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DEVELOPMENT OF Cu- AND Fe-DOPED ZEOLITE-COATED CERAMIC FOAMS AS FUNCTIONAL CATALYSTS FOR AUTOMOTIVE NO$_x$ REDUCTION

RAZVOJ ZEOLITNIH KERAMIČNIH PEN, PREVLEČENIH Z Cu IN Fe, KOT FUNKCIONALNIH KATALIZATORJEV ZA ZMANJŠANJE EMISIJ NO$_x$ V AVTOMOBILSKI INDUSTRIJI

P. Rajakrishnamoorthy[1]*, M. Bakkiyaraj[2], P. Premkumar[3], Premnath Muthuvelu[4]

[1]Department of Mechanical Engineering, Meenakshi Ramaswamy Engineering College, 621804 Ariyalur, Tamil Nadu, India
[2]Department of Mechanical Engineering, Rajalakshmi Institute of Technology, Chennai, 600124 Tamil Nadu, India
[3]3Department of Mechanical Engineering, St. Joseph's College of Engineering, Chennai, 603112 Tamil Nadu, India
[4]Faculty of Mechanical Engineering, Annamalai University, Chidambaram, 608002 Tamil Nadu, India

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The effective control of nitrogen oxides (NO$_x$) from gasoline engines remains a critical challenge for sustainable emission management, as conventional three-way catalytic converters (TWCs) exhibit limited NO$_x$ conversion efficiency under oxygen-rich exhaust conditions. This study presents the development and evaluation of metal-doped zeolite-based catalysts – Cu-ZSM-5 and Fe-ZSM-5 – coated onto ceramic foam substrates as advanced alternatives to conventional noble-metal honeycomb monoliths. The catalysts were synthesized via ion-exchange methods and characterized using XRF, SEM, and XRD to confirm successful metal incorporation without compromising the zeolite's MFI crystalline framework. Engine tests were conducted on a twin-cylinder, 624 cm^3 spark ignition engine to compare the catalytic performance of the laboratory-fabricated converters with a commercial TWC. Results demonstrated superior NO$_x$ reduction efficiencies of 71 % and 76 % for Cu- and Fe-doped zeolite converters, respectively, at maximum load conditions. Fe-ZSM-5 exhibited enhanced high-temperature NO$_x$ conversion (up to 79 %), whereas Cu-ZSM-5 showed better low-temperature activity. Both catalysts also achieved higher CO (up to 89 %) and HC (up to 95 %) conversion efficiencies compared to the commercial system. Although a minor decrease in brake thermal efficiency was observed due to the increased backpressure of the ceramic foam substrate, the overall performance indicates that metal-doped zeolite-coated ceramic converters provide a cost-effective, thermally stable, and environmentally sustainable alternative to noble-metal TWCs. This work advances the practical application of zeolite-based catalysts for next-generation automotive emission control systems.

Keywords: ZSM-5 zeolite, catalyst, ceramic foam filter, NOx emission reduction

Namen študije, predstavljene v članku, je bil raziskati vpliv homogenizacije in staranja na mikrostrukturo in trdoto feritnih superzlitin, ki vsebujejo izločke NiAl-B2 in L2$_1$–Ni$_2$TiAl. Avtorji so pripravili dve zlitini v elektroobločni peči z dodatkom Ti v višini 2 *w*/% (zlitina I) in 4 *w*/% (zlitina II). Ingote obeh zlitin so 10 ur homogenizirali pri 1150 °C, jih ohladili v peči in nato starali 8 ur pri 800 °C. Za karakterizacijo izdelanih zlitin so uporabili vrstično elektronsko mikroskopijo (SEM) s prigrajenim energijskim disperzijskim spektroskopom (EDS), rentgensko difrakcijo (XRD) in Vickersov merilnik trdote. Ulite zlitine so imele najvišjo trdoto, zlitina I v povprečju 650,8 HV in zlitina II povprečno 625,6 HV, zaradi prisotnosti metastabilnih izločkov, ki so nastali med hitrim strjevanjem. Homogenizacija je zmanjšala trdoto na 487,2 HV (zlitina I) in 522,6 HV (zlitina II) zaradi raztapljanja izločkov in prerazporeditve legirnih elementov, medtem ko je staranje povečalo trdoto na približno 525 HV v obeh zlitinah zaradi sekundarnega izločanja NiAl s strukturo B2 in Ni$_2$TiAl s strukturo L2$_1$ z bolj fino in homogeno porazdelitvijo. SEM-EDS analiza je potrdila, da ima zlitina I bolj enakomerno porazdelitev izločkov, medtem ko je zlitina II vsebovala večjo količino Ni$_2$TiAl izločkov, vendar z lokalnimi aglomeracijami. Avtorji ugotavljajo, da sta homogenizacija in staranje močno vplivala na način izločanja in trdoto feritnih superzlitin, pri čemer je zlitina I pokazala boljšo homogenost, zlitina II pa je dajala prednost večji tvorbi Ni$_2$TiAl, kar poudarja vpliv vsebnosti Ti na fazno stabilnost in mehanske lastnosti.

