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AUTOMOBILE EXHAUST AFTER-TREATMENT SYSTEM OF DIESEL ENGINE: A TECHNICAL REVIEW

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Abstract: Due to the widespread usage of diesel engines in the transportation sector, there are increasing regulations and guidelines regarding the exhaust emissions from these engines. Manufacturers of automobiles and exhaust designers are working to build diesel engine exhausts that meet government announced environmental standards from various nations and encourage technological innovation in the transportation industry. The development of diesel engine exhaust after-treatment is used in this article to make the diesel engine eco-friendly. This paper offers insights with its intricate integration of analysis between the emission rules of various locations and its forecast on the present and future growth of diesel engine exhaust after-treatment system.

***Keywords* -** Diesel engine, emission standards, nitrogen oxide (NO_x), exhaust after-treatment.

I. Introduction

The advent of diesel engines in automobiles has significantly revolutionized the automotive industry due to their high efficiency and torque output. However, along with their advantages, diesel engines also produce emissions that contribute to air pollution, particularly nitrogen oxides (NO_x), particulate matter (PM), hydrocarbons (HC), and carbon monoxide (CO). In response to increasingly stringent emission regulations worldwide, exhaust after-treatment systems have become indispensable components in modern diesel engines.

Exhaust after-treatment systems are designed to reduce harmful emissions from the exhaust gases before they are released into the atmosphere. These systems have evolved over the years to incorporate various technologies, aiming for higher efficiency and compliance with emission standards. The core technologies employed in after-treatment systems include diesel particulate filters (DPF), selective catalytic reduction (SCR) systems, diesel oxidation catalysts (DOC), and exhaust gas recirculation (EGR).

This paper provides a comprehensive technical review of exhaust after-treatment systems for diesel engines used in automobiles. It begins by discussing the emission regulations that have driven the development of after-treatment systems. Subsequently, it delves into the functioning and characteristics of each major component within these systems, including their advantages, limitations, and operating principles. Moreover, the paper explores the advancements made in after-treatment technologies and their impacts on emission reduction and engine performance.

Understanding the intricacies of exhaust after-treatment systems is crucial for automotive engineers, researchers, and policymakers. This review aims to offer insights into the current state-of-the-art technologies, challenges, and future trends in automobile exhaust after-treatment, thereby contributing to the development of cleaner and more sustainable transportation systems.

II. LITERATURE REVIEW

2.1 History of exhaust after-treatment system of diesel engine

Ford produced the first study on exhaust after-treatment in 1957, discussing an oxidation catalyst for a single cylinder. Soon after, diesel engines began to employ them frequently as well. The earliest paper related with diesel oxidation catalyst (DOC) was released in 1971 by Cummins, followed by diesel particulate filter (DPF) by Esso in 1980 and selective catalytic reduction (SCR) by Degussa in 1986. Exhaust gas recirculation (EGR) was believed to have been put into place in 1973, yet there is no definitive publication on that date. Early after-treatment systems were typically built by filling a big container with precious metal pellets, which led to extremely low efficiency and higher fuel use. Further, research revealed that the complexity of system design has increased where at first, single stage crude SCR was used in diesel engines and later with a mixture of DOC.

2.2 Diesel exhaust after-treatment system packaging and flow optimization on a heavy-duty diesel engine powered vehicle For a vehicle to comply with the strict packing requirements of the car and the environmental protection act (EPA) 2010 and final Tier 4 emission criteria, diesel exhaust after-treatment systems are mandated. The fuel dosing system, mixing components, fuel reformer lean NO_x trap (LNT), diesel particulate filter (DPF), and selective catalytic reduction (SCR) catalysts make up the after-treatment system for this investigation. Utilizing injected diesel fuel, the fuel reformer produces carbon monoxide (CO) and hydrogen (H_2) [1, 2]. The LNT catalyst is regenerated and desulphated using these reductants. By combining LNT with SCR catalysts, NO_x emissions are decreased. Ammonia (NH_3) is purposefully released from the LNT during LNT regeneration and stored on the downstream SCR catalyst to further reduce NO_x that passed through the LNT catalyst [2, 3 and 4].

