

## Experimental investigation on the emission reduction potential of metal oxide-coated ceramic foam filters as substrates for diesel engines

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Received: 01-June-2021; Revised: 19-August-2021; Accepted: 20-August-2021

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### Abstract

*The applicability of ceramic foam filter as a honeycomb structure substitute to achieve a reduction in the amount of engine exhaust emitted from a diesel engine at various brake powers is tested and studied experimentally. Initially, ceramic foam filters were wash-coated in-house using metal oxides such as Aluminum Oxide (Al<sub>2</sub>O<sub>3</sub>), Copper Oxide (CuO), and Titanium Oxide (TiO<sub>2</sub>). The wash-coated ceramic foams were installed inside the outer casing of the Catalytic Converter (CC), which was fabricated in-house according to the dimensions of the CC manufactured by the Original Equipment Manufacturer (OEM). The CC manufactured by OEM consists of honeycomb monolith wash-coated with Platinum (Pt), Palladium (Pd), and Rhodium (Rh) as catalyst materials. The initial performance and emission tests were conducted using the manufactured CC. Following this, the experiments were conducted using ceramic foam-modified CC. The experimental results show that the brake thermal efficiency exhibited by the ceramic foam filter was less than that recorded for the honeycomb monolith substrate. At full load, the Brake Thermal Efficiency (BTE) of the OEM manufactured CC, ceramic foam filter-wash coated with Al<sub>2</sub>O<sub>3</sub>, CuO, and TiO<sub>2</sub>, were 33.14%, 31.6%, 30.2%, and 29.2%, respectively. Reduced emission output parameters, such as Hydrocarbon (HC), Carbon Monoxide (CO), and Oxides of Nitrogen (NO<sub>x</sub>) emissions, were recorded for the metal oxide-coated ceramic foam filter. The CO and HC conversion efficiencies observed for the ceramic foam filter were significantly higher than the efficiencies of the CC manufactured by OEM. The NO<sub>x</sub> conversion efficiency was marginally higher than that recorded for the manufactured CC.*

### Keywords

*Ceramic foam filter, Honeycomb monolith, Metal oxides, Performance, Emission.*

## 1. Introduction

In the field of road transportation, the majority of the vehicles are powered either by diesel or gasoline engines. These engines are fuelled using fossil fuel, resulting in carbon monoxide, unburned hydrocarbon, nitrogen oxides, and soot emission. The emissions from these engines-powered vehicles are one of the major contributors to environmental pollution [1]. The emission from road transport vehicles accounts for two-thirds of the total emissions recorded from the transportation sector [2].

Diesel-based engines are widely used in buses, heavy trucks, commercial light-duty vehicles, and passenger cars.

They exhibit higher torque, load-carrying capacity, thermal efficiency, and low maintenance cost compared to gasoline-based engines [3].

On the other hand, diesel-powered vehicles emit higher amounts of toxic gases compared to gasoline-powered vehicles [4]. The extent of air pollution caused by the emissions from these vehicles is continuously increasing as the demand for vehicles is increasing with time to meet the requirements of the ever-growing population [5].

The emissions adversely affect the environment, resulting in climatic changes. Human health is also adversely affected by toxic emissions [6]. To control the pollution caused by vehicles, pollution control authorities laid out emission norms (revised once every five years) to cut down the levels of vehicular

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emission to a certain limit [7]. In the year 2020, most of the countries have rejected the EURO IV norms and implemented the EURO VI. The EURO VI norms are very stringent compared to the EURO IV norms (especially for diesel engine-based vehicles) [8]. This imposes a greater challenge on the automobile manufacturers and researchers to keep the vehicular emissions within acceptable limits under various driving conditions. Emissions from diesel-based vehicles can be controlled by improving the engine design, combustion efficiency, and exhaust gas treatment devices. Different techniques are used to reduce the extent of vehicular emission. The methods include the treatment of exhaust gases, controlling the operating parameters, tuning the parameters, and in-cylinder combustion control [9]. New ideas to upgrade the technologies used for the development of engines and engine concepts to control emission are rarely being researched at present [10]. The field has reached a saturation point. As a result of this, researchers are showing more interest in upgrading the existing devices or development new after-treatment devices to control the emissions. This involves developing new catalyst materials, designing new Catalytic Converter (CC) substrates, and tuning the material properties.

The diesel engine-based vehicles are equipped with after-treatment devices to control the emission of toxic substances. These after-treatment devices use a honeycomb-shaped ceramic substrate as a filter. This filter is coated with expensive noble catalyst materials such as Pt, Pd, and Rh, for the oxidation and reduction of toxic emissions. The drawbacks of the currently used honeycomb monolith filters are [11]:

- The flow of exhaust gases across the monolith is uneven, i.e., most of the gases, flow through the center of the monolith, whereas the outer periphery of the monolith remains unused. This results in the underperformance of the honeycomb monolith.
- There is a lack of thermal homogeneity across the monolith. As the flow inside the honeycomb monolith is laminar, and most gases flow through the center, a high-temperature zone is observed at the center. The temperature of the central region is higher than the temperature of the outer region. This leads to a faster deterioration of the central part compared to the peripheral part of the monolith.
- To address the above issues, a long monolith should be developed. An increase in the length results in an increase in the surface area. The process, however, increases the manufacturing costs. Increased amounts of expensive catalyst materials are needed for coating under these conditions. This again increases the overall cost of the unit.

- The distribution of the exhaust gases at the downstream region of the honeycomb monolith is non-homogeneous. This adversely affects the performance of the after-treatment devices present in the exhaust tailpipe. In Euro-VI guideline-conforming diesel engines, three after-treatment devices fabricated using similar honeycomb monolith substrates with different set-ups are fitted in a cascade configuration at the tailpipe.

The Empa laboratories for material science [12] have reported that ceramic foam filters possess excellent characteristics that can be exploited to overcome the drawbacks of the honeycomb-based ceramic monolith. A brief literature survey has been provided to discuss the performance of ceramic foam filters.

## 2.Literature review

Panayotis and Christian [13] and Dimopoulos et al. [14] have reported that the ceramic foam filters could be potentially used as alternatives to the conventional honeycomb substrates. They reported that foam filter exhibits better emission conversion efficiency compared to the honeycomb monolith-installed CC.

Bach and Dimopoulos [15] compared the conversion efficiencies of the Diesel Oxidation Catalyst (DOC)-wash coated ceramic foam substrates and the conventional honeycomb substrates. They reported that the Carbon Monoxide (CO) and Hydrocarbon (HC) conversion efficiencies of the ceramic foam were comparable to the efficiency recorded for the honeycomb substrate, while the NO to NO<sub>2</sub> conversion efficiencies were better than the efficiency exhibited by the honeycomb substrate.