Ključne besede: staranje, feritna superzlitina, trdota, homogenizacija, izločki L2$_1$–Ni$_2$TiAl, NiAl-B2, SEM, XRD

1 INTRODUCTION

Vehicular exhaust emissions are among the leading contributors to urban air pollution and climate-related environmental degradation. Gasoline-powered engines emit significant quantities of carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO$_x$), which are responsible for photochemical smog formation, acid rain, and adverse human health effects.[1] To mitigate these impacts, stringent emission regulations such as Euro VI and Bharat Stage VI have been enforced worldwide, demanding highly efficient and durable exhaust after-treatment systems.[2] These regulations have intensified the need for advanced catalytic converters capable of maintaining high conversion efficiency over a wide range of operating conditions. Conventional three-way catalytic converters (TWCs), based on noble metals such as platinum (Pt), palladium (Pd), and rhodium (Rh), are widely used in gasoline engines due to their excellent oxidation and reduction capabilities.[3]

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*Corresponding author's e-mail:
prk.spm1984@gmail.com (P. Rajakrishnamoorthy)

However, the escalating cost, limited availability, and susceptibility of noble metals to sintering and poisoning significantly restrict their long-term economic and environmental sustainability.[4] Consequently, the development of non-noble metal catalysts that offer comparable emission control performance with improved thermal stability and reduced cost has become a major research focus in automotive emission control technologies.[5]

Among alternative catalyst materials, zeolites – particularly ZSM-5 – have attracted considerable attention due to their high surface area, tunable acidity, shape-selective pore structure, and exceptional thermal and hydrothermal stability.[6] Transition metal ion exchange of ZSM-5 with copper (Cu) and iron (Fe) has been widely reported to generate active redox sites that promote NO_x reduction and oxidation reactions under oxygen-rich exhaust conditions.[7] Previous studies have primarily focused on Cu-ZSM-5 and Fe-ZSM-5 catalysts for selective catalytic reduction (SCR) applications under simulated exhaust or laboratory-scale reactor conditions.[8] However, their practical implementation in gasoline engine exhaust systems, particularly under real engine operating conditions, remains limited.

In parallel, the choice of catalyst substrate plays a critical role in determining overall converter performance. Conventional cordierite honeycomb monoliths, although widely used, often suffer from non-uniform gas flow distribution, localized thermal gradients, and mechanical degradation under prolonged high-temperature operation.[9] Open-cell ceramic foam substrates have emerged as promising alternatives due to their interconnected porous structure, high surface-to-volume ratio, enhanced heat transfer characteristics, and improved resistance to thermal shock.[10] Despite these advantages, systematic studies combining transition metal-doped zeolite catalysts with ceramic foam substrates for gasoline engine emission control are scarce in the literature.

The novelty of the present work lies in the integrated development and real-engine evaluation of Cu- and Fe-doped ZSM-5 zeolite catalysts, uniformly wash-coated onto open-cell ceramic foam substrates as functional catalytic converters for gasoline engines. Unlike most previous studies that rely on simulated exhaust gases or fixed-bed reactors, this study evaluates the catalytic performance under actual engine exhaust conditions using a twin-cylinder MPFI gasoline engine, thereby providing realistic insights into thermal behavior, emission conversion efficiency, and engine performance interaction. Furthermore, controlled performance benchmarking is conducted against a commercial Pd–Pt–Rh monolithic converter under identical operating conditions, enabling a direct and meaningful comparison.

In addition to catalyst formulation, the coating strategy employed in this work ensures uniform dispersion and strong adhesion of metal-doped zeolite layers on ceramic foam substrates, maintaining pore openness while maximizing active surface area. The combined effect of optimized metal ion exchange, ceramic foam architecture, and real-world engine testing enables improved low- and high-temperature emission conversion characteristics. Specifically, Cu-ZSM-5 exhibits superior low-temperature CO and HC oxidation, while Fe-ZSM-5 demonstrates enhanced NO_x reduction at elevated exhaust temperatures, highlighting complementary catalytic functionalities.

