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Performance Enhancement of Three-way Catalytic Converter using External Heating Source: An Experimental Approach

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ABSTRACT:

The stringent emission norms for ultra-low emission vehicle pose challenging problems on automotive exhaust gas treatment. When engine starts, the catalytic converter does almost nothing to reduce emission characteristics, until it is desirably heated. Preheating the catalytic converter is a noble technique to reduce exhaust emissions. Present work lays the method of low temperature conduct of the converter, when the mainstream of the emissions befalls. The test was conducted on a four-cylinder, spark-ignition engine in order to enhance the performance of the catalytic convertor when heated two minutes prior to engine start, through a heating gun actuated with a radio key at around 500K. The values of HC and CO were measured at idling rpm using MRU DELTA 1600L exhaust gas analyser and NOx values were measured using CRYPTON 295 five-gas analyser. Preheating Catalytic Convertor (CC), results in reduction of CO (58.82%), HC (47.01%) and NOx (36.36%) at engine start-up condition; when compared with exhaust of CC at 1500rpm, employed without heating gun. Similar trends of reduction of exhaust emissions were found at 2000 and 2500rpm.

KEYWORDS:

Exhaust gas analyser; Exhaust emissions; Heating gun; Inverter; Radio key; Three-way catalytic converter

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ACRONYMS AND NOMENCLATURE

CO	*Carbon monoxide (% by volume, ppm)*
HC	*Hydro Carbon (ppm)*
NO_X	*Nitrogen Oxides (ppm)*
CC	*Catalytic Converter*
PHCC	*Preheated Catalytic Converter*
OEM	*Original Equipment Manufacturer*
cc	*Cubic Centimetre*
ppm	*Parts per million*
RF	*Radio Frequency*
EHMC	*Externally Heated Metallic Converter*

1. Introduction

India is an emerging economy with an overwhelming growth rate; it is expected to overtake China in upcoming years [1]. The number of automobiles in India is increasing at a dizzying pace which accelerates the growth of pollutants such as CO, CO_2, NO_x and HC in an atmosphere leading to continuous environmental degradation. Of the total air pollution that occurs, motor vehicle contributes a major share to environmental pollution (=70%) [5]. Catalytic converter (CC) was invented in 1970s, which led to a significant improvement in the quality of exhaust gases. Inefficiency of CC during engine start-up, to convert harmful exhaust gases to more superior quality, remains an area of concern since long. Previous investigations show that there can be a considerable reduction in pollutants of exhaust gas at the time of cold start of engine, if system can be developed that could be able to regulate the catalyst active surface at the time of cold starting of the engine proportionally to the exhaust gas volume [7].

Researchers proposed several methods to enhance the cold starting efficiency of CC, among which preheating the converter is the most effective approach which has been widely accepted [2,3]. It includes, preheating the converter by the use of resistance electric heaters. Externally Heated Metallic Convertor is one of the method by which the efficiency of the CC is marginally increased at the time of cold starting of the engine [1]. A low mass EHMC is fitted just before the chief catalytic converter at the exhaust flow pipe. Added, successful approach for eliminating cold start emissions is vacuum insulation and phase change material CC [6]. Karkanis [7] provided a technical approach for reducing cold start emissions by catalysts surface control. At the time of cold start of engine, the amount of exhaust gas is considerably smaller in amount than under full load, possibly the reason why only a minor part of the active catalyst surface is required to process exhaust gases. The greater the surface, the more time would be required to heat up, which significantly increases the time required for a light-off.

Pre-heating the CC with an electrical resistance heater structurally encompassed with it, is effective technique to increase the efficiency during engine start-up [11]. In this, ignition battery is used for heating the electrical resistance element. The catalyst is pre-heated to an intermediate temperature prior to engine being started between ambient temperature and the catalytic converter's operating temperature, maintaining the catalyst at intermediate temperature for a provisional period of time determined by battery's immediate energy level. Selective Catalytic Reduction (SCR) is one of the most vital ways of reducing NO_x from vehicle exhaust there-by increasing the competence of a CC. NO_x could be catalytically reduced by means of hydrocarbons originating from the engine fuel (HC-SCR). For this a silver-alumina ($Ag\text{-}Al_2O_3$) based prototype HC-SCR was used for removal of NOx emissions from a turbocharged engine. By this approach approximately 70% NO_x removal efficiency was obtained [9].