2.3 Engines and exhaust after-treatment systems for future automotive applications

In contemporary cultures, when mobility is increasing and resources are scarce, safe, clean, and efficient engines will become more crucial. Passenger automobile gasoline engines are now designed to produce more power while emitting less emission. As a result, the engine systems now consist of several subsystems and are very complicated [2, 5].

The diesel engine is typically found in heavy duty vehicles due to its dependability and efficiency, but in recent times, its high torque when combined with a turbocharger has made it more popular in passenger cars and even sport vehicles [1, 2 and 3]. This is the advancement of diesel engines, particularly those with direct injection and common rail high pressure injection.

2.4 Catalytic automotive exhaust after-treatment

The use of vehicle engines' catalytic exhaust after-treatment is growing in favor of improved air quality, particularly in the world's major cities. Catalytic converters are beneficial for the removal of primary pollutants from both spark-ignition and compression-ignition engines. Additionally, catalysts are used in diesel engine particulate filters as regeneration aids in a variety of ways [1, 6 and 7]. For the emissions control engineer, every engine application presents a unique set of difficult exhaust gas characteristics. Stricter emissions standards can only be met with very durable and active catalysts, as well as better engine management and exhaust system design. The potential of catalytic systems for vehicle emission management is reviewed in this research. The assessment addresses the running catalyst technology [2, 3].

2.5 Study of an exhaust after-treatment system applied to hybrid vehicle

This paper introduces a new exhaust after-treatment system that is specifically made for hybrid vehicles in order to address the issue, which states that the exhaust after-treatment system frequently operates in the failure zones, which is brought on by the frequent starting and stopping of the engine of the hybrid vehicles. This paper adds hydrocarbon absorber traps and activated carbon fiber canister to the conventional exhaust after-treatment system in accordance with the unique requirements of hybrid vehicles (diesel-electric and gasoline-electric). These components can collect and eliminate harmful emissions when the temperature of the catalytic converters is lower than their ignition temperature. The emissions of hybrid cars can be reduced in this way [2, 4, 6, 7 and 8].

III. WORKING PRINCIPLES

The diesel engine, a widely used engine type in the present automobile industry, is an internal-combustion engine that transfers diesel's chemical energy to mechanical energy to power the machines. In the market, diesel engines are usually shown as the two stroke diesel engines and the four-stroke diesel engine. Although two-stroke diesel engines have higher theoretical efficiencies, the worse emission conditions for two-stroke diesel engines make it mostly applied in small tools and machines, like the handhold chainsaw. Larger sized machines, like transportation vehicles, are using four-stroke diesel engines; the working principle of diesel engines is different from that of gasoline engines which are used in personal vehicles generally. The combustion of diesel in diesel engines is caused by the extremely high temperature and high pressures instead of the ignition from spark plugs. So, it is necessary to consider the advantage of four-stroke engines when analyzing the emission and exhausts. When the strokes of intake, compression, power, and exhaust are separated in four cycles, the ratio of diesel that hasn't been combusted in the emission gas is significantly decreased. Hence, understanding the theory of diesel engines is necessary for developing exhaust after-treatment technologies. Even though EGR will reduce the level of NO_x compared with EGR non-equipped engines, the generated NO_x isn't being converted. To make this conversion possible SCR works in combination with a reducing agent. A constant supply of that agent is injected into the exhaust stream before entering the SCR. Inside the SCR unit the reducing agent will form ammonia, which in turn reacts with the NO_x and converts them to water vapor and nitrogen.