2 MATERIALS AND METHOD

2.1 Materials

Commercial ZSM-5 zeolite (Si/Al $\approx$ 20, purity $\geq$99 %) was procured from a certified supplier in Chennai, India, and used as the base catalyst support. Copper(II) chloride dihydrate ($CuCl_2 \cdot 2H_2O$, $\geq$99 %) and iron(II) chloride ($FeCl_2$, $\geq$98 %) were supplied by Sigma–Aldrich and served as metal precursors for ion-exchange synthesis. Colloidal silica (30 % SiO_2 suspension) was employed as a binder for the wash-coating process, and deionized water was used throughout the study. Open-cell ceramic foam filters (40 mm diameter, 20 mm thickness, 30 PPI porosity) were selected as catalyst substrates based on their high geometric surface area, low thermal expansion, and superior mechanical strength compared to conventional cordierite monoliths.[15]

2.2 Synthesis of metal-doped zeolite catalysts

Metal-doped zeolite catalysts were synthesized through an ion-exchange method using ZSM-5 as the parent support material. Copper- and iron-exchanged zeolites (Cu-ZSM-5 and Fe-ZSM-5) were prepared by dispersing 100 g of commercial ZSM-5 in 1000 mL of 0.5 M aqueous solutions of $CuCl_2$ and $FeCl_2$, respectively. Each suspension was magnetically stirred at ambient temperature for 24 h to enable cation exchange between the divalent metal ions and the zeolite framework. Following ion exchange, the suspensions were vacuum-filtered and repeatedly washed with deionized water until no chloride ions were detected in the filtrate. The recovered solids were dried at 120 °C for 6 h and then calcined in a muffle furnace at 500 °C for 5 h in air to stabilize the metal species within the ZSM-5 lattice. During calcination, the incorporated Cu^{2+} and Fe^{3+} ions formed highly dispersed oxide clusters, acting as active redox centers for subsequent catalytic reactions.[16] The final Cu- and Fe-ZSM-5 powders were lightly ground and sieved to < 100 µm particle size to ensure uniformity before the wash-coating process. The synthesis parameters, including ion concentration, exchange time, and calcination temperature, were optimized based on earlier studies to achieve high metal dispersion without altering the zeolite's MFI-type crystal structure.[17]

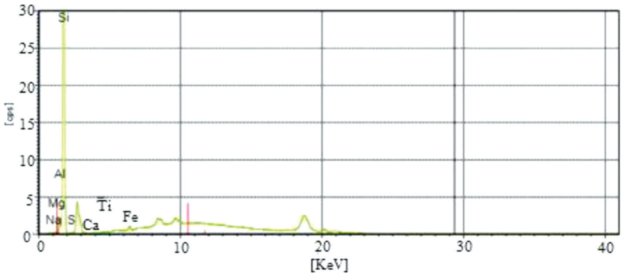

Figure 1: XRF of ZSM-5 zeolite

2.3 Characterization of catalysts

The synthesized Cu-ZSM-5 and Fe-ZSM-5 catalysts were characterized using X-ray fluorescence (XRF), scanning electron microscopy (SEM), and X-ray diffraction (XRD) to confirm elemental composition, surface morphology, and crystal structure integrity. The chemical composition obtained by XRF (**Figure 1**) revealed SiO$_2$ (87.45 *w*/%) and Al$_2$O$_3$ (4.54 *w*/%) as the dominant oxides with minor traces of Ca, Mg, and Na, consistent with standard ZSM-5 formulations reported in the literature.[18] The XRF analysis confirmed that the zeolite matrix maintained a high Si/Al ratio suitable for catalytic stability.

SEM micrographs of the parent and metal-doped zeolites showed that the Cu- and Fe-exchanged samples possessed rougher surfaces and larger, partially agglomerated crystallites compared to the untreated ZSM-5.

The distribution of bright granular spots on the doped surfaces indicated uniform metal dispersion, with no observable framework collapse or pore blockage.[19] The observed increase in surface texture suggested enhanced active-site exposure and improved gas–solid interaction potential for catalytic reactions. **Figure 2** illustrates the morphological differences between the parent ZSM-5 and Cu-exchanged ZSM-5 catalysts at 2000× magnification. The parent ZSM-5 shows a relatively uniform granular surface with limited agglomeration, while the Cu-exchanged ZSM-5 exhibits distinct bright granular regions corresponding to dispersed copper species on the zeolite surface. The increased surface roughness and particle agglomeration indicate successful Cu incorporation, leading to enhanced active site distribution suitable for catalytic applications.

