CAT-TRAP exhaust after treatment system for diesel engine

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Accepted 3rd February, 2011

This paper presents development of new developed cost effective CAT-TRAP system for diesel engine to reduce NOx and particulate matter. CAT-TRAP system is a combination of pellets type catalytic converter (CAT) and foam type particulate Trap (TRAP). The CAT was developed based on catalyst materials consisting of combination of metal catalyst such as cerium oxide (CeO₂), zirconium dioxide (ZrO₂) and silver nitrate (AgNO₃) with pellets substrate. These catalyst materials are inexpensive in comparison with conventional catalysts (noble metals) such as palladium or platinum. The Trap was developed with indigenous materials for minimum pressure drop and maximum filtration efficiency. The CAT-TRAP (CAT C2D1L1 (C2 = Ag/CeO₂/ZrO₂ catalysts, D1 =132 mm and L1=20 mm) + TRAP P1D2L1 (P1 = 70-75%, D2 =125 mm and L1=20 mm) gives back pressure range (50-266 mbar). Minimum increase in brake specific fuel consumption was (0.4 - 3.70%), minimum decrease in brake thermal efficiency was (0.38- 2.26%) and loss in brake power was (0.57 - 1.60%). The CAT-TRAP (C2D1L1 + P1D2L1) gives filtration efficiency range (65-72%) and NOx conversion efficiency was (65%). The objective of this paper is to develop cost effective CAT-TRAP system to reduce NOx and particulate matter from the exhaust of diesel engine. Detailed review on catalytic converter, Trap, inexpensive CAT-TRAP development, performance evaluation and engine test results have been presented with discussions.

Key words: Catalyst, emissions, trap, C.I. engine, spherical pellets, Ag/CeO₂/ZrO₂.

INTRODUCTION

The modern diesel engine is one of the most versatile power sources available for automotive applications. The high fuel economy and torque benefits coupled with excellent drivability of the turbo-charged diesel engine is leading to its global use in heavy and light duty applications. The diesel engine has superior thermal efficiency than its gasoline counterpart owing to its increased compression ratio. Also, fuel is directly injected into the cylinder based on the accelerator pedal position, thus minimizing the throttling losses in diesel engine. The fuel consumption for diesel is 35% lower than a similar gasoline engine. The diesel engine, along with these advantages of superior performance, presents a very challenging problem in terms of its emissions reduction and control. Diesel engines convert the chemical energy contained in diesel fuel into mechanical power. The exhaust gases that are discharged from the engine contain several constituents that are harmful to human health and to the environment (Hesterberg et al 2009). Typical diesel engine emissions consist of two major components, namely: particulate matter (PM) and oxides of nitrogen (collectively referred to as NOx), (Richards et al., 2001; Timothy et al., 2010). These exhaust components are typically present in an oxygen rich environment, at temperatures ranging between 150 - 450°C. The adverse effects of vehicular emission or pollutants due to increase in vehicular population will become ten fold in next ten years. So, it is essential to play attention on the emission control activity that is, on the development of the emission control devices.
A catalytic converter is a device used to reduce the exhaust pollutant gases from an internal combustion engine. Pollutant gases flowing out of the engine pass through it and undergo chemical processes by which they are converted into relatively harmless gases. Gas flows through the passages and reacts with catalyst within the porous wash-coat (Akkarat et al., 2008). Diesel particulate Trap (DPT) or filter (DPF) is a device which is fitted to the exhaust system in diesel driven vehicles and reduces the smoke density of diesel exhaust by Trapping of particulate matter.

In this investigation, a new type of catalytic converter based on Ag/CeO$_2$/ZrO$_2$ materials with pellets substrate and cost effective particulate TRAP with indigenous ceramic materials has been developed to reduce NOx emissions and particulate matter from diesel engine exhaust (Julia et al., 2004; Bose et al., 2005). The advantages of this CAT-TRAP system are stated as inexpensive, domestically available and higher substrate area which is efficient to oxidize/reduction of particulate matter and NOx emission.