In a recent research by Thomas [10], a significant consideration was given on materials of monoliths used in CC. The research suggested that the use of Iron-Chromium-Aluminium (less expensive than metallic monoliths) will provide a more surface area to support the catalyst wash-coats. The research also suggested the use of Titanium dioxide, Aluminium oxide, Silicon dioxide or a combination of Silica and Alumina for increasing the competence of CC. An investigation done by Kamble and Ingle [12] suggested perforated copper plate as a catalyst for CC. The conversion efficiency of the converter was expressively increased with the increase in number of plates. The objective of this work is to find out the emission characteristics of three-way catalytic converter by heating it for 2 minutes prior to engine (S.I) start. The setup uses the battery for supplying current to the heating gun which gets actuated with the help of a radio key mechanism. Tests were conducted in three phases:

i) Vehicle with disengaged CC.
ii) Vehicle engaged with original equipment manufacturer (OEM) three-way catalytic converter.
iii) Vehicle engaged with preheated three-way catalytic converter heated for 2 minutes prior to engine starts using heating gun.

The values of HC and CO were measured at idling rpm using MRU DELTA 1600L exhaust gas analyser and NO_x values were measured using CRYPTON 295 five-gas analyser. The test concludes that CC with preheating resulted in better reduction of NOx, HC and CO during engine start-up leading to increased converter efficiency.

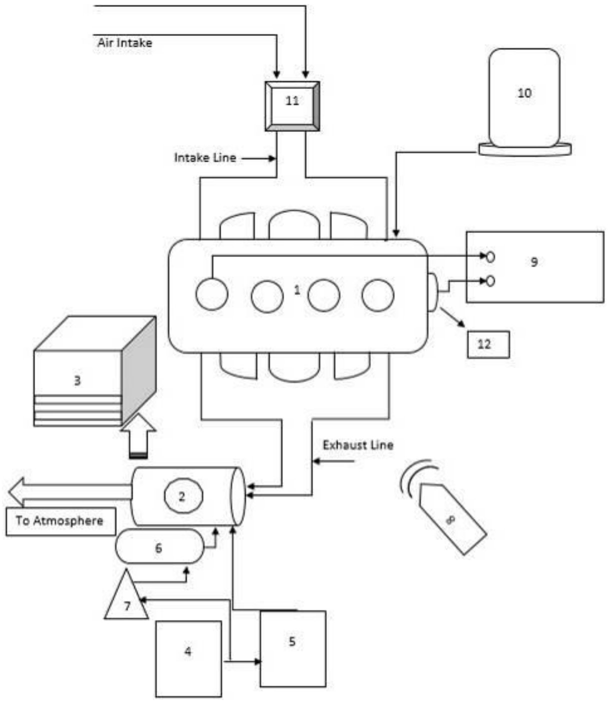
2. Experimental set-up

2.1. Engine description

This study used a four stroke, 4-cylinder, in-line, naturally aspirated, Spark Ignition (SI) engine with a 3-way catalytic converter connected to the exhaust line of the engine. The probes is connected prior and post the catalytic convertor to measure the amount of main pollutants (HC, CO and NO_x) with and without the catalytic convertor respectively using exhaust gas analysers. The complete experimental setup used for the analysis is shown in the Fig. 1. The technical specifications of the engine are shown in Table 1.

Table 1: Engine technical specifications

Parameter	Description
S.I Engine 15 spec.	4 Stroke, 4 cylinder, In-line, Water cooled, Naturally aspirated
Bore x Stroke, (mm)	78.0 x 78.4
Compression ratio	10.1:1
Displacement volume, (cc)	1498
Rated power, (BHP)	96 at 6000rpm
Rated torque, (kgm)	13.6 at 4000rpm
Valve gear	4 valve per cyl, DOHC



(1) Engine, (2) 3-way catalytic convertor, (3) Exhaust gas analyser (HC), (4) Battery-12V, 50Ah (Fully Charged), (5) Inverter- 1800W, (6) Heating gun- 1600W (60°-600°C working temperature), (7) Triggering switch, (8) Radio key, (9) Combustion analyser, (10) Fuel tank, (11) Mixing chamber and air filter, (12) Shaft encoder.

Fig. 1: Schematic diagram of the experimental setup

3. Engine accessories

3.1. Three-way catalytic convertor

Catalytic convertor is a manoeuvre where secondary combustion takes place. It is divided into two sections namely, the oxidation section, coated with platinum and palladium which oxidises HC and CO and secondly, the reduction section, coated with rhodium where cracking of NO_x take place. The convertor employs a honey comb bed structure on which the chemical catalyst is earmarked. The CC is coupled to the engine exhaust line as shown in the Fig. 2.