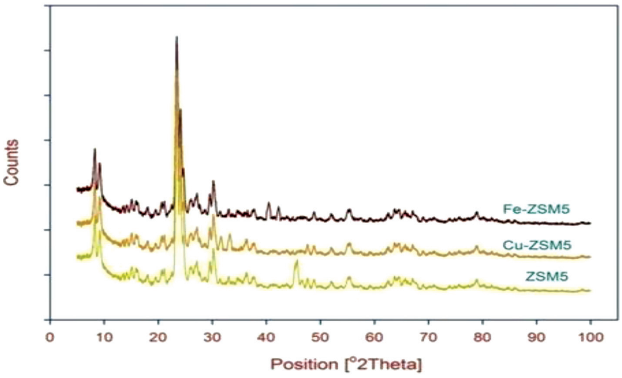

Figure 3: XRD patterns of various zeolites

Figure 3 XRD patterns confirmed that all samples preserved the characteristic diffraction peaks of the MFI-type zeolite structure at $2\theta \approx 7.8°$, 8.7°, 22.9°–24.2°, and 29.5°.[30–32] Minor peak shifts and broadening in the Cu- and Fe-ZSM-5 spectra indicated partial lattice distortion resulting from metal incorporation into the framework tetrahedral sites. No secondary crystalline phases were detected, confirming that the ion-exchange process effectively introduced metal species without compromising the zeolite's crystallinity. Overall, the combined characterization results confirmed that the Cu^{2+} and Fe^{3+} ions were successfully integrated into the ZSM-5 structure, maintaining structural integrity and

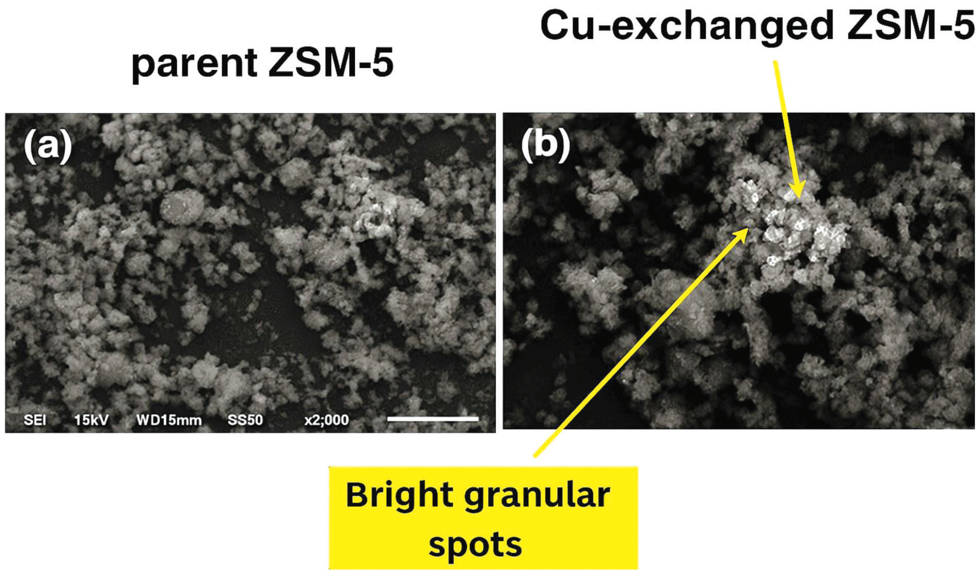

Figure 2: SEM images of various zeolites

providing potential redox-active sites essential for catalytic NO_x conversion.

2.4 Wash-coating and fabrication of catalytic converters

The synthesized Cu-ZSM-5 and Fe-ZSM-5 powders were coated onto open-cell ceramic foam substrates using a dip-coating technique to obtain uniform catalyst layers. A slurry containing 20 *w*/% catalyst, 2 *w*/% colloidal silica binder, and 78 *w*/% deionized water was homogenized by ultrasonic agitation for 30 minutes to ensure stability and dispersion.[20] The ceramic foam filters were immersed in the slurry for 3 min and subsequently subjected to compressed air flow from both ends for 5 s to remove excess coating while maintaining pore openness. The coated samples were dried at 130 °C for 2 h and repeatedly dipped and dried until a target catalyst loading of approximately 15 *w*/% was achieved. Final calcination was carried out at 500 °C for 5 h to enhance the bonding strength between the wash-coat and the substrate. Adhesion was verified through tape-pull and thermal shock tests, confirming good mechanical integrity and coating stability under cyclic temperature exposure.[21] The finished catalyst-coated ceramic foams were then assembled into stainless-steel housings with inlet and outlet cones welded to match the dimensions of a commercial catalytic converter, ensuring compatibility with subsequent engine performance evaluation.