**Catalyst and substrate preparation**

**Material selection for catalyst**

In this study, combination of catalyst with proper aqueous molar ratios and weight ratios are used. Cerium oxide, zirconium dioxide and silver nitrate were used as a metal catalyst. Silver nitrate is used as a reducing agent. Cerium oxide acts as an oxygen buffer by storing excess oxygen under oxidizing (lean) conditions and releasing it in rich (reducing) conditions. Zirconium dioxide is used to enhance the thermal stability and strength of catalyst (Akkarat et al., 2008).

**Silver nitrate / CeO$_2$ – ZrO$_2$ catalyst slurry**

The Ag/CeO$_2$-ZrO$_2$ catalyst was prepared by the incipient wetness method with aqueous solution of AgNO$_3$. The desired amount of AgNO$_3$ aqueous solution was added to certain amount of CeO$_2$ and ZrO$_2$, the resulting solution was first stirred at room temperature for 8 h on magnetic stirrer with magnetic pad to evaporate water. 15 gm of silver nitrate with 7.5 gm cerium oxide and 2.5 gm zirconium dioxide were added in 200 ml distilled water to get slurry (Julia et al., 2004). The silver catalysts were prepared by incipient wetness impregnation of AgNO$_3$.

**Substrate coating**

The pellets were coated with the metal catalysts with dipping technique. In this process, spherical pellets were immersed into prepared catalyst slurry for 2 h duration (Figure 1).

Pellets were removed from catalyst slurry and were kept at a room temperature for 1 h. Coated pellets were dried in an electric oven at 110°C for 4 h. Then the pellets were removed from oven for blowing off residual catalyst from alumina pellets surface. Further the coated pellets were then calcined in muffle furnace. Calcination process takes 6 h at a temperature of 500°C. After the calcination process the coated pellets were arranged in perforated circular housing to form substrate (Kalam et al., 2009). (Figure 2)

**Fabrication of TRAP**

The cost effective particulate Trap was developed with indigenous ceramic materials (Miwa et al., 2001; Abraham et al., 2005). Different percentage compositions of indigenous ceramic raw materials were tried to develop Traps. Three different percentage compositions of ceramic raw materials were recommended to develop porous structure. The percentage composition for Trap “P1” was local clay 39%, Feldspar 7.8%, Quartz 5.2%, Kaishulghar 20%, and wood saw dust 28%. Percentage composition for Trap “P2” was local clay 39%, Feldspar 7.8%, Quartz 5.2%, Kaishulghar 20%, and wood saw dust 28%, and then slip of this composition (80% by volume) added with Terracotta slip (20% by volume). Percentage composition for Trap “P3” was local clay 35%, Feldspar 6%, Quartz 5%, Kaishulghar 14%, and coconut shell powder 40%. In the final composition of Trap ‘P1’, ‘P2’, and ‘P3’, separately 5% Grog was added. Slip casting method was used to develop Trap. Porosities of developed Traps were grouped with P1 = 70-75%, P2 = 65-70%, and P3 = 60-65 % (Deshpande et al., 2010) (Figure 3).

**Fabrication of CAT-TRAP assembly**

The CAT-TRAP assembly consists of components namely: catalytic converter canister, perforated circular housing, spacer ring, exhaust gas flow deflector, Trap canister, heating coil, ‘O’ ring for Trap, fixed supporting ring, arrangement for back pressure measurement, location for thermocouples and socket for heating coil. Commercial spherical pellets were used to form substrate for catalytic converter. A total of 1400 catalyst coated spherical pellets of average diameter 5 mm were arranged into perforated circular housing to form a substrate for catalytic converter (CAT) (Figure 1). The inner and outer diameter of circular housing was 132 and 140 mm respectively. A suitable flow deflector was located in the divergent portion of CAT-TRAP. A spacer fixed ring is fitted with housing to prevent leakage of exhaust gases. A catalyst coated (copper nitrate + cerium oxide) Trap/filter of diameter 125 mm and length 20 mm
was fitted in Trap canister. Thermocouples are used to measure the inside temperature of exhaust gas at various points.