3.2. Reactions in catalytic convertor

Reduction of nitrogen oxides to nitrogen and oxygen:

$$2NO_x \rightarrow xO_2 + N_2$$

Oxidation of carbon monoxide to carbon dioxide:

$$2CO + O_2 \rightarrow 2CO_2$$

Oxidation of un-burnt hydrocarbons (HC) to carbon dioxide and water:

$$C_xH_{2x+2} + [(3x+1)/2]O_2 \rightarrow xCO_2 + (x+1)H_2O$$

Water Gas Shift:

$$CO + H_2O \rightarrow CO_2 + H_2$$

Steam reforming:

$$HC + H_2O \rightarrow CO_2 + H_2$$

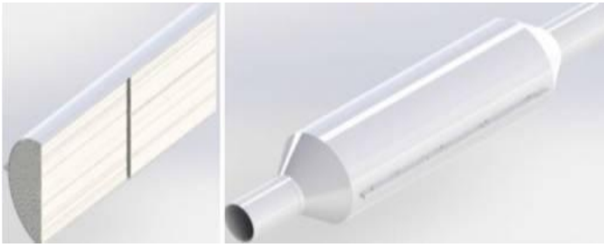


Fig. 2: Cross-section of the catalytic convertor and its arrangement with the exhaust line

3.3. Heating gun

Heating gun is a convection heating device comprising of a heating element, a fan driven by a motor, nozzle and a triggering switch. Heating element creates a temperature, which then further carried by the air drawn by the fan and concentrated through the nozzle towards the exhaust tail pipe. The heating gun employed for the study is shown in Fig. 3. It shows the triggering switch integrated inside the motor which was activated through radio key switch. The total time to completely discharge the fully charged battery if gun is made to continuously draw the current from is calculated. The specification of the heating gun is shown in Table 2.

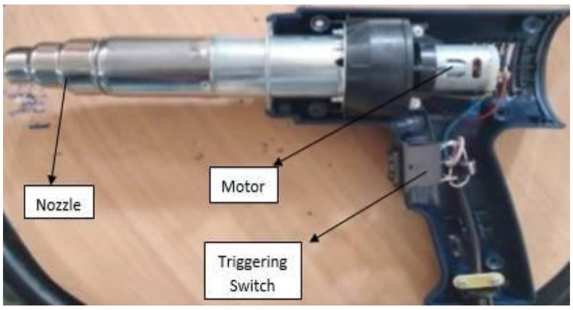


Fig. 3: The heating gun used

Table 2: Technical specifications of heating gun

Specification	Description
Power input, (W)	1600
Voltage, (V)	220-240AC
Current, (A)	8
Length*Height, (cm)	28.5*6.7
Weight, (g)	200
Working temperature, (°C)	60-600
Air flow, (L/min)	300-500

3.3.1. Calculations:

The specifications of the battery used during study were: 12V, 50Ah (Fully charged). Our heating element draws a current of 8A. Therefore, at this rate, time required to discharge the 50Ah battery completely is calculated as 50Ah÷8A = 6.25hrs. The experiment performed showed that the concept requires a run time of not more than 3 min at max during the start while it is significantly within the feasting limits.

3.4. Inverter and radio key

Inverter converts 12V DC voltage from car battery to 220-240V AC voltage with a power output of 2000W required to operate the heating device. This is a voltage source single phase bridge (full wave) inverter. The inverter circuitry consists of four transistor switches. In this at a time two transistors (either S1S4 OR S2S3) will be in ON or OFF position. The inverter specification is shown in the Table 3. The radio switch assembly consists of a radio key switch and a triggering key switch. The radio switch operates in the 433-MHz ISM band. It uses the same principle as the RKE system used in automobile. Radio key switch uses a small battery inside it to power it when key fob is pressed. Components of the radio switch include four ICs, a transmitter, a receiver, and two identical microcontrollers that encode and decode a 24-bit key code. A push button switch on the radio key switch initializes the system by waking up the central processing unit (CPU) inside it which sends a data stream to a radio frequency (RF) transmitter.

