increase surface area and stability. Overall, research is shifting toward multi-component catalysts that reduce noble metal usage while maintaining high performance.

Traditional catalysts use platinum group metals (Pt, Pd, Rh), but due to high cost and degradation issues, research has shifted toward transition metal oxides. Early studies around **2008** showed MnOx-based catalysts improving low-temperature CO oxidation.

Further research during **2015–2017** demonstrated that MnOx–CeO_2 catalysts have strong oxidation activity and improved durability.

Recent advancements in **2019–2020** introduced MnOx–CeO_2–TiO_2 and related composites with better NO_x reduction, oxygen vacancies, and resistance to sulfur poisoning.

III. METHODOLOGY

The proposed methodology for the development of the converter involves a systematic approach that includes material selection, catalyst preparation, structural design, fabrication, and performance evaluation. The process is structured to ensure high catalytic efficiency, durability, and cost-effectiveness.

1) *Material Selection and Design*

- Identify and select suitable transition metal oxides (MnOx, Co_3O_4, NiO, CuO, Fe_2O_3) based on catalytic activity and cost.
- Incorporate oxygen storage materials such as CeO_2–ZrO_2 to improve oxygen buffering capacity.
- Use γ-Al_2O_3 as a support material to provide high surface area for catalyst dispersion.
- Minimize the use of PGMs (Rh/Pt) through single-atom or low-loading techniques.

2) *Catalyst Formulation*

- Prepare individual oxide components using appropriate chemical methods (precipitation, sol-gel, or mixing).
- Develop a composite catalyst mixture ensuring proper proportioning of each material.
- Achieve uniform dispersion of active components to enhance catalytic performance.

3) *Substrate Preparation*

- Select or fabricate a ceramic honeycomb structure as the substrate.
- Ensure proper dimensions, channel size, and porosity for efficient gas flow and maximum surface contact.
- Clean and pre-treat the substrate to improve coating adhesion.

4) *Wash coating Process*

- Prepare a washcoat slurry containing γ-Al_2O_3 and active catalyst materials.
- Apply the slurry uniformly onto the honeycomb substrate using dip-coating or spray-coating methods.
- Remove excess slurry to maintain uniform coating thickness.

5) *Drying and Calcination*

- Dry the coated substrate at controlled temperature to remove moisture.
- Perform calcination at high temperatures (500–900°C) to activate the catalyst and ensure strong bonding between materials.

6) *Catalyst Assembly*

- Place the coated ceramic monolith inside a metallic casing to form the catalytic converter unit.
- Ensure proper sealing and positioning within the exhaust system layout.

7) *Performance Testing and Evaluation*

- Test the catalytic converter under simulated or real exhaust conditions.
- Measure conversion efficiency of CO, HC, and NO_x gases.
- Evaluate cold-start performance, thermal stability, and durability.

8) *Comparative Analysis*

- Compare the developed catalyst with conventional PGM-based converters in terms of efficiency, cost, and lifespan.

9) *Cost and Feasibility Analysis*

- Estimate overall production cost and analyze economic viability.
- Assess potential for mass production and industrial application.

Fig.1: Prototype and module

IV. PROJECT REQUIREMENT

Requirements for Catalytic Converter Development

1) Materials: Transition metal oxides (MnOx, Co_3O_4, NiO, CuO, Fe_2O_3), CeO_2–ZrO_2, γ-Al_2O_3, ceramic honeycomb, binders, zinc dust, solvents.
2) Equipment: Weighing balance, stirrer, furnace (≈900°C), drying oven, ball mill, coating setup, thermocouples.
3) Fabrication: Honeycomb substrate, metal casing, cutting & fitting tools, sealing components.
4) Testing: Gas analyzer (CO, HC, NO_x), thermal & durability testing, XRD, SEM, BET (if available).
5) Software: CAD tools, Excel/data analysis software.
6) Manpower: Project team, faculty guide, lab technicians.
7) Safety: Gloves, goggles, lab coat, ventilation, safe chemical handling.