Cho et al. [16] reported that the particulate matter reduction rate achieved using the Diesel Particulate Filter (DPF) developed using foam filters was 59%, which is 23% higher than that achieved using conventional DOC.

Tsinoglou et al. [17] has developed a mathematical model to study and compare the transport phenomenon between wash-coated honeycomb and ceramic foam substrates. They reported that a faster mass transfer rate in the gas phase and a slower diffusion rate through the pores of the wash coat (compared to the rates achieved using honeycomb substrates) could be achieved using ceramic foam.

Setiabudi et al. [18] reported that high soot oxidation rates could be achieved using Pt-coated ceramic foam in the presence of NO<sub>2</sub>. Researchers [19–21] also

studied the effect of ceramic foam filters on the rate of exhaust gas flow by analyzing various parameters such as pressure drop across the foam filter and flow uniformity (downstream). Their reports revealed a uniform flow downstream and higher pressure drop (compared to the honeycomb substrate) across the ceramic foam filter.

Garrido et al. [22] investigated the impact of pore sizes and porosity of the filters on the exhaust gas mass transfer rate and drop in pressure across the filter. The results from the studies conducted by Empa [11, 12] revealed that compared to the surface of the honeycomb substrates, the surface of the foam filter was utilized more efficiently. They also claimed that the efficiency of the foam filter, half the length of a honeycomb substrate, was equal to the efficiency of the honeycomb substrate. This, in turn, reduces the material cost and use of expensive catalyst material.

The catalyst materials presently used for the fabrication of the OEM-bases CC is Pt and Pd (for oxidation) and Rh for reduction. These metals are classified as noble metals because they are resistant to chemical oxidation at high temperatures. The role of these catalysts is to increase the contact area to achieve high oxidation activity and promote the oxidation and reduction processes at a temperature that is significantly lower than the temperatures at which these processes are carried out at present [23]. These metals are regarded as precious metals, and hence the fabrication of CC using these metals becomes expensive. The use of rare-earth metals increases with an increase in vehicular demand. This also results in future inflation in the price of metals and vehicles. Due to this reason, the price of diesel/petrol-based vehicles might increase in the coming years [24]. To address this problem, researchers are trying to use metal oxides as catalyst materials as they are low in cost and exhibit good thermal stability [25].

Ciambelli et al. [26] reported that  $Al_2O_3$ -supported ceramic foams had shown shorter regeneration and better conversion efficiency compared to commercial foams.

Makwana et al. [27] reported that in a diesel-based engines, the CO emission achieved when nickel is used as a catalyst is lower than that achieved using the OEM CC fabricated with Pt or Pd as a catalyst.

Kalam et al. [28] experimentally tested metal oxides such as  $TiO_2$  and Cobalt Oxide (CoO) as catalyst materials and compared their properties with the

properties of the OEM CC. They inferred that the use of  $TiO_2$  helps reduce the HC and CO emission by 40% and 41% compared to that of OEM CC. It was also found that these metal oxides exhibited light-off temperatures that were higher than those recorded for OEM catalysts.

Venkatesan et al. [29] studied the feasibility of using Copper Oxide (CuO)-based catalysts as substitutes for conventionally used Pt and Pd catalysts. It was observed that the use of CuO-coated CC helped achieve better HC and CO conversion efficiencies at all load conditions, compared to OEM CC, fabricated using Pt or Pd as the catalysts.

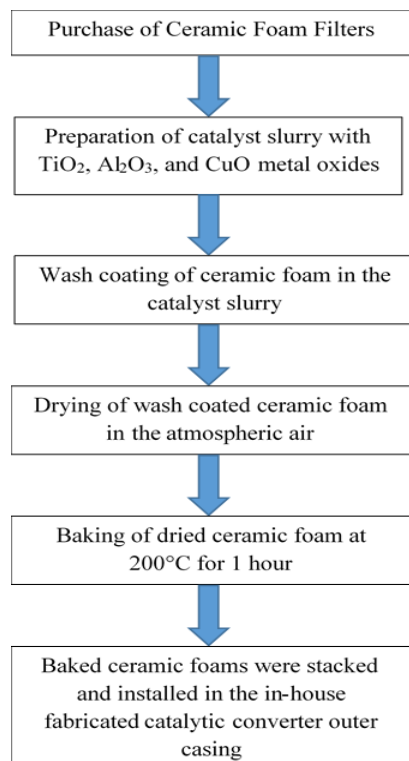
Chauhan [30] compared the conversion efficiencies of four different metal oxides ( $TiO_2$ , Calcium Oxide (CaO),  $Al_2O_3$ , and silicate kaolin) as oxidation catalysts and found that the HC and CO conversion efficiencies recorded with  $TiO_2$  were higher than those achieved using Pt and Pd catalysts. It has also been reported that these metal oxides also exhibit NOx reduction ability [31, 32].

Analysis of literature reports revealed that ceramic foam filters performed better than a honeycomb monolith in terms of emission conversion efficiency. However, limited studies are available on the engine emissions and performance characteristics of ceramic foam filters used as substrates in CC. To date, researchers have studied the performance of the ceramic foam filters using Pd, Pt, and Rh as catalyst materials. Studies using metal oxides as catalyst materials (in combination with ceramic foam filters) have not been reported. This research gap was addressed by us. We tested ceramic foam filters (in a diesel engine) coated with metal oxides. The performance was evaluated in terms of emission conversion efficiency and engine Brake Thermal Efficiency (BTE), and the results were compared with that of OEM's CC (3-way CC), which was installed with Pd, Pt, and Rh metal-coated honeycomb monolith.

The metal oxides  $TiO_2$ ,  $Al_2O_3$ , and CuO, used for our studies, have been identified as the most potential substitutes for Pt and Pd (oxidation catalyst metals) and Rh (reduction catalyst metal) by analyzing literature reports. These metal oxides are easily available and cheaper than noble metals. Hence, these metal oxides were used as catalyst materials to coat the ceramic foam filters. Their influence on oxidation and reduction of toxic gases (HC, CO, and  $NO_x$ ) were also studied.

### 3.Methods

The catalytic converter installed with metal oxide-wash coated ceramic foam filter substrate was fabricated in-house. *Figure 1* depicts a flow chart, which presents the outline of the procedure involved in the fabrication of the ceramic foam filter catalytic converter. The conventional methods followed for the fabrication of OEM-manufactured CC were used for the preparation of the catalyst slurry, coating of slurry on the foam filter, and fabrication of CC [33].