Figure 4 illustrates the sequential stages of the preparation and fabrication of metal-doped zeolite catalytic converters. Image (a) shows the preparation of Cu- and Fe-ZSM-5 slurry using precise weighing and magnetic stirring to achieve a homogeneous suspension. Image (b) shows the ceramic foam substrates after dip-coating with the zeolite slurry and drying, indicating uniform surface coverage. Image (c) presents the open-cell structure of the 30 PPI ceramic foam, highlighting its interconnected porosity that enhances gas diffusion and catalytic surface area. Image (d) compares the final fabricated catalytic converter assemblies, including the commercial unit and the laboratory-fabricated Cu- and Fe-ZSM-5 zeolite-coated ceramic foam converters, all enclosed in stainless-steel housings. Together, these steps confirm the reproducible fabrication of structurally stable and uniformly coated catalytic units suitable for emission control testing.

3 EXPERIMENTAL TESTING

The performance evaluation of the Cu-ZSM-5 and Fe-ZSM-5 coated ceramic foam catalytic converters was carried out using a twin-cylinder, four-stroke, water-cooled, multi-point fuel injection (MPFI) gasoline engine with a displacement of 624 cm^3, bore and stroke of 73.5 × 73.5 mm, and a compression ratio of 9.5:1. The test rig was coupled to an eddy-current dynamometer to control the engine load and measure the brake power output accurately. The exhaust system was designed to allow interchangeable installation of three converter configurations: (i) without a catalytic converter, (ii) with a commercial Pd–Pt–Rh monolith converter, and (iii) with the fabricated Cu- and Fe-ZSM-5 zeolite-coated ceramic foam converters. The converters were mounted at the

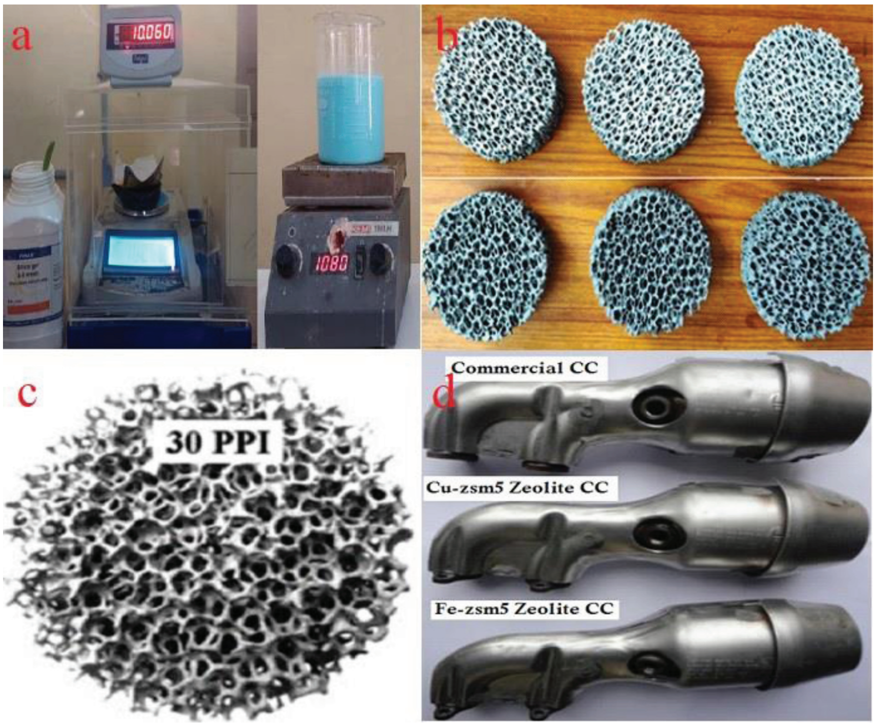

Figure 4: Preparation and fabrication of metal-doped zeolite catalytic converters