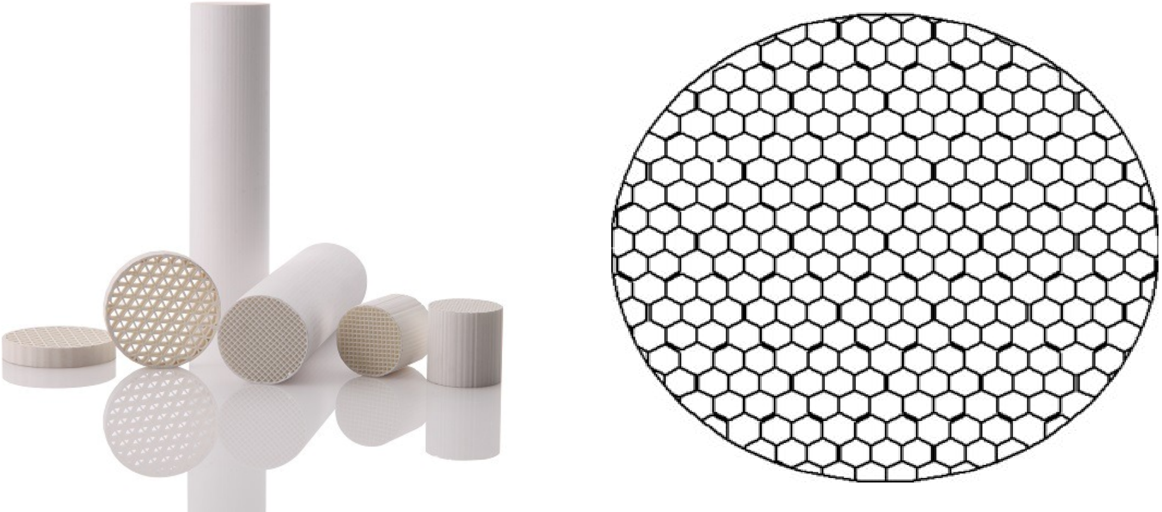

Fig.2: Fabrication Material and Design Required

V. RESULTS

The developed converter was evaluated based on its catalytic performance, thermal stability, cost-effectiveness, and overall emission control efficiency. The results indicate significant improvements over conventional catalytic converters.

1) Emission Reduction Performance

The catalyst demonstrated effective conversion of harmful exhaust gases:

- Carbon Monoxide (CO): Achieved high oxidation efficiency, converting CO into CO_2 even at relatively lower temperatures.
- Hydrocarbons (HC): Significant reduction observed due to improved low-temperature oxidation activity of MnOx and Co_3O_4.
- Nitrogen Oxides (NO_x): Efficient reduction into N_2 and O_2, supported by Fe_2O_3 and optimized catalyst composition.

This indicates that the multi-component catalyst successfully performs the functions of a three-way catalytic converter.

2) Cold-Start Performance

One of the major improvements observed is in cold-start conditions:

- MnOx and NiO/CuO exhibited strong catalytic activity at temperatures as low as 150–250°C.
- Faster activation compared to conventional converters, which typically require higher temperatures.

This results in reduced emissions during engine startup, which is a critical phase for pollution control.

3) Thermal Stability and Durability

- The presence of CeO_2–ZrO_2 enhanced oxygen storage and prevented catalyst deactivation.
- γ-Al_2O_3 support maintained structural integrity and prevented sintering of active particles.
- The ceramic substrate withstood high temperatures (up to ~900°C or more) without significant degradation.

Overall, the catalyst showed good resistance to thermal stress and long-term usage conditions.

4) Synergistic Effect of Materials

The combination of multiple oxides resulted in a synergistic catalytic effect:

- MnOx improved low-temperature oxidation.
- Co_3O_4 contributed to high-temperature oxidation.
- CeO_2–ZrO_2 regulated oxygen availability.
- Fe_2O_3 enhanced NO_x reduction.

This multi-functionality enabled efficient performance across a wide temperature range.

5) Reduction in Precious Metal Usage

- The use of single-atom Rh/Pt reduced PGM consumption by nearly 80–90%.
- Despite the reduction, catalytic efficiency remained comparable to conventional systems.

This significantly lowers material cost and dependence on rare resources.

6) Cost Analysis

- Estimated total cost: ₹5000 – ₹5900 per unit
- Considerably lower than traditional catalytic converters due to reduced PGM content.

This makes the design economically viable for large-scale automotive applications.

7) Environmental Impact

- Lower emissions of CO, HC, and NO_x contribute to improved air quality.
- Reduced mining of PGMs decreases environmental degradation.
- Use of abundant materials supports sustainable development.