**Figure 1** Procedure involved in the fabrication of the ceramic foam filter catalytic converter

#### 3.1 Ceramic foam filters

The ceramic foam filters were purchased from Ceraflux India Private Limited. The foam filters were made of silica carbide. The foams were cylindrical (diameter: 40 mm; thickness: 20 mm). Six such foams were stacked following the wash coating process to obtain a ceramic foam of length 110 mm to match the length of the honeycomb monolith used by OEM to manufacture CC. Three such stacked ceramic foam filters were fabricated (one for each metal oxide catalyst). A ceramic foam filter with a cell density of 20 Pores per Inch (PPI) and porosity of 0.8 was used for analysis. The cell density and diameter of the honeycomb monolith manufactured by OEM were 400 Cells per Square Inch (cps) and 40 mm, respectively. *Figures 2a, 2b, 2c* present the honeycomb monolith, single ceramic foam filters, and stacked ceramic foam filters, respectively. For the same volume, ceramic foam filters have a lesser surface area compared to the honeycomb structure.

#### 3.2 Preparation of the catalyst slurry

A slurry was prepared using a solution of sodium silicate and powdered metal oxide to wash coat the ceramic foam filters with metal oxides ( $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{CuO}$ ). Sodium silicate acts as a binder and helps to bind the catalyst material to the ceramic substrate. In this process, 500 ml of a solution of sodium silicate was taken in a glass beaker, and 10 g of the powdered metal oxide added to it. A small amount of distilled water was added to the mixture to lower the viscosity of the solution. The slurry was stirred continuously for 3 h using a magnetic stirrer. Separate slurry was prepared for each metal oxide sample. *Figure 3* shows the process of slurry preparation for the wash coating process.



**Figure 2** a) Honeycomb monolith, b) single ceramic foam filter, and c) stacked ceramic foam filter





**Figure 3** Preparation of metal oxide catalyst

### 3.3 Wash coating of ceramic foam in catalyst slurry

The wash coating process using ceramic foams was conducted by manually dipping the foam samples in the prepared catalyst slurry. The foam samples were held in the slurry for 2 min. Subsequently, the foams were taken out and air-dried for 1 h. Then pores blocked by the slurry solution were opened by carefully spraying compressed air through it without damaging the wash coat deposited on the other parts of the foams. Following this, the wash-coated ceramic foams were baked in the furnace at 200 °C for 1 h to fuse the coated slurry to the substrate. This process was repeated until the weight of the foams increased

by approximately 15% of its base weight. *Figure 4* shows the wash-coated ceramic foam filters prepared for testing.

The role of the wash coat is to increase the surface area of the substrate to achieve maximum exposure to the exhaust gas. This can help achieve high conversion efficiency. The wash coating process results in the formation of rough pores and irregular structures on the substrate. The use of metal oxide as a catalyst material helps generate active sites on the substrate on which the catalytic reaction takes place.

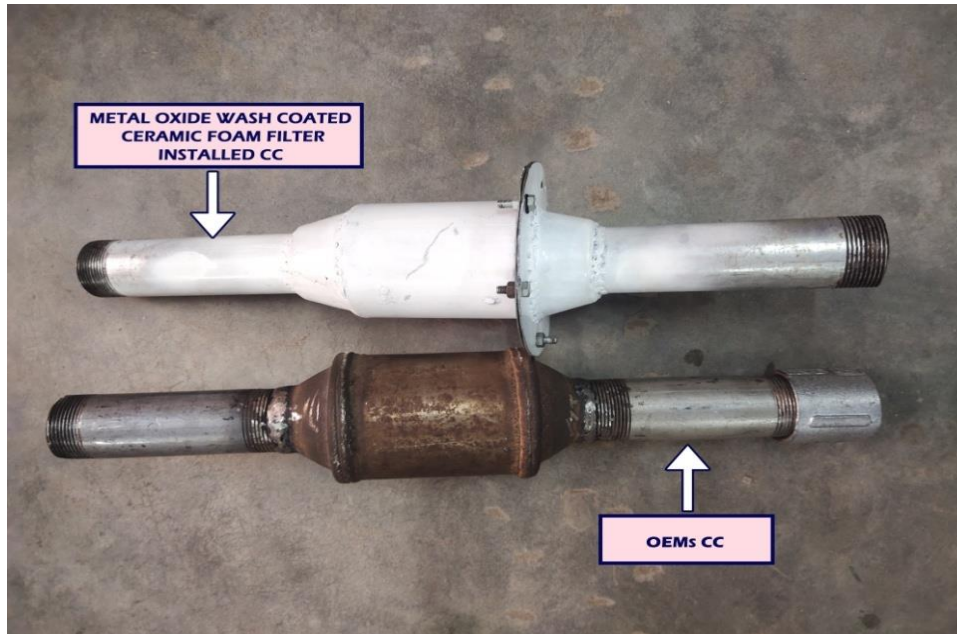


**Figure 4** Wash-coated ceramic foam filters

### 3.4CC fabrication

The outer casing of the CC was fabricated in-house as per the CC dimensions reported by OEM to install the in-house fabricated wash-coated ceramic foam filters. Following this, the metal oxide wash-coated ceramic foam filter was installed in the fabricated CC. *Figure*

5 shows the image of the honeycomb monolith-installed CC manufactured by the OEM. The metal oxide wash-coated ceramic foam filter was subsequently installed.



**Figure 5** Images of OEM-manufactured CC and ceramic foam-installed CC

### 3.5Research engine

We used a four-stroke-twin cylinder diesel engine (make: Mahindra) to conduct the experiments. The engine could be water-cooled. An eddy current dynamometer was connected to the engine via shafts and the process of coupling to tune the applied load on the engine. The dynamometer was loaded with the help of an S-type load cell, which was controlled electronically using a loading device. A cold water circuit surrounding the dynamometer cooled the engine by removing the heat generated during loading. The speed of the engine was maintained at 1500 rpm under all load conditions by adjusting the accelerator pedal position, which consists of a position sensor. The accelerator was adjusted manually with the help of a rotating handwheel.