CAT-TRAP housing (Figure 4b) should be capable to hold the perforated circular housing and Trap in vibrations during running tests and also to prevent the leakage of exhaust gas. This gives accurate emission conversion efficiency, filtration efficiency and back pressure results. CAT-TRAP assembly consists of mainly two parts that is, converter canister and Trap canister converter canister consists of perforated circular housing. Spacer ring is used to reduce back pressure. The material used for fabrication is mild steel. A heating coil was fitted near the Trap entry at a distance of 90 mm from Trap outlet canister which was used for heating exhaust gas before it flows to the Trap. Heating coil was made up of circular asbestos sheet with Nicrom wire of diameter 0.6 mm. To avoid short circuit, silicon bids were used with Nicrom wire and male female coil supply socket made up of poresillin were fitted in the grove of mild steel. Electric current socket was fitted on outer surface of CAT-TRAP housing. Trap was fitted in Trap 'O-ring with fixed supporting ring.

Trap was rested on this fixed supporting ring in a canister. This arrangement holds the Trap in same position during tests. Schematic diagram of CAT-TRAP assembly is given in Figure 4a.

**Reaction in catalytic converter**

Gases from exhaust port entered into substrate of catalytic converter. In the catalytic converter two chemical processes are occurred such as catalytic reduction and catalytic oxidation.

When an NO or NO₂ molecule contacts the catalyst, the catalyst rips the nitrogen atom out of the molecule and holds on to it, freeing the oxygen in the form of O₂. The nitrogen atoms bond with other nitrogen atoms that are also stuck to the catalyst, forming N₂. (Kalam et al., 2009; Julia et al., 2004)

\[
2\text{NO} \Rightarrow \text{N}_2 + \text{O}_2 \quad \text{or} \quad 2\text{NO}_2 \Rightarrow \text{N}_2 + 2\text{O}_2
\]

**Regeneration of the Trap**

At temperature level exceeding 400°C, CeO₂ (ceria) homogeneously mixed in the soot promotes the regeneration of the Trap. The soot is oxidized without any kind of external energy feed.

The regeneration mechanism can be described as follows:
This is an exothermic reaction, which increases the temperature with in the Trap. Oxidation of Carbon monoxide

\[
\text{CO} + \frac{1}{2} \text{O}_2 = \text{CO}_2 \quad (2)
\]

This reaction takes place in the exhaust gas and is exothermic too.

Oxidation of Ce₂O₃

\[
\text{Ce}_2\text{O}_3 + \frac{1}{2} \text{O}_2 = 2 \text{CeO}_2 \quad (3)
\]

This is very fast reaction with in diesel exhaust gas as Ce₂O₃ is an unstable component.

The critical temperature level of 400°C is achieved either by heating coil (active regeneration) or by heat transfer from exhaust.

**EXPERIMENTATION**

Computerized single cylinder four stroke diesel engine with eddy current dynamometer set is used in present experimentation as shown in (Figure 4c). It is water cooled, vertical four stroke compression ignition engine.

**Steps for experimentations**

Developed CAT was tested with different combinations of metal catalysts to identify the best catalyst for NOx emission reduction. (The observations are recorded at load 0, 12.5, 25, 37.5, 50, 62.5, 75, 87.5 and 100% respectively and testing time for each CAT test decided as 2 h)

Developed Traps were tested according to different porosities, diameters and length of Trap, to identify best Trap for particulate filtration. (Testing time for each TRAP test decided as 2 h and observations were recorded after 20 min). Optimized CAT-TRAP (Figure 4b) (combination of CAT and TRAP) was tested 16 h for their performance and emission characteristics (For continuous
Figure 4c. Computerized diesel engine test set up with CAT-TRAP, five gas analyzer and smoke meter.

Engine CAT test with combination of metal catalysts

Developed circular housing (Figure 4b) are grouped according to catalyst combination that is, C1 (Cu/CeO$_2$/ZrO$_2$), C2 (Ag/CeO$_2$/ZrO$_2$) and C3 (Ag/Cu/CeO$_2$/ZrO$_2$). These combinations of metal catalysts are tested on sophisticated engine test set up to find out effect of catalyst combination of CAT on the performance of catalytic converter and engine.