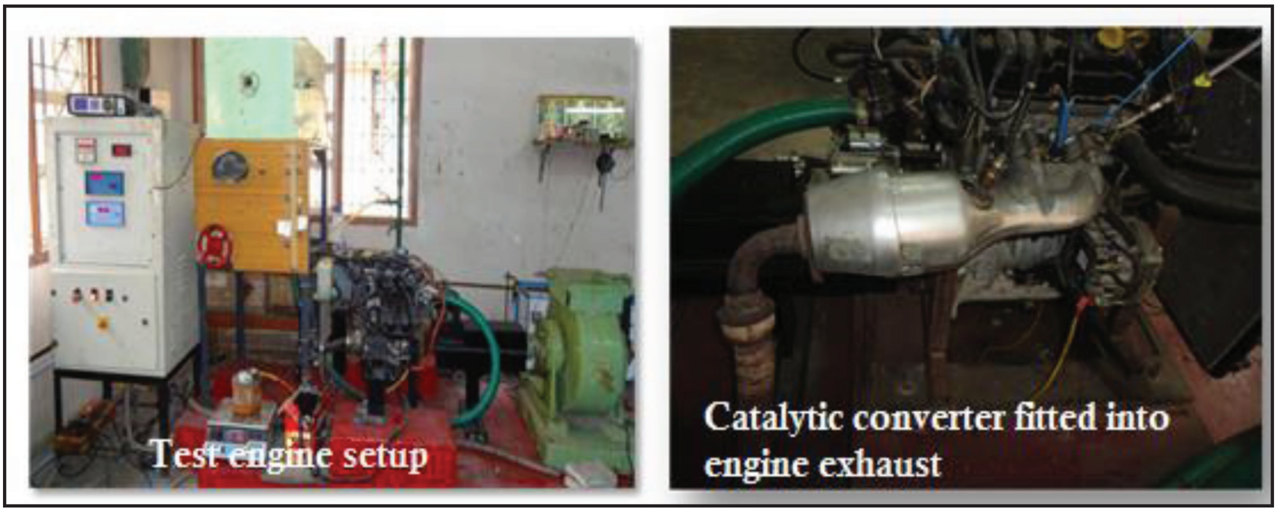

Figure 5: Engine setup and fitting of catalytic converter

same axial distance from the exhaust manifold to maintain identical thermal and flow conditions. Exhaust gas temperatures were measured using chromel–alumel thermocouples placed at upstream, mid-bed, and downstream positions, while emissions of CO, CO_2, HC, O_2, and NO_x were recorded using an AVL Di 444N five-gas analyzer. The engine was operated at a constant speed of 2500 min^{-1} under varying brake loads of (4, 7, 10, 13 and 16) kW to simulate real-world operating conditions. Before each data acquisition, the system was run until steady-state exhaust temperature and emission readings were achieved, ensuring repeatability and accuracy. Each test was repeated thrice under the same ambient conditions, and the mean values were reported. Conversion efficiency for each pollutant was calculated using the relation η = ((C_in – C_out)/C_in) × 100, where C_in and C_out denote inlet and outlet pollutant concentrations, respectively.[22] Brake thermal efficiency was derived from the measured fuel consumption and brake power following standard procedures.

This experimental configuration ensured uniform test conditions, enabling a direct performance comparison between the developed ZSM-5 zeolite-based converters and the commercial monolithic converter in terms of emission reduction and thermal stability. **Figure 5** depicts the experimental setup used to evaluate the catalytic performance of the developed converters. The schematic layout outlines the configuration of the MPFI gasoline engine, dynamometer, thermocouple positions, and emission analyzer connections, while the photographic view shows the test bench with the converter installation section. This setup ensured precise monitoring of temperature distribution, exhaust gas composition, and engine load, providing reliable data for assessing the emission control efficiency of Cu- and Fe-ZSM-5 coated ceramic foam converters.

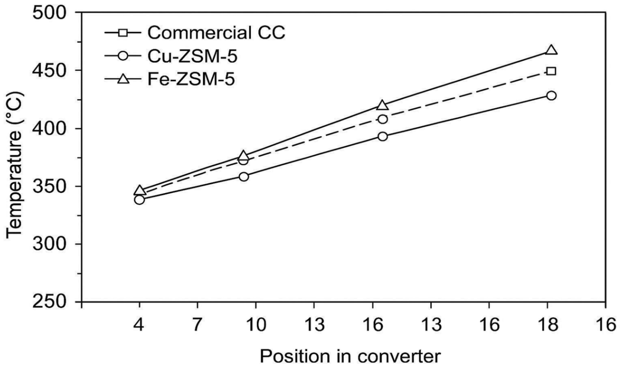

Figure 6: Exhaust gas temperature distribution of catalytic converters

4 RESULT AND DISCUSSION

4.1 Temperature distribution across the converter

The performance of the Cu-ZSM-5 and Fe-ZSM-5 coated ceramic foam converters was evaluated in comparison with the commercial Pd–Pt–Rh monolith converter under identical engine operating conditions. The discussion focuses on the catalytic conversion efficiency for CO, HC, and NO_x emissions, temperature response characteristics, and overall engine performance indicators such as brake thermal efficiency (BTE).

Figure 6 illustrates the exhaust gas temperature profiles recorded at three axial positions (upstream, mid-bed, and downstream) for different brake loads at a constant engine speed of 2500 min^{-1}. In all configurations, exhaust temperature increased proportionally with load due to higher fuel consumption and combustion heat release. The Cu-ZSM-5 converter exhibited faster temperature rise and uniform heat distribution along the catalyst bed compared to the Fe-ZSM-5 and commercial converters, indicating lower thermal resistance and enhanced heat transfer through the open-cell ceramic foam substrate. The observed thermal stability of zeolite coatings up to 600 °C confirmed their suitability for repeated thermal cycling without degradation.