Bosh Electronic Control Unit (ECU) is provided for the Electronic Fuel Injection (EFI) system. The EFI

system consists of a low and high-pressure fuel pump, a common rail, and an electronic fuel injector. The ECU controls the fuel injection quantity at various operating conditions as per the user's specified settings. In an open ECU, different parameters, such as fuel injection pressure, main injection angle, pilot injection angle, and pilot injection quantity, can be specified by the user using the "tuner pro" software. We set the fuel injection pressure at 300 bars under all the tested operating conditions. The other parameters were kept unaltered under standard settings. The fuel consumption was measured using an electronic weighing machine. An exhaust gas analyzer (make: Netel) was used to measure the CO, NO<sub>x</sub>, and HC contents in the exhaust gas. *Figure 6* shows the schematic representation of the engine under study with various accessories. The engine specifications are given in *Table 1*. *Figure 7* shows the image of the CC-fitted diesel engine.

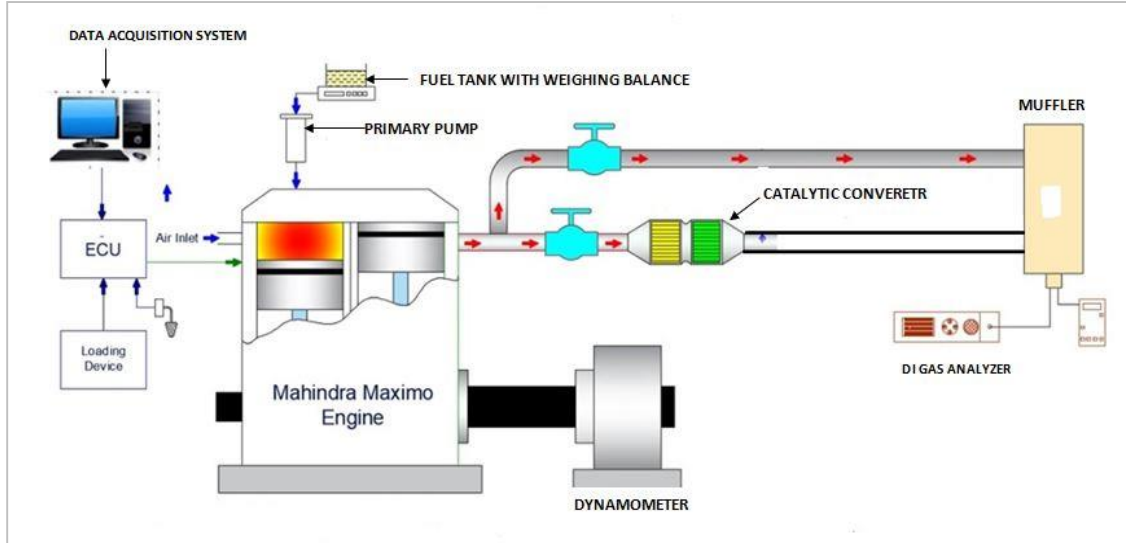


Figure 6 Schematic representation of the engine



Figure 7 Image of the CC-fitted with a diesel engine

Table 1 Specification of diesel engine

S.No.	Parameters	Specification
1	Make/Model	Mahindra Maximo
2	Bore Diameter	83mm
3	Stroke length	84mm
4	Fuel Injection Type	CRDI (Common Rail Direct Injection)
5	Displacement (swept Volume)	909 cc
6	Maximum Torque	50 Nm
7	Maximum Power	19.2 kW
8	Maximum Load in Dynamometer Load cell	18 kg
9	Fuel	Diesel



### 3.6 Engine operating procedure

Initially, the engine was allowed to run for 15 min in the presence of diesel under idling conditions. This helped the engine and the CC to warm up for operation. The emission tests were performed at various engine brake powers such as 1.08, 2.17, 3.26, 4.34, and 5.43 kW. The engine speed was set at 1500 rpm. Initially, the emission readings for the OEM-manufactured CC were recorded. The OEM consists of two honeycomb substrates: one wash-coated with Pt and Pd and the other with Rh. The OEM-manufactured 3-way catalyst CC follows the BS-IV emission norms. Then metal oxide-wash coated

ceramic foam filter installed CC (one CC for each metal oxide catalyst) was fitted at the exhaust tailpipe, and the readings were separately recorded for each metal oxide catalyst. At each brake power, fuel consumption and emissions (HC, NO<sub>x</sub>, and CO) were noted thrice, and the mean values were used to determine the performance and emission abilities. At the beginning of each measurement, the leftover gases from previous experiments present in the gas analyzer probe were purged completely. *Table 2* shows the ranges and accuracy of the measuring devices used for testing.

**Table 2** Range and accuracy of the measuring device

S.No.	Device	Measured	Range	Accuracy
1	Load cell	Load	0-100 kg	± 0.2 kg
2	Magnetic pickup sensor	Speed	0-5000 rpm	± 10 rpm
3	Electronic weighing machine	Fuel consumption	0-10 kg	± 0.001 kg
4	NETEL multi-gas analyzer	CO	0-10% vol.	± 0.02 %
		HC	0-2000 ppm	±5 ppm
		NO <sub>x</sub>	0-5000 ppm	±20 ppm

### 3.7 Calculations

The derived parameters, such as BTE, CO, HC, and NO<sub>x</sub> conversion efficiencies were calculated from the measured parameters, such as fuel consumption, CO, HC and NO<sub>x</sub> emission, respectively, using the following formulae:

$$\text{BTE} = \frac{\text{Brake Power}}{\text{CV} \times \text{m}_f} \times 100 (\%), \quad (1)$$

Where CV and m<sub>f</sub> indicate the calorific value (kJ/kg) and mass flow rate of fuel (kg/s), respectively.

$$\text{CO Conversion Efficiency} = \frac{\text{CO}_{\text{woc}} - \text{CO}_{\text{wc}}}{\text{CO}_{\text{woc}}} \times 100 (\%) \quad (2)$$

Here, CO<sub>woc</sub> and CO<sub>wc</sub> denote the CO emission measured in the presence and absence of CC (% volume), respectively.

$$\text{HC Conversion Efficiency} = \frac{\text{HC}_{\text{woc}} - \text{HC}_{\text{wc}}}{\text{HC}_{\text{woc}}} \times 100 (\%) \quad (3)$$

Here, HC<sub>woc</sub> and HC<sub>wc</sub> denote the HC emission measured in the presence and absence of CC (ppm), respectively.

$$\text{NO}_x \text{ Conversion Efficiency} = \frac{\text{NO}_{x\text{woc}} - \text{NO}_{x\text{wc}}}{\text{NO}_{x\text{woc}}} \times 100 (\%) \quad (4)$$

Here, NO<sub>xwoc</sub> – NO<sub>xwc</sub> denotes the NO<sub>x</sub> emission measured in the presence and absence of CC (ppm).

The estimated values of BTE, CO, HC, and NO<sub>x</sub> conversion efficiencies with respect to various engine brake powers for Original Equipment Catalytic Converter (WOECC) containing honeycomb monolith as a substrate and supported with Pt and Pd as catalyst materials, and TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and CuO metal oxide-coated ceramic foam filters are presented in *Appendix-I*.

## 4. Results

### 4.1 Brake thermal efficiency (BTE)

*Figure 8* compares the BTE recorded for WOECC and that recorded for the ceramic foam filter wash coated with TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and CuO. The BTE increases with an increase in the engine brake power. This is due to the improvement in the engine in-cylinder operating conditions which enhances the rate of fuel evaporation and improves the air-fuel mixing process. This results in better combustion.

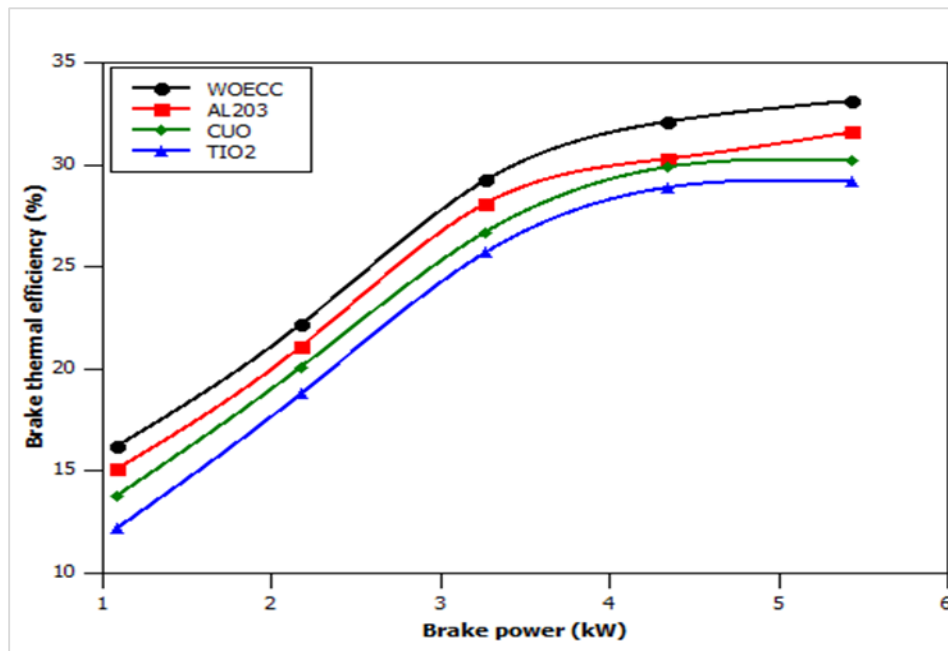
The BTE recorded for the ceramic foam filter as a substrate was lower than that recorded for WOECC. At 5.43 kW, the BTEs of the ceramic foam filter wash-coated with Al<sub>2</sub>O<sub>3</sub>, CuO, and TiO<sub>2</sub> were 31.6%, 30.2%, and 29.2%, respectively. The values were lower than the value obtained using the honeycomb substrate [33.14%]. This can be attributed to a comparatively higher drop in pressure across the ceramic foam substrate (compared to that observed across the honeycomb monolith substrate). The high drop in pressure could be attributed to a greater flow



resistance offered by the former in comparison to the latter [15, 21]. This resulted in higher back pressure, which pushed the exhaust gases back to the engine side and increased the contents of the diluent gas inside the engine cylinder. This increase in the amounts of the diluents (exhaust gases) resulted in a loss in engine power. A slight increase in fuel consumption, resulting in the reduction in BTE for the ceramic foam filters, was observed. Under conditions of minimum BP, the BTEs recorded for  $\text{Al}_2\text{O}_3$ ,  $\text{CuO}$ , and  $\text{TiO}_2$  were 6.9%, 14.9%, and 24.7% lesser than the BTE recorded for the honeycomb monolith, respectively.

It was also observed that BTE varied with the type of metal oxides used as the catalyst material in the ceramic foam filter. The trend of BTEs recorded with

the metal oxides was determined:  $\text{Al}_2\text{O}_3 > \text{CuO} > \text{TiO}_2$ . The same trend was observed under conditions of all the tested engine brake powers. At 1.08 kW, the BTEs of the ceramic foam filter wash coated with  $\text{Al}_2\text{O}_3$ ,  $\text{CuO}$ , and  $\text{TiO}_2$  were 15.1%, 13.8%, and 12.2%, respectively. This can be attributed to the variation in the catalytic activities of the different metal oxide catalysts. The trend in the catalytic activities was determined:  $\text{Al}_2\text{O}_3 < \text{CuO} < \text{TiO}_2$  [34, 35]. A higher catalytic activity increases the flow resistance across the ceramic substrate, which in turn increases the pressure drop and reduces the BTE of  $\text{CuO}$  and  $\text{TiO}_2$  catalysts. The BTEs recorded for these catalysts were lower than that recorded for  $\text{Al}_2\text{O}_3$  wash coated ceramic foam substrate.



**Figure 8** Comparison of BTE WOECC and ceramic foam filter wash coated with different oxide-based catalysts

#### 4.2 CO conversion efficiency

The CO conversion efficiencies recorded for WOECC and the ceramic foam filter substrate wash coated with metal oxides are presented in *Figure 9*. A similar trend was observed for both CCs. The CO emission conversion efficiency decreased gradually with an increase in the brake power. At 1.08 kW, the CO conversion efficiencies recorded for WOECC and  $\text{TiO}_2$ -coated ceramic foam installed CC were 89% and 95%, respectively, whereas, at 5.43 kW, the values were 80% and 88%, respectively. This is due to a slight increase in an equivalence ratio (i.e., the mixture at higher loads is richer than the mixture at lower loads). This results in low oxygen levels in the exhaust under

conditions of high loads [2, 5]. This, in turn, lowers the catalytic activity and results in lesser conversion efficiency under conditions of high loads.