Engine TRAP test on the basis of porosity and diameter of Trap

Developed Traps 'P' are grouped according to porosity range that is, P1 (70-75%), P2 (65-70%) and P3 (60-65%). These Traps are tested to find out effect of different porosities of TRAP on the performance of Traps and engine.

Engine CAT-TRAP test

The best combination of metal catalyst for CAT and best combination of porosity, diameter and length for TRAP is selected for further CAT-TRAP test on the basis of performance. The metal catalyst of combination CAT C2D1L1 (CAT with Ag/CeO$_2$/ZrO$_2$, 132 mm, 20 mm) and the TRAP P1D2L1 (TRAP with porosity 70-75%, diameter 125 mm and Length 20 mm) was used for the testing.

Performance of CAT-TRAP at varying load conditions was recorded. During test, the effect of varying load condition on various parameters of engine like back pressure, smoke density, NOx reduction, variation in BSFC, variations in BTE, variations in BP and effect of regeneration on performance of Trap were observed. CAT-TRAP is tested 16 h continuous running tests as per Bureau of Indian Standard (BIS) 10000 PART IX. For continuous running test (16 h) data is recorded after interval of 30 min. The engine was tested for 3 cycles (each of 16 h continuous running) at rated load.

Test cycle for continuous running test (16 h)
100% of rated load with running time 4 h.
50% of rated load with running time 4 h.
110% of rated load with running time 1 h.
No load (idling) with running time 0.5 h.
100% of rated load with running time 3 h.
50% of rated load with running time 3.5 h.

RESULT AND DISCUSSION

Effect of continuous running test (CRT) on back pressure

To understand the effect of full and part load condition (CRT) on back pressure, graph is plotted (Figure 5). Results of two CRT (CRT-2 and CRT-3) show similar trends. As expected, back pressure increases as trial duration time increases. But back pressure crossed suddenly above 300 mbar after 6 h during CRT-2 (CAT-TRAP without heating coil). This is because of clogging of TRAP in absence of heating coil. That is, without regeneration system. During CRT-3 (CAT-TRAP with heating coil), to reduce light off temperature of oxidation of Trap, a current of 5.6 ampere was supplied to the heating coil after every 4 h. It increases dropped temperature of Trap up to 538°C and helped for oxidation of particulate Trapped. It is noticed from Figure 5 that when load condition changes on engine, back pressure substantially decreases for some time and again rises as test proceed. This is because of exhaust flow variation at the time load alteration.

Effect of continuous running test (CRT) on filtration efficiency

To understand the effect of full and part load condition on filtration efficiency for CAT-TRAP, continuous running tests (CRT-2 and CRT3) were carried out. The results in the form of graph (Figure 6) show that filtration efficiency decreases as testing time increases. Continuous accumulation of soot clogged the Trap (CRT-2). As trial duration time increases, soot particles start to release to the atmosphere because of heated TRAP, as current was supplied to heating coil after every 4 h for oxidation of Trap (CRT-3). The filtration efficiency was found in the range of 65 to 72% with heating coil.

Effect of continuous running test (CRT) on BSFC

Continuous running tests (CRT) were carried out for CAT-TRAP to understand the effect of full and part load conditions on specific fuel consumption. The graph is plotted (Figure 7) for brake specific fuel consumption (BSFS) Vs testing time. From the Figure 7, trends of results for CRT shows that variation in specific fuel consumption increases as testing time increases, this is because of increased back pressure during experimentation. Increased back pressure adversely affects the specific fuel consumption. The BSFC increased for
CRT-3 was found in the range of 0.40-3.70% (with CAT-TRAP).

**Effect of continuous running test (CRT) on BTHE**

To understand the effect of full and part load condition on brake thermal efficiency (BTHE) for CAT-TRAP, continuous running tests were carried out (CRT-1 and CRT-3). Graph is plotted (Figure 8) for variation in brake thermal efficiency (BTHE) Vs testing time. It indicates from Figure 8, that brake thermal efficiency (BTHE) decreases as testing time increases. The decrease in BTHE was found in the range of 0.38-2.98%.
Continuous running tests (CRT) of CAT-TRAP was carried out to study the effect of various full and part load conditions on brake power (BP) of engine. The graph is plotted (Figure 9) for brake power (BP) Vs testing time. The trends in Figure 9 shows that loss in BP occurred as trial duration time increases. Clogged Trap increases back pressure which adversely affect the BP of engine. The decrease in brake power was found in the range of 0.57-1.60%.