IV. REGULATIONS REGARDING EMISSIONS

Even though exhaust system research began early, automakers were more concerned with reducing the impact of smell and sight impact on individuals as opposed to getting rid of the pollution in the exhaust flow. The early technologies had restricted functionality and were likewise imprecise. Nonetheless, the current laws and regulations were established when governments across the globe realized how harmful emissions were to the environment and how crucial it was to safeguard it. This is why exhaust after-treatment systems are being used today. While the US EPA requires Tier I to Tier IV F from 1996 to 2015, the European Union implements the Euro I through Euro VI requirements from 1992 to 2012.

V. CATALYTIC CONVERTER

One tool used to lessen the harmfulness of emissions from internal combustion engines is a catalytic converter (Fig.1). America-born French mechanical engineer Eugene Houdry, a specialist in catalytic oil refinement, is credited with its invention. After the release of findings of preliminary research on smog the early 1950 in Los Angeles, Houdry became interested in the role that the vehicle exhausts play in air pollution. He established OxyCatalyst, a unique company, to develop catalytic converters for gasoline engines, which was an innovative idea for which he received a patent.

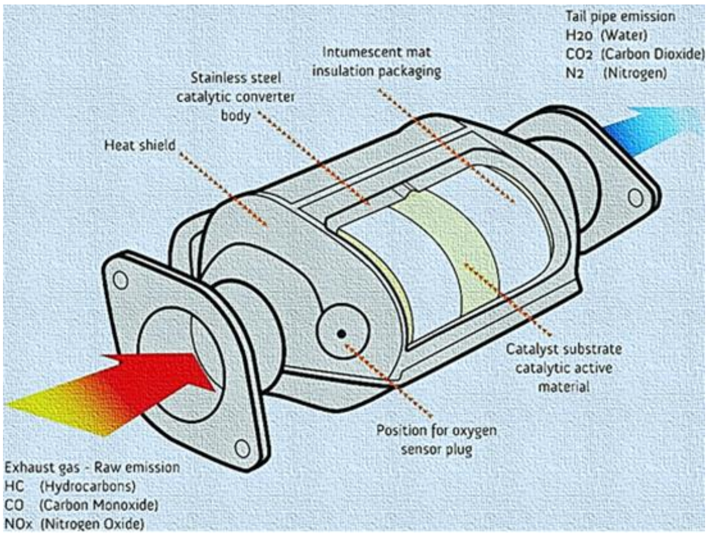

Figure 1 Schematic diagram of catalytic converter.

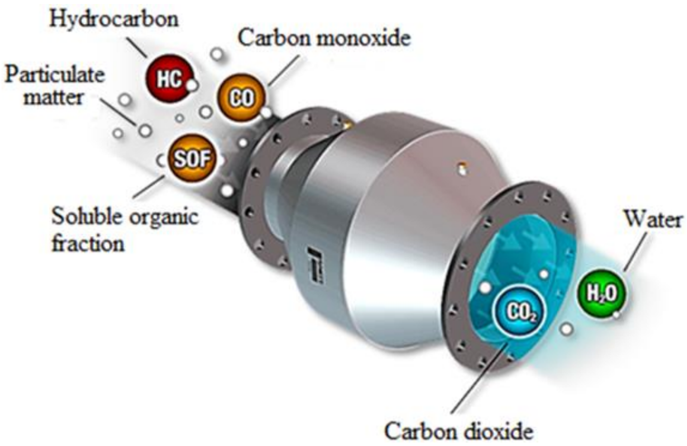

Figure 2 Diesel oxidation catalyst.