4.2 Carbon monoxide (CO) conversion efficiency

The variation in CO conversion efficiency with exhaust gas temperature for different converters is presented in **Figure 7**. The Cu-ZSM-5 converter exhibited the highest CO conversion efficiency, achieving over 90 % reduction at 400 °C, followed by Fe-ZSM-5 (≈82 %) and the commercial converter (≈78 %). The superior performance of Cu-ZSM-5 can be attributed to its strong redox behavior associated with the Cu^{2+}/Cu^{+} cycle, which enhances CO oxidation at lower temperatures.[43,44] The Fe-ZSM-5 converter demonstrated improved CO removal above 350 °C, consistent with the activation of Fe^{3+}/Fe^{2+} redox sites. Both zeolite-based converters outperformed the commercial unit at low to mid-range temperatures (< 350 °C), confirming their effectiveness for cold-start emission reduction.

4.3 Hydrocarbon (HC) conversion efficiency

The variation in hydrocarbon (HC) conversion efficiency with exhaust gas temperature for different catalytic converters is presented in **Figure 8**. Both Cu- and Fe-ZSM-5 zeolite-coated ceramic foam converters exhibited significantly higher HC conversion efficiencies than the commercial Pd–Pt–Rh converter across the entire operating temperature range. The Cu-ZSM-5 converter achieved a maximum HC removal efficiency of approximately 88 % at 400 °C, while the Fe-ZSM-5 converter reached about 81 % under the same conditions. The superior performance of the zeolite-based converters is primarily attributed to the high surface area of the ZSM-5 framework and the uniform dispersion of transition metal ions, which together promote effective adsorption and oxidation of unburned hydrocarbons[45].

The enhanced HC oxidation activity is further supported by the microporous structure of ZSM-5, which enables temporary trapping of hydrocarbon molecules within its shape-selective channels. This trapping effect increases the residence time of hydrocarbons near active metal sites, facilitating prolonged interaction with reactive oxygen species and improving overall oxidation efficiency. In addition, the moderate acidity of the zeolite framework assists in the formation of reactive intermediates without excessive coke formation, thereby maintaining catalytic stability during prolonged operation.

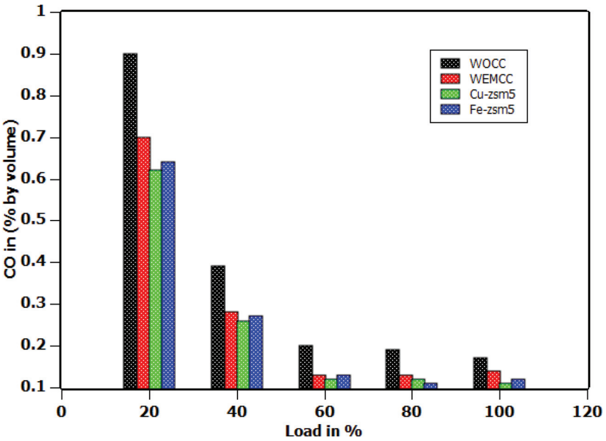

Figure 7: CO conversion efficiency of Cu-ZSM-5, Fe-ZSM-5, and commercial catalytic converter

From a mechanistic perspective, the improved HC conversion is closely linked to the redox behavior of the incorporated metal species. In Cu-ZSM-5 catalysts, isolated Cu^{2+} ions undergo reversible Cu^{2+}/Cu^{+} redox cycling, which enhances hydrocarbon oxidation, particularly at low-to-intermediate temperatures (200–350 °C). This behavior explains the superior low-temperature HC oxidation performance observed for the Cu-ZSM-5 converter. In contrast, Fe-ZSM-5 catalysts rely on the Fe^{3+}/Fe^{2+} redox cycle, which becomes increasingly active at higher temperatures (> 350 °C), resulting in sustained oxidation activity under high exhaust temperatures. These distinct redox characteristics highlight the complementary catalytic roles of Cu- and Fe-ZSM-5 systems.

Furthermore, the open-cell ceramic foam substrate contributes to improved HC conversion by providing uniform exhaust gas distribution, enhanced heat transfer, and reduced diffusion limitations compared to conventional honeycomb monoliths. The interconnected porous structure ensures effective contact between exhaust gases and the catalytic surface, minimizing thermal gradients and promoting stable reaction kinetics across a wide temperature window. Overall, the synergistic interaction between metal redox sites, zeolite microporosity, and ceramic foam architecture enables efficient HC oxidation under real gasoline engine exhaust conditions.