In continuous running tests (CRT), clogged Trap increases back pressure, which adversely affect the parameters BSFC, BTHE, and BP. By using effective regeneration like coating of catalyst on Trap surface and heating coil, we can easily minimize losses in BSFC,
Continuous running tests (CRT) of CAT-TRAP was carried out to study the effect of various full and part load conditions on NOx emission of engine. The graph is plotted (Figures 10 and 11) for NOx Vs testing time. The trends in (Figure 10) show that variation in NOx increases as testing time increases with and without heating coil, this is because of increase in the temperature of exhaust gas as trial duration time increases. Catalyst combination Ag/ CeO$_2$ helped for reduction process and CeO$_2$ stored excess oxygen to enhance the process. The NOx conversion efficiency was found in the range of 65 % with selected CAT C2D1L1 (Figure 11).
Figure 11. NOx variation under full load (100%).

Table 1. Engine exhaust condition without CAT-TRAP 100% of rated load of engine.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Parameters</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Load on engine (0 – 110% of rated load)</td>
<td>0 - 7.15 bar BMEP</td>
</tr>
<tr>
<td>2</td>
<td>Exhaust gas back pressure without CAT</td>
<td>08 – 19 mbar</td>
</tr>
<tr>
<td>3</td>
<td>Exhaust gas temperature without CAT</td>
<td>120 - 486°C</td>
</tr>
<tr>
<td>4</td>
<td>Exhaust gas velocity without CAT</td>
<td>189 - 282 m/sec</td>
</tr>
<tr>
<td>5</td>
<td>Exhaust gas volumetric flow rate without CAT</td>
<td>0.19 – 0.29 m³/sec</td>
</tr>
<tr>
<td>6</td>
<td>Smoke opacity (0 – 110% of rated load)</td>
<td>20 - 90 HSU</td>
</tr>
<tr>
<td>7</td>
<td>NOx emission (100% of rated load)</td>
<td>730 ppm</td>
</tr>
</tbody>
</table>

Table 2. Continuous running test cycle.

<table>
<thead>
<tr>
<th>Testing cycle</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRT-1</td>
<td>Test conducted without CAT-TRAP.</td>
</tr>
<tr>
<td>CRT-2</td>
<td>Test conducted without heating coil</td>
</tr>
<tr>
<td>CRT-3</td>
<td>Test conducted with heating coil</td>
</tr>
</tbody>
</table>

Conclusion

The following conclusions may be drawn from the present study.

The CAT with combination (Ag/CeO$_2$ /ZrO$_2$ catalyst) reduces NOx emission with emission conversion efficiency of 65%.

Slip casting method is recommended to develop TRAPS. Porosities of developed Traps were grouped viz. P1 = 70-75%, P2 = 65-70%, and P3 = 60-65%.

Specific gravity of casting slip is important factor. Appropriate specific gravity of slip forms the porous structure and gives strength to TRAP. A variation in slip specific gravity has significant impact on the porous structure and strength of TRAP. The successful specific gravity of slip found for TRAP was 1.4.

The CAT -TRAP (CAT C2D1L1 (C2 = Ag/CeO$_2$-ZrO$_2$ catalysts, D1 =132 mm and L1=20 mm) + TRAP P1D2L1 (P1 = 70-75%, D2 =125 mm and L1=20 mm) gives back pressure range (50-266 mbar). Minimum increase in brake specific fuel consumption was (0.4-3.70%), minimum decrease in brake thermal efficiency was (0.38-2.26%) and loss in brake power was (0.57- 1.60%).

The CAT -TRAP (C2D1L1 + P1D2L1) gives filtration efficiency range (65-72%). The NOx conversion efficiency was (65%).

The proposed CAT -TRAP is inexpensive as compared to existing system.

REFERENCES


Akkarat W (2008). Effect of Cerium Oxide and Zirconium Oxide to