5.1 Two-way catalytic converter

One kind of catalytic converter known as an oxidation catalyst function mainly by enabling the oxidation of toxic gases like carbon monoxide (CO) and hydrocarbons (HC) into less toxic substances like carbon dioxide (CO_2) and water vapor. Metals like palladium and platinum are commonly found in these catalysts because they operate as active agents for chemical reactions. These catalysts aid in the oxidation processes that add oxygen molecules to the contaminants found in exhaust fumes.

a. Oxidation of carbon monoxide: $2CO + O_2 \rightarrow 2CO_2$
b. Oxidation of hydrocarbons: $C_xH_y + (x + y/4)\ O_2 \rightarrow xCO_2 + (y/2)\ H_2O$

5.2 Three-way catalytic converter

Vehicles with three-way catalytic converters (TWCs) installed use emissions control systems to lower down dangerous pollutants in exhaust fumes. They function by initiating chemical reactions that result in the conversion of toxic gases like nitrogen oxides (NO_x), hydrocarbons (HC), and carbon monoxide (CO) into less toxic compounds like nitrogen (N_2), carbon dioxide (CO_2), and water vapor (H_2O). The catalyst used in TWCs usually consists of rhodium, palladium, and platinum, which promote these reactions. They are essential in lowering car emissions and assisting in the reduction of air pollution.

VI. DIESEL OXIDATION CATALYST

Diesel oxidation catalysts (DOC) are specialized catalytic converters made to lower down emissions of carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) in diesel engines and equipment. DOCs are easy to use, affordable, require no maintenance, and work with all kinds and sizes of diesel engines. A monolith honeycomb substrate covered in platinum group metal catalyst and housed in a stainless steel container constitutes a modern catalytic converter. The honeycomb construction offers a large catalytic contact surface to exhaust gases since it has several tiny parallel channels (Fig. 2). Several exhaust contaminants are transformed into innocuous compounds, such as carbon dioxide and water, as the heated gases come into contact with the catalyst. Carbon monoxide, gas phase hydrocarbons, and the soluble organic fraction (SOF) component of diesel particulate matter are all intended to be oxidized to CO_2 and H_2O by the diesel oxidation catalyst.

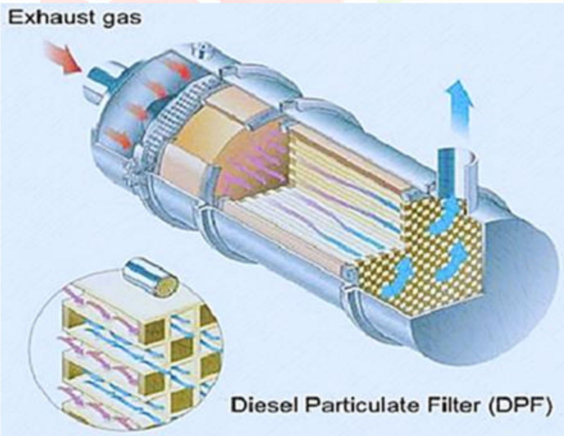

Figure 3 Diesel particulate filter.

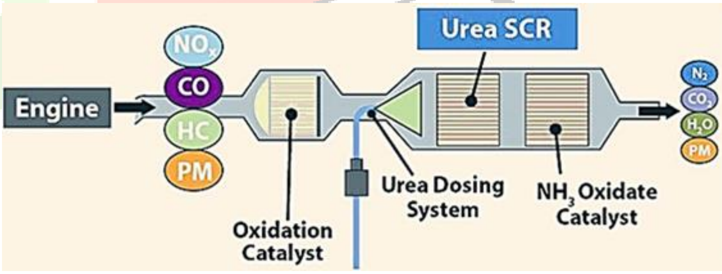

Figure 4 Selective catalytic reduction system.

VII. DIESEL PARTICULATE FILTER

Under some conditions, wall-flow diesel particulate filters (DPF) (Fig. 3) can achieve soot removal efficiency close to 100%. Typically, they remove 85% or more of the soot. Certain filters are designed to be disposed of after they become fully clogged with ash. Some employ a fuel burner to heat the filter to soot combustion temperatures, or they use passive methods such using a catalyst to burn off the collected particulate. This is achieved by programming the engine to run in a way that increases exhaust temperature (when the filter is full), in combination with an additional fuel injector in the exhaust stream that injects fuel to react with a catalyst element to burn off accumulated soot in the DPFs, or by