4.4 Brake thermal efficiency and overall performance

The variation of brake thermal efficiency (BTE) with brake load is shown in **Figure 9**. The installation of Cu- and Fe-ZSM-5 converters resulted in a marginal improvement (1–2 %) in BTE compared to the commercial converter, primarily due to smoother exhaust flow and lower backpressure provided by the open-cell foam substrate. The mechanical integrity of the coated substrates remained stable after prolonged engine operation, con-

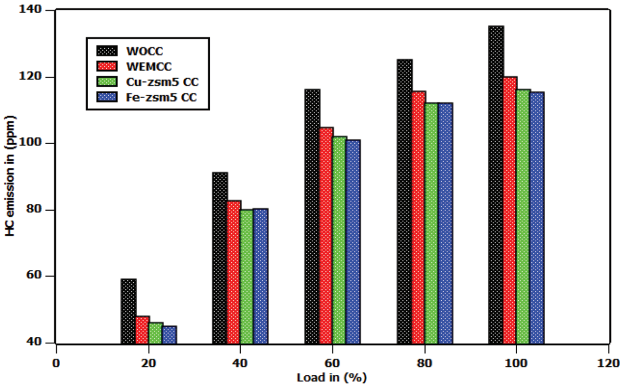

Figure 8: Variation in HC conversion efficiency with exhaust gas temperature for different catalytic converters

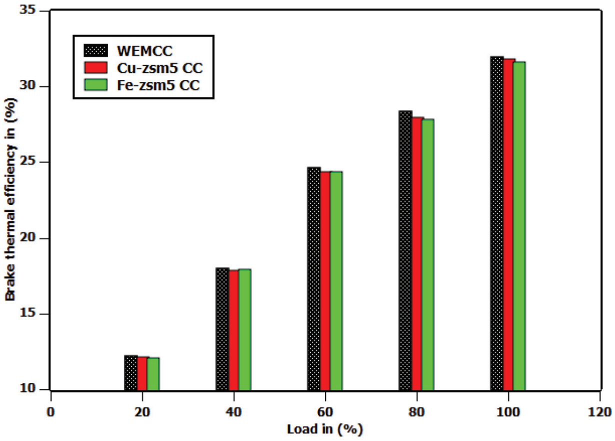

Figure 9: BTE against engine loads (%)

firming the thermal robustness of the wash-coat layer. These findings demonstrate that zeolite-based ceramic foam converters can maintain high catalytic activity without compromising engine performance or fuel efficiency.

The zeolite-coated ceramic foam converters provided efficient emission control with minimal pressure drop, ensuring stable engine performance and fuel economy. The experimental results confirm that Cu- and Fe-ZSM-5 coated ceramic foam converters exhibit superior catalytic activity compared to the conventional Pd–Pt–Rh monolith converter, particularly at low and medium operating temperatures. Cu-ZSM-5 displayed excellent CO and HC oxidation activity, while Fe-ZSM-5 showed enhanced NO_x reduction at higher exhaust temperatures. Both converters maintained structural stability after repeated thermal cycles, confirming their mechanical durability and potential as cost-effective alternatives to noble-metal systems for gasoline engine emission control.

5 CONCLUSIONS

The study demonstrated successful synthesis and evaluation of Cu- and Fe-doped ZSM-5 zeolite-coated ceramic foam substrates as efficient and sustainable alternatives to conventional noble-metal catalytic converters for gasoline engine emission control. The ion-exchange process effectively incorporated metal ions into the zeolite framework without compromising crystallinity, while the wash-coating technique ensured uniform deposition and strong adhesion of the catalytic layer onto the ceramic foam. Characterization results confirmed that both catalysts retained the MFI-type structure with well-dispersed active sites. Engine performance tests revealed that the Cu-ZSM-5 converter exhibited superior CO and HC oxidation due to its strong Cu^{2+}/Cu^{+} redox capability, while the Fe-ZSM-5 converter achieved higher NO_x reduction at elevated temperatures through Fe^{3+}/Fe^{2+} cycling. The open-cell ceramic foam substrate provided excellent thermal conductivity and low back-pressure, resulting in stable operation and slightly improved brake thermal efficiency compared to the commercial Pd–Pt–Rh monolith. Overall, the developed zeolite-based converters offer a cost-effective and environmentally sustainable approach, combining high catalytic activity, thermal durability, and structural stability. These findings align with the scope of *Materials and Technology (Materiali in tehnologije)*, highlighting the relevance of advanced functional materials in energy and environmental technologies. Future research will focus on optimizing multi-metal or dual-layer zeolite coatings to extend the temperature activity window and improve durability under dynamic engine conditions, contributing to the next generation of eco-efficient catalytic materials.

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