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Automotive Exhaust Technology for the Reduction of Emission in a Vehicle

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ABSTRACT: *Today, modern cars emit up to 99% less exhaust pollutants than 30 years ago. But due to incomplete combustion in the engine, there are a number of incomplete combustion products CO, HC, NO_x, particulate matters etc. These pollutants have negative impact on air quality as well as on human health. This paper gives an overview of the advanced technologies currently used for abating emissions from the gasoline and diesel internal combustion engines also discusses automotive exhaust emission and its harmful impact, automotive exhaust emission control technique, catalytic converter and its types, DOC, limitation of catalytic converter, DPF, SCR and also significance of catalytic converter.*

Keywords: *Exhaust emission, Catalytic Converter, Gasoline Application, DOC, DPF, SCR*

I. INTRODUCTION

Automobiles are a „necessary evil‟ , while they have made living easy and convenient; they have also made human life more complicated and vulnerable to both toxic emissions and an increased risk of accidents. Due to incomplete combustion in the engine, there are a number of incomplete combustion products CO, HC, NO_x particulate matters etc. These pollutants have negative impact on air quality as well as on human health also on environment that leads in stringent norms of pollutant emission. Numbers of alternative technologies like improvement in engine design, fuel pre-treatment, use of alternative fuels, fuel additives, exhaust treatment etc. are being considered to reduce the emission levels of engine . Among all the types of technologies developed so far, use of catalytic converters is the best way to control automotive exhaust emissions.

This review paper discusses automotive exhaust emission and its harmful impact, automotive exhaust emission control technique, catalytic converter and its types, diesel oxidation catalyst, limitation of catalytic converter, diesel particulate filter, selective catalytic reduction and also significance of catalytic converter.

II. EXHAUST EMISSION

Due to incomplete combustion in the engine, there are a number of combustion products. Typical exhaust gas composition at the normal engine operating conditions is:

- Carbon monoxide (CO, 0.5 vol. %)
- Unburned hydrocarbons (HC, 350 vppm)
- Nitrogen oxides (NO_x, 900 vppm)
- Hydrogen (H_2, 0.17 vol. %)
- Water (H_2O, 10 vol. %)
- Carbon dioxide (CO_2, 10 vol. %)
- Oxygen (O_2, 0.5 vol. %)

HC, CO and NOx are the major pollutants. HC and CO occur because the combustion efficiency is < 100% due to incomplete mixing of gases and the wall quenching effects of the colder cylinder walls. The NOx is formed during the very high temperatures (>1500^0 C) of the combustion process resulting in thermal fixation of the nitrogen in the air which forms NOx Hydrocarbons react in the presence of nitrogen oxides and sunlight to form ground- level ozone, a major component of smog. Ozone irritates the eyes, damages the lungs, and aggravates respiratory problems. Nitrogen oxides, like hydrocarbons, are precursors to the formation of ozone.

They also contribute to the formation of acid rain. Carbon monoxide reduces the flow of oxygen in the blood stream and is particularly dangerous to person with heart disease. Carbon dioxide does not directly impact human health, but it is a "greenhouse gas" that traps the earth‟ s heat and contributes to the potential for global warming.

III. CATALYTIC CONVERTER

A Catalytic converter is a device used to reduce the toxicity of emissions from an internal combustion engine. It was invented by Eugene Houdry, a French mechanical engineer and expert in catalytic oil refining who lived in the United States. About 1950, when the results of early studies of smog in Los Angeles were published, Houdry became concerned about the role of automobile exhaust in air pollution and founded a special company, Oxy Catalyst, to develop catalytic converters for gasoline engines an idea ahead of its time for which he was awarded a patent (US2742437).