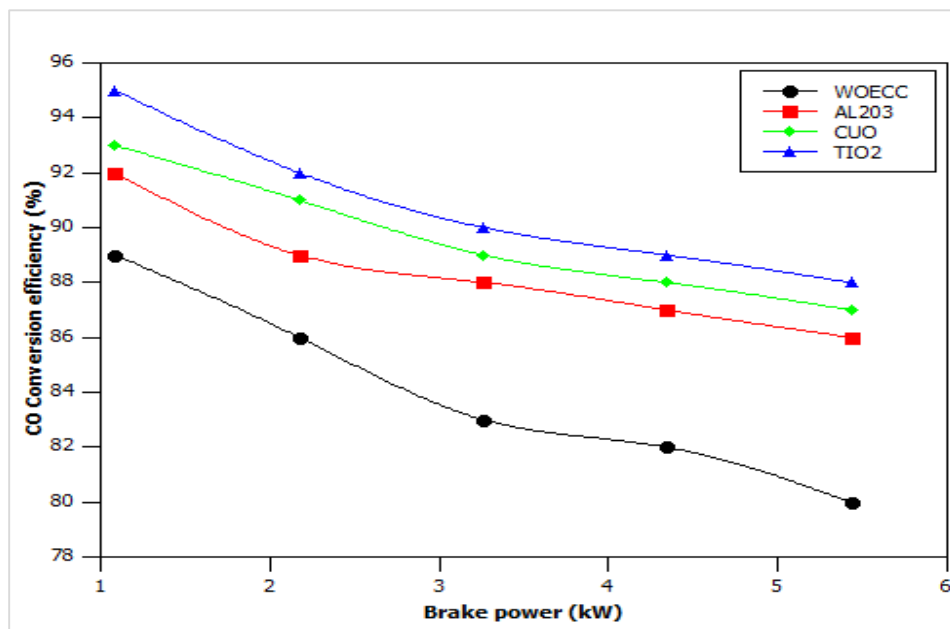
Compared to WOECC, the metal oxide wash-coated ceramic foam substrate shows higher CO conversion efficiency. At maximum brake power, the CO conversion efficiencies across the honeycomb monolith ceramic foam filter coated with  $\text{Al}_2\text{O}_3$ ,  $\text{CuO}$ , and  $\text{TiO}_2$  were 80%, 86%, 87%, and 88% respectively. At minimum power, it was 89%, 92%, 93%, and 95%, respectively. This can be attributed to the fact that the structure of the ceramic foam induces turbulent flow across the foam filter, whereas, inside the honeycomb,

the flow is laminar [11]. The turbulent flow enhances the heat and mass transfer characteristics, resulting in the better activation of the ceramic foam filter compared to the honeycomb substrate [19, 36, 37]. Under conditions of turbulent flow, the species mixing ability is enhanced. Subsequently, the contact area for the exhaust gas species with the substrate increases. This leads to higher conversion rates in the presence of ceramic foam filters. Even though for the same volume, ceramic foam filter exhibits a lesser surface area than the honeycomb structure, the turbulent flow inside the former increases the conversion rates compared to the latter.

It was observed that the differences between the CO conversion efficiencies recorded for WOEC and metal oxide wash-coated ceramic foam substrates were higher under conditions of elevated engine loads than those recorded under conditions of lesser loads (Figure 9). This is because, compared to the Pt and Pd catalysts, the efficiencies of the metal oxide catalysts are higher at higher temperatures [32]. An increase in

the engine power results in an increase in the exhaust gas temperature [30, 31]. Thus the difference in conversion efficiency is higher under conditions of higher engine brake power.

Among the three metal oxide-coated ceramic filters, the TiO<sub>2</sub> wash-coated ceramic foam filter exhibits the maximum CO conversion efficiency. This is followed by CuO and Al<sub>2</sub>O<sub>3</sub>. At 1.08 kW, the CO conversion efficiency recorded for TiO<sub>2</sub> is higher by approximately 2% and 3% compared to CuO and Al<sub>2</sub>O<sub>3</sub>, respectively. At 5.43 kW, it is higher by approximately 1% and 2%, respectively. This is because TiO<sub>2</sub> exhibits better catalytic activity in comparison to the other two metal oxides. The major reason is that titanium has a greater affinity for oxygen compared to the other two metals [38]. Hence, oxygen is conveniently adsorbed onto the active sites formed by TiO<sub>2</sub>, resulting in better oxidation of CO. Hence, the conversion rate is high for the TiO<sub>2</sub> wash-coated ceramic foam filter.



**Figure 9** CO conversion efficiencies recorded for WOEC and different oxide catalyst wash coated ceramic foam filters

#### 4.3 HC conversion efficiency

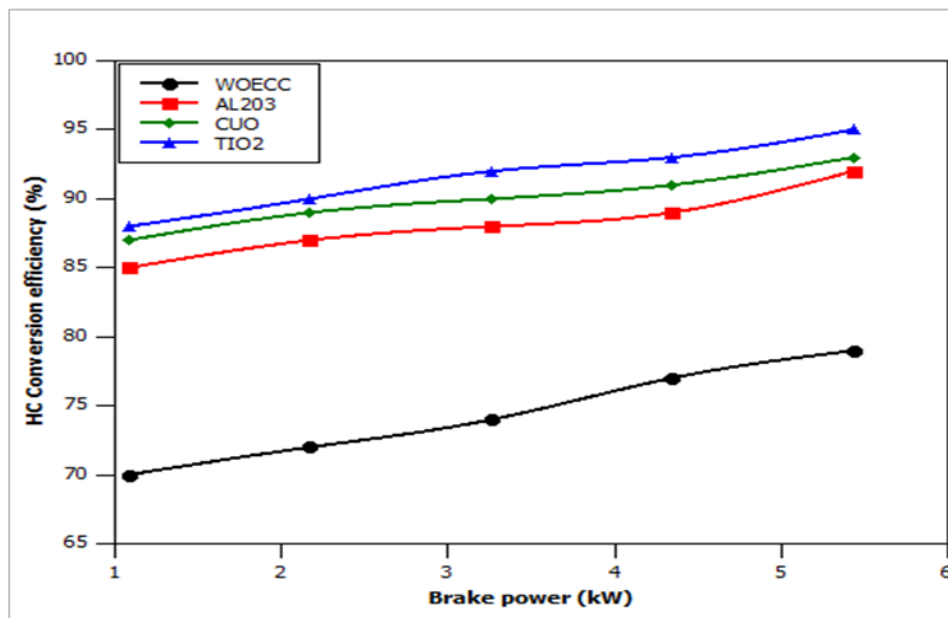
Figure 10 depicts the trend of the HC conversion efficiency exhibited by WOEC and metal oxide wash-coated ceramic foam filters. It was observed that the HC conversion efficiency, increased gradually with the increase in the brake power. Similar trends were exhibited by both honeycomb and ceramic foam

substrates. The reason is that an increase in the brake power results in an increase in the exhaust gas temperature. This, in turn, enhances the catalytic activity and results in increased conversion efficiency [25].

When compared to the honeycomb substrate, the ceramic foam exhibits higher conversion efficiency as higher turbulence are induced when the exhaust gas flows through the ceramic foam [15, 20]. The effect of turbulence on conversion is discussed in the aforementioned Section 4.2. At 5.43 kW, the HC conversion efficiencies across the honeycomb monolith, ceramic foam filter coated with  $\text{Al}_2\text{O}_3$ ,  $\text{CuO}$ , and  $\text{TiO}_2$  were 79%, 92%, 93%, and 95%, respectively, whereas, at 1.08 kW, the efficiencies were 70%, 85%, 87%, and 88%, respectively. The use of metal oxides helps increase the conversion efficiency because effective oxidation of unburned hydrocarbons can be achieved in their presence [29, 30]. The metal oxides form rich, acidic sites and

inherent oxygen present in them, contributing to the oxidation process [32]. Thus, a high HC conversion efficiency can be achieved using metal oxides as catalyst materials.

It is also inferred from *Figure 10* that among all the metal oxides, the maximum conversion efficiency is recorded for  $\text{TiO}_2$ . As titanium has a greater affinity toward oxygen [38, 39], it can potentially help in faster oxygen adsorption on the active catalytic sites where the oxidation reaction takes place. This factor also contributes to the enhancement in the rate of oxidation and helps in achieving high conversion efficiency.



**Figure 10** HC conversion efficiencies recorded for WOEC and metal oxide catalyst wash coated ceramic foam filters

#### 4.4 NO<sub>x</sub> conversion efficiency

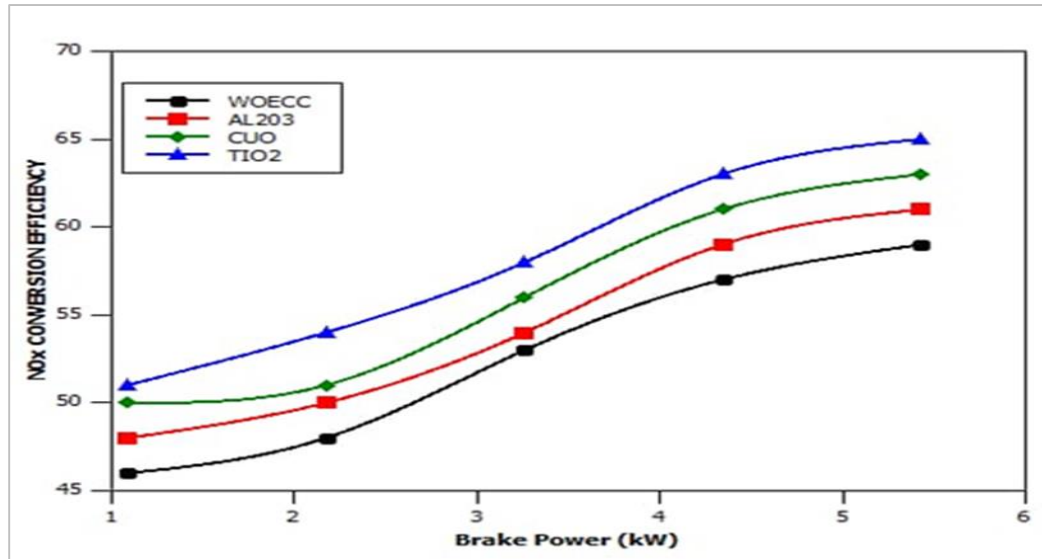
*Figure 11* shows the NO<sub>x</sub> conversion efficiencies recorded for WOEC and metal oxide-coated ceramic foam filters. The NO<sub>x</sub> conversion efficiency increases with an increase in the brake power for both honeycomb and ceramic foam substrates. This can be attributed to the increase in the temperature of the exhaust, which enhances the catalytic activity across the substrate [30, 31]. The metal oxide coated ceramic foam can help reduce NO<sub>x</sub> emissions. This can be attributed to the excellent redox property of the metal oxides [32]. Also, the turbulence created by the ceramic structure played a vital role in the reduction of NO<sub>x</sub> emission. The turbulence enhances the rate of contact and heat transfer characteristics, which help activate the entire foam bed in a short period. These

results in an improved emission conversion rate and better performance of the foam filter. The conversion efficiency exhibited by the metal oxide-coated ceramic foam is slightly higher than that recorded for WOEC. At 5.43 kW, the NO<sub>x</sub> conversion efficiencies for WOEC,  $\text{Al}_2\text{O}_3$ ,  $\text{CuO}$ , and  $\text{TiO}_2$  coated ceramic foam were 59%, 61%, 63%, and 65%, respectively. At 1.08 kW, the NO<sub>x</sub> conversion efficiencies for  $\text{Al}_2\text{O}_3$ ,  $\text{CuO}$ , and  $\text{TiO}_2$  coated ceramic foam were 4.3%, 8.6%, and 10.8%, respectively, higher than that recorded for WOEC.

The maximum conversion efficiency was exhibited by  $\text{TiO}_2$ . The Rutile phase of  $\text{TiO}_2$  is stable at very high temperatures. This helps catalyze the decomposition of NO to  $\text{N}_2$  and O [39, 40]. Though metal oxide wash-

coated foam filter helps reduce NO<sub>x</sub> emission, the level of emission achieved post treatment is still higher than the current emission standards (BS-VI norms). The NO<sub>x</sub> conversion efficiency can be improved further if the catalysts are used in combination with the

Selective Catalytic Reduction (SCR) system. Complete list of abbreviations is shown in *Appendix II*.



**Figure 11** NO<sub>x</sub> conversion efficiencies recorded for WOECC and oxide catalyst wash coated ceramic foam filter

## 5. Discussion

It was observed that the ceramic foam filters (used as converter substrates) performed better than the conventional honeycomb monoliths irrespective of the engine brake power. This can be attributed to the fact that an exchange of momentum perpendicular to the direction of flow induces turbulence within the ceramic foam filters, enhancing the heat and mass transfer characteristics. The enhanced characteristics can be attributed to the significantly higher Sherwood and Nusselt numbers recorded in these cases (compared to the numbers recorded during the laminar flow inside honeycomb substrate). Homogeneous thermal and chemical loads inside the ceramic foam filters are generated under these conditions. The turbulence helps in better mixing of species, which facilitates the complete oxidation of HC and CO. It also helps achieve high conversion rates.