Table 3: Inverter technical specifications

Specification	Description
Input, (V)	11-12DC
Output, (V)	220-230AC
Frequency, (Hz)	50-60
Power, (W)	1800

3.5. Battery

The primary source of power input having 6 cells with an output voltage of 12V. Battery also transmits power to triggering switch too as shown in Fig. 1. The technical specification of the battery is shown in Table 4.

Table 4: Battery technical specifications

Specification	Description
Battery type	Li-Ion
Voltage and Capacity, (V) & (Ah)	12DC; 50
Max. discharging current, (A)	420(5 sec)
Internal resistance, (mΩ)	8

4. Connections

The engine exhaust line was connected to the 3-way catalytic converter as shown in Fig. 1. Two probes were connected prior and post the catalytic convertor so as to measure the values of the main pollutants (HC, CO and NO_x) without and with the catalytic convertor respectively using exhaust gas analyser. The exhaust line is then welded with an extension stand so as to place a heating gun before the catalytic convertor whose nozzle is directed toward the CC. The schematic CAD model diagram is shown in the Fig. 4. The extension pipe is welded to the exhaust pipe having dimensions 215mm in length, 40mm in diameter and having bend R83 constructed of stainless steel. The CAD model of actual exhaust pipe constructed of stainless steel having dimensions 627mm in length, 63mm in diameter and having a bend R131.The distance of the gun from the CC was taken to be 5cm (no specific measurement technique was used to house the gun). The heating gun is powered with the help of a battery whose DC current is converted into AC current with the help of an inverter. To trigger the heating gun, a triggering switch is employed which is activated through a radio key which is also used for central locking the car. As engine used was S.I. engine, petrol was used a fuel for the study. The specifications of the fuel used are shown in the Table 5.

Fig. 4: The complete catalytic convertor assembly along with mounting and the exhaust line

Table 5: Technical specifications of the fuel

Parameter	Description
Molecular weight, (kg/mol)	114.18
Density (g/cm^3), liquid	0.73
Lower heating value, (MJ/kg)	44
Stoichiometric air fuel ratio	14.6
Auto-ignition temperature, (K)	501-744
Laminar flame speed, (m/s)	0.37
Diffusion coefficient, (cm^2/s)	0.05
Research octane number	91-98

5. Results and discussion

Catalytic converter is almost inefficient at the time of engine start. The study was conducted at three conditions; without CC, with CC and PHCC. These three conditions were tested under no load @ 1500, 2000 and 2500 rpm. It can be observed from Figs. 5, 6 and 7, the values of HC, CO and NO_x are the minimum for PHCC, when compared with vehicle employed with CC and without CC. On condition of 1500rpm, without catalytic converter and at the time of engine start, the amount of CO, HC and NO_x measured was 3.02% by volume (30200ppm), 219ppm and 58ppm respectively as shown in Fig. 5. The values obtained were high possibly because of the absence of catalytic conversion of the exhaust gases as catalytic converter was not employed during this test. When the vehicle is employed with Original Equipment Manufacturer (OEM) catalytic converter the values of CO, HC and NO_x measured just after the engine start (cold starting of CC) were 0.68% by volume (6800 ppm), 119ppm and 28ppm respectively. This reduction effect is possibly because of temperature dependence characteristics of rhodium catalyst for reducing NO_x and platinum; palladium (Pd: Pt) catalyst for oxidising HC, CO from the catalytic converter. Further, preheating catalytic converter for 2 minutes prior to engine start shows the values of HC, CO and NO_x at 1500rpm as 0.28% by volume (2800ppm), 60ppm and 15ppm respectively, as shown in Fig. 5.

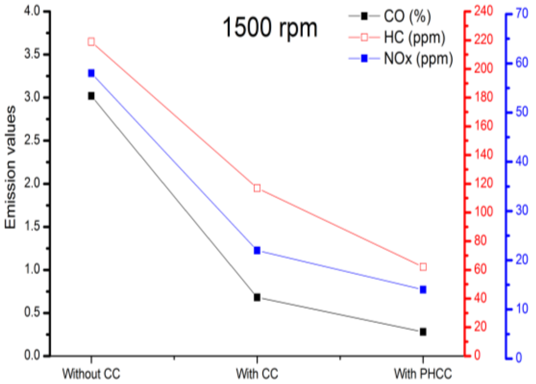


Fig. 5: Variation of HC, CO and NOx at 1500rpm at different test conditions

It has been found that there is reduction in 47.01% of HC, 58.82% of CO and 36.36% of NO_x exhaust emissions during cold starting of the catalytic converter, when compared with CC (OEM) installed vehicle. This variation in conversion efficiency of the catalytic convertor strongly depends on the temperature of the exhaust gases. Prior heating of the catalytic convertor increases the effectiveness and rate of reaction of the catalyst bed. Experimentally, it was inferred that the true effectiveness of the 3-way catalytic converter was negligible at the initial stage, because catalyst twitches functioning only when it gains adequate temperature of around 750°F. PHCC prior to 2 minutes of engine start, assists CC gaining this operating temperature (400°C) well before the engine is started. Thus, the conversion efficiency is augmented and the diminished values of the exhaust emissions originate are fully defensible.