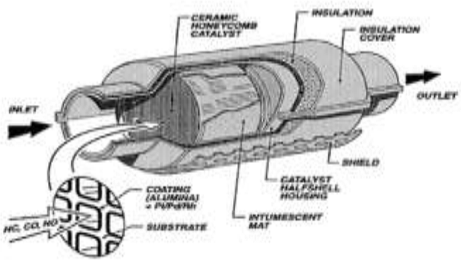

Fig. 1. Anatomy of Catalytic Converter

3.1.Body Structure of Catalytic Converter:

- ***Steel Housing:***
  A steel housing provides protection and structure support for substrate; insulation material (mat or wire mesh) provides heat insulation and support between steel housing and substrate; seals are there to protect mat material from been burned by the exhaust gas.
- ***Substrate:***
  The substrate is often called a "catalyst support". It is a ceramic honeycomb or a stainless steel foil honeycomb in modern catalytic converters. The ceramic substrate was invented by Rodney Bagley, Irwin Lachman and Ronald Lewis at Corning, in use to increases the amount of surface area available to support the catalyst.
- ***Washcoat:***
  The washcoat is used to make converters more efficient, often as a mixture of silica and alumina. When a washcoat is added to the substrate, it forms a rough, irregular surface, which has a far greater surface area than the flat core surfaces do, which then gives the substrate a larger surface area, providing more sites for active precious metal – the catalytic which is added to the washcoat (in suspension) before being applied to the substrate.
- ***Catalyst:***
  The catalyst itself is most often a precious metal. Platinum is the most active catalyst and is widely used. However, because of unwanted additional reactions and/or cost, Palladium and rhodium are two other precious metals that are used. Platinum and rhodium are used as a reduction catalyst, while platinum and palladium are used as an oxidization catalyst. Cerium, iron, manganese and nickel are also used, although each has its own limitations.

3.2.Oxidation / Two-way catalytic converter:

The first catalysts used a simple formulation of platinum deposited on aluminium oxide which in turn was coated onto a support material so that it could be placed in the exhaust stream of the vehicle. These designs were essentially two-way oxidation catalysts, so called because they reduce tailpipe emissions of both carbon monoxide and hydrocarbons by oxidizing them to carbon dioxide and water. This type is known as a two-way catalytic converter, because it can only operate with hydrocarbons (unburned fuel) and carbon monoxide (caused by partially-burned fuel). Oxidation converter elements are usually covered in platinum.
A two-way (or "oxidation") catalytic converter has two simultaneous tasks:

1. Oxidation of carbon monoxide to carbon dioxide: $2CO + O_2 \rightarrow 2CO_2$
2. Oxidation of hydrocarbons (unburnt and partially burnt fuel) to carbon dioxide and water: $C_xH_{2x+2} + [(3x+1)/2]\ O_2 \rightarrow xCO_2 + (x+1)\ H_2O$ (a combustion reaction)

3.3.Reduction / Three-way catalytic Converter:
Similar to the oxidation converter, the reduction catalytic converter helps eliminate hydrocarbons and carbon-monoxide emissions, plus oxides of nitrogen emissions, or NOx. NOx emissions are produced in the engine combustion chamber when it reaches extremely high temperatures more than 2,500 degrees Fahrenheit, approximately. The reduction and oxidation catalysts are typically contained in a common housing, however in some instances they may be housed separately. A three-way catalytic converter has three simultaneous tasks:

1. Reduction of nitrogen oxides to nitrogen and oxygen: $2NO_x \rightarrow xO_2 + N_2$
2. Oxidation of carbon monoxide to carbon dioxide: $2CO + O_2 \rightarrow 2CO_2$
3. Oxidation of unburnt hydrocarbons (HC) to carbon dioxide and water:

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

3.4.Working of Catalytic Converter:
In the catalytic converter, there are two different types of catalyst at work, a reduction catalyst and an oxidation catalyst. Both types consist of a ceramic structure coated with a metal catalyst, usually platinum, rhodium and/or palladium. The idea is to create a structure that exposes the maximum surface area of catalyst to the exhaust stream.

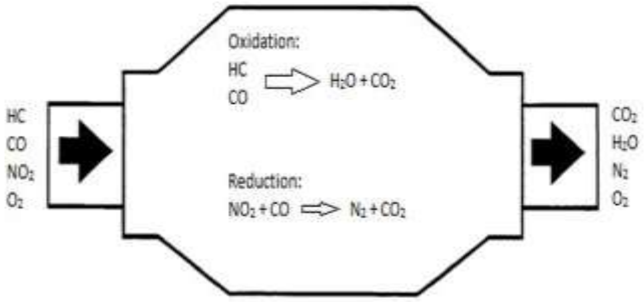

Fig. 2. Working of Catalytic Converter

The reduction catalyst is the first stage of the catalytic converter. It uses platinum and rhodium to help reduce the NOx emissions. When an NO or NO_2 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 O_2. The nitrogen atoms bond with other nitrogen atoms that are also stuck to the catalyst, forming N_2.