The emission conversion efficiency recorded for the ceramic foam filters was higher than that recorded for the honeycomb monolith substrate. The metal oxides were better catalyst materials than the conventional catalyst materials (Pd, Pt, and Rh) under the testing conditions. The BTEs recorded for the ceramic foam filters were lower than those recorded for the honeycomb monolith. This can be attributed to a higher pressure drop, attributable to the higher flow

resistance offered by the former in comparison to the latter. The structure of the ceramic foam should be modified to reduce the extent of pressure drop. Structural modifications of the ceramic foams are being simulated by numerous researchers.

The key findings are presented as follows:

- Metal oxide-coated ceramic foam offers high HC, CO, and NO<sub>x</sub> emission conversion efficiencies at the expense of engine BTE.
- The maximum conversion efficiency is achieved using TiO<sub>2</sub>, followed by CuO and Al<sub>2</sub>O<sub>3</sub>.

The potential limitations of this study are:

1. The performance and emission tests were limited to a stationary engine. The emission test should be performed during driving cycles, which would simulate the real road driving conditions.
2. The conversion efficiencies of the foams were tested after the light-off temperature was reached. The performances should be studied under cold conditions.
3. The filters got clogged with the particulate matter when the engine was run using ceramic foam filters that were ≤ 10 PPI. This resulted in severe engine backpressure, and subsequently, the engine stopped.



## 6. Conclusion and future work

The ceramic foam filters were wash coated with different metal oxides such as  $\text{Al}_2\text{O}_3$ ,  $\text{CuO}$ , and  $\text{TiO}_2$ , which were used as catalyst materials. The wash-coated ceramic foam filters were installed in the in-house fabricated CC casing. The performance of the engine fabricated with ceramic foam CC and the CO and HC emission conversion efficiencies was tested for a diesel engine. The results were compared with the results obtained with the OEM-manufactured CC that was installed with honeycomb monolith as the substrate and wash-coated with the conventionally used Pd and Pt metal catalysts. The results obtained from the experiments have been summarized as follows:

The BTEs recorded in the engine fabricated with  $\text{Al}_2\text{O}_3$ ,  $\text{CuO}$ , and  $\text{TiO}_2$  wash coated ceramic foam filters were 31.6%, 30.2%, and 29.2%, respectively. The values were lower than the BTE values recorded for the OEM-manufactured CC under conditions of the maximum engine load. The BTE recorded for the OEM-manufactured CC was 33.14%.

The CO conversion efficiencies recorded for the CCs fabricated using  $\text{Al}_2\text{O}_3$ ,  $\text{CuO}$ , and  $\text{TiO}_2$  coated ceramic foams at full load were 86%, 87%, and 88%, respectively, at 5.43 kW. The values were higher than the values recorded for the Pd and Pt-coated honeycomb monolith (80%). The HC conversion efficiency of the ceramic coated with metal oxides was higher than the HC conversion efficiency of the OEM-manufactured CC. The HC conversion efficiencies of the OEM-manufactured CC,  $\text{Al}_2\text{O}_3$ ,  $\text{CuO}$ , and  $\text{TiO}_2$ -coated ceramic foam were 79%, 92%, 93%, and 95%, respectively, under conditions of full load. The  $\text{NO}_x$  conversion efficiency recorded for the metal oxide-coated ceramic foam filter was higher than that recorded for the honeycomb monolith substrate coated with rhodium. It can be concluded that a ceramic foam filter with metal oxide coating can be potentially used to replace the conventionally used noble metal-coated honeycomb monolith when the pressure drop across the foam (resulting in reduced BTE) is low.

The sustainability and efficiency of the ceramic foam filters at long hours of engine run is to be studied in the future to find out its limitations and probability of their applicability in commercial engines. Also, the catalytic activity of metal oxides at low temperatures should be studied.

## Acknowledgment

None.

## Conflicts of interest

The authors have no conflicts of interest to declare.

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## Appendix I Observation

**Table 3** Brake power Vs brake thermal efficiency

BP	WOECC	Brake thermal efficiency		
		Al <sub>2</sub> O <sub>3</sub>	CUO	TiO <sub>2</sub>
1.08	16.22	15.1	13.8	12.2
2.17	22.2	21.1	20.1	18.8
3.26	29.23	28.1	26.7	25.7
4.34	32.12	30.3	29.9	28.9
5.43	33.14	31.6	30.2	29.2

**Table 4** Brake power Vs Nox conversion efficiency

BP	WOECC	NO <sub>x</sub> conversion efficiency		
		Al <sub>2</sub> O <sub>3</sub>	CUO	TiO <sub>2</sub>
1.08	46	48	50	51
2.17	48	50	51	54
3.26	53	54	56	58
4.34	57	59	61	63
5.43	59	61	63	65

**Table 5** Brake power Vs CO conversion efficiency

BP	WOECC	CO conversion efficiency		
		Al <sub>2</sub> O <sub>3</sub>	CUO	TiO <sub>2</sub>
1.08	89	92	93	95
2.17	86	89	91	92
3.26	83	88	89	90
4.34	82	87	88	89
5.43	80	86	87	88

**Table 6** Brake power Vs HC conversion efficiency

BP	WOECC	HC conversion efficiency		
		Al <sub>2</sub> O <sub>3</sub>	CUO	TiO <sub>2</sub>
1.08	70	85	87	88
2.17	72	87	89	90
3.26	74	88	90	92
4.34	77	89	91	93
5.43	79	92	93	95

**Appendix II**

S. No.	Abbreviation	Description
1	Al <sub>2</sub> O <sub>3</sub>	Aluminium Oxide
2	BTE	Brake Thermal Efficiency
3	CaO	Calcium Oxide
4	CC	Catalytic Converters
5	CO	Carbon Monoxide
6	CoO	Cobalt Oxide
7	cpai	Cells per Square Inch
8	CRDI	Common Rail Direct Injection
9	CuO	Copper Oxide
10	DPF	Diesel Particular Filter
11	DOC	Diesel Oxidation Catalyst
12	ECU	Electronic Control Unit
13	EFI	Electronic Fuel Injection
14	HC	Hydrocarbon
15	NO, NO <sub>2</sub> , NO <sub>x</sub>	Oxides of Nitrogen
16	OEM	Original Equipment Manufacturer
17	Pd	Palladium
18	PPI	Pores per Inch
19	Pt	Platinum
20	Rh	Rhodium
21	SCR	Selective Reduction Catalyst
22	TiO <sub>2</sub>	Titanium Dioxide
23	WOECC	With Original Equipment Catalytic Converter