Results revealed that the use of heating gun with the catalytic convertor produces significantly lower emissions than catalytic convertor employed with disengaged heating gun. Similar trends of reduction in exhaust emission were seen at 2000 and 2500 rpm at no load condition as shown in Fig. 6 and 7. Moreover, preheating catalytic converter for 2 minutes prior to engine start shows the values of CO, HC and NO_x at 2000rpm as 0.32% by volume (3200ppm), 64ppm and 17ppm respectively, as shown in Fig. 6.

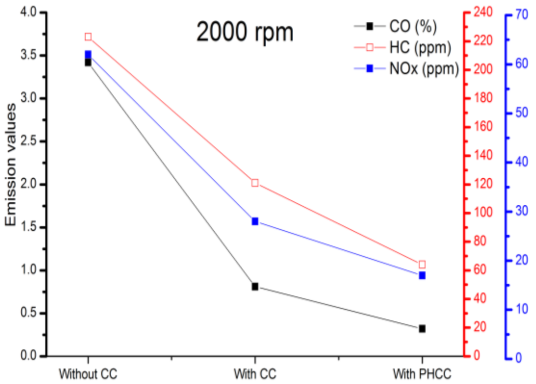


Fig. 6: Variation of HC, CO and NOx at 2000rpm at different test conditions

It has been found that there is reduction in 47.11% of HC, 60.49% of CO and 39.29% of NO_x exhaust emissions during cold starting of the catalytic converter, when compared with CC (OEM) installed vehicle. Further, at 2500rpm and at no load condition preheating catalytic converter for 2 minutes prior to engine start shows the values of CO, HC and NO_x at 2500rpm as 0.34% by volume (3400ppm), 69ppm and 20ppm respectively, as shown in Fig. 7. It has been found that there is reduction in 47.73% of HC, 65.31% of CO and 42.86% of NO_x exhaust emissions during cold starting of the catalytic converter, when compared with CC (OEM) installed vehicle.

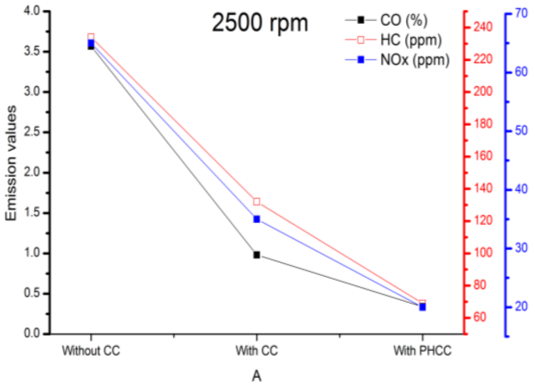


Fig. 7: Variation of HC, CO and NOx at 2500rpm at different test conditions

6. Conclusion

Test was conducted on a four cylinder, SI Engine in order to enhance the performance of the catalytic converter during engine start up. Following conclusions could be drawn from the experimental study at 1500rpm and no load condition:

- The CO conversion efficiency of OEM and preheated catalytic converter is 77.48% and 90.73% respectively when compared with vehicle employed with disengaged CC. The preheated catalytic converter reduces 13.25% higher emissions than OEM catalytic converter.
- The HC conversion efficiency of OEM and preheated catalytic converter is 46.58% and 71.69% respectively. The preheated catalytic converter reduces 25.11% higher emissions than OEM catalytic converter.
- The NO_x conversion efficiency of OEM and preheated catalytic converter is 62.07% and 75.86% respectively. The preheated catalytic converter reduces 13.16% higher emissions than OEM catalytic converter.
- Comparable drifts are observed when the conversion efficiencies of exhaust emissions of OEM and preheated catalytic converters are compared with vehicle employed with disengaged CC at 2000 and 2500 rpm.

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