The oxidation catalyst is the second stage of the catalytic converter. It reduces the unburned hydrocarbons and carbon monoxide by burning (oxidizing) them over a platinum and palladium catalyst. This catalyst aids the reaction of the CO and hydrocarbons with the remaining oxygen in the exhaust gas.

IV. DIESEL OXIDATION CATALYST

For compression-ignition (i.e., diesel) engines, the commonly used catalytic converter is the diesel oxidation catalyst (DOC). In most applications, a diesel oxidation catalyst consists of a stainless steel canister that contains a honeycomb structure called a substrate or catalyst support. There are no moving parts, just large amounts of interior surface area. The interior surfaces are coated with precious metals such as platinum or palladium as oxidation catalytic material. It is called an oxidation catalyst because the device converts exhaust gas pollutants into harmless gases by means of chemical oxidation.

In the case of diesel engine exhaust, the catalyst oxidizes CO, HC, and the liquid hydrocarbons adsorbed on carbon particles. In the field of mobile source emission control, liquid hydrocarbons adsorbed on the carbon particles in engine exhaust are referred to as the soluble organic fraction (SOF) the soluble part of the particulate matter in the exhaust. Diesel oxidation catalysts are efficient at converting the soluble organic fraction of diesel particulate matter into carbon dioxide and water, typically can achieve 25% to 40% over all particulate reduction by simply burning the SOF component of particulate matter. About 30 percent of the total particulate matter (PM) mass of diesel exhaust is attributed to liquid hydrocarbon. Under certain operating conditions, DOCs have achieved SOF removal efficiencies of 80 to 90 percent.

V. LIMITATIONS OF CATALYTIC CONVERTER

On a global basis, most passenger cars are equipped with stoichiometric Otto engines. Although the exhaust gas after-treatment for such type of engines is well-known, the three-way converter (TWC) has been the primary emission control technology on light-duty gasoline vehicles since the early 1980s. The use of TWCs, in conjunction with the oxygen sensor-based, closed-loop fuel delivery system, allows for simultaneous conversion of the three criteria pollutants, HC, CO, and NOx, produced during the combustion of fuel in a spark-ignited engine.

In gasoline catalytic converter application, the active catalytic materials are present as a thin coating of precious metal (Pt, Pd, & Rh), and oxide-based inorganic promoters and support materials on the internal walls of the honeycomb substrate. The substrate typically provides a large number of parallel flow channels to allow for sufficient contacting area between the exhaust gas and the active catalytic materials without creating excess pressure losses.

In the harsh conditions experienced in the exhaust stream with temperatures up to 1000 °C the metal in the catalyst is prone to deactivation by sintering, leading to a reduction in surface area and hence catalytic activity. The conventional means to meet tightening legislative emissions control targets is simply to increase the amount of PGM in the auto catalyst. The need to guarantee catalyst performance over the typical vehicle lifetime of 80,000 km also means that excess metal must be added, since the performance of the catalyst drops off over time. In addition rising PGM demand and costs are incentives towards achieving lower metal loadings and higher activity.

The compounds of the PGM are generally considered highly toxic while the Pd and Rh are carcinogenic in nature. Due to the fact that the PGM are produced due to the abrasion of automotive catalyst washcoat. That is why the road traffic is responsible for metallic and organic pollutant – emissions which contaminate the environment.

VI. DIESEL PARTICULATE FILTER

Diesel particulate filters remove particulate matter found in diesel exhaust by filtering exhaust from the engine. In order to meet the stringent particulate emissions that are required for diesel light duty vehicles starting with the 2007 model year, the highest efficiency particulate filter is required. The filters are commonly made from ceramic materials such as cordierite, aluminium titanate, mullite or silicon carbide.

The basis for the design of wall flow filters is a honeycomb structure with alternate channels plugged at opposite ends. As the gasses passes into the open end of a channel, the plug at the opposite end forces the gasses through the porous wall of the honeycomb channel and out through the neighbouring channel. The ultrafine porous structure of the channel walls results in greater than 90% percent collection efficiencies of these filters. Wall flow filters capture particulate matter by interception and impaction of the solid particles across the porous wall. The exhaust gas is allowed to pass through in order to maintain low pressure drop.

VII. SELECTIVE CATALYTIC REDUCTION

The Selective Catalytic Reduction (SCR) - an emissions-reduction Technology with the ability to deliver near-zero emissions of Nitrogen Oxides (NO_x), a smog causing pollutant and greenhouse gas. This technology requires treating the exhaust stream with a spray of diesel exhaust fluid (DEF) - an ammonia based solution. DEF, along with the exhaust heat and a catalyst, converts NO_x into nitrogen and water vapor, which are clean, harmless and present in the air we breathe every day. Three forms of DEF can be used in SCR systems: pure anhydrous ammonia, aqueous ammonia and urea.

1) Urea SCR System
2) Ammonia SCR System

Selective Catalytic Reduction (SCR) of NO_x using an ammonia compound as reductants has been used for many years in stationary diesel engine applications, as well as for mobile applications. In the SCR process, NO_x reacts with the ammonia, which is injected into the exhaust gas stream before a special SCR Catalyst.

The main chemical reaction which occurs in ammonia SCR system is shown by this Equation:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

An ammonia SCR control system is an open loop configuration, where a pre-programmed map of engine NOx emissions is used to control the ammonia injection rate. This open loop configuration is capable of some 95% NOx reductions. The automotive industry recognizes that it offers the most effective SCR solution for mobile applications. The System is comprised of sensors for exhaust gas temperature, intake air temperature, engine load information, throttle position, engine rpm, exhaust back-pressure, the electronic control unit (ECU) and a SCR converter.

The system will still use the existing engine architecture, diesel oxidation catalyst (DOC) and diesel particulate filter (DPF), with additional SCR hardware. This technology allows the engine to function at optimal combustion temperatures, which increases fuel efficiency and reliability. The main components of the SCR system are the SCR catalyst, the DEF injection unit, the DEF storing tank and the DEF dosing control unit.

DEF is a solution of purified water and urea, an organic nitrogen compound that turns to ammonia when heated. When DEF is injected into the exhaust pipe downstream of the engine, the heat of the engine exhaust gases decomposes DEF into ammonia and CO_2. Vaporized DEF and hot exhaust gases enter a catalytic converter located in the exhaust system after the DPF (diesel particulate filter). When the NO_x reacts inside the catalyst with the ammonia, the harmful NO_x molecules in the exhaust are converted to harmless nitrogen and water.

Following are the automotive urea SCR reaction equations:

Urea decomposition:

$$CO(NH_2)_2 + H_2O \rightarrow 2NH_3 + CO_2$$

SCR reactions (with diesel catalyst @ 150-550 ^{0}C):

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$$

$$2NO_2 + C \rightarrow 2NO + CO_2$$

$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$$

Ammonia SCR systems have several benefits over urea SCR systems:

- Low temperature climate compatibility, ammonia is injected directly into the exhaust stream, unlike the urea that needs heat to decompose into ammonia at first.
- An advantage concerning infrastructure issues.
- A higher conversion rate and a smaller less complex system.

VIII. SIGNIFICANCE OF CATALYTIC CONVERTER

The reactions occur most efficiently when the catalytic converter receives the exhaust gas from an engine running slightly above the stoichiometric point. Below Table shows the necessary mixing rate of the most common fuels:

Fuel	By mass	% Fuel by mass
Gasoline	14.7 : 1	6.8%
Natural gas	17.2 : 1	5.8%
Diesel	14.6 : 1	6.8%

Three-way catalysts will function properly only if the exhaust gas composition corresponds to nearly (±1%) stoichiometric combustion.

If the exhaust is too lean – NO_x *is* not destroyed.

If the exhaust is too rich – *CO* and *HC* are not destroyed.

IX. CONCLUSION

Today numbers of alternative technologies available to reduce the exhaust emission level. Among this all technologies, use of catalytic converters have proven to be reliable and effective in reducing automotive exhaust emissions. However, they may have some adverse environmental impacts in use. As a fuel economy consideration, the requirement of a rich burn engine to run at a the stoichiometric point at means uses more fuel than a “lean burn” engine running at a mixture of 20:1 or less.

However, NO_x control on lean burn engines is problematic. But the Selective Catalytic Reduction (SCR) technology with the ability to deliver near-zero emissions of Nitrogen Oxides (NO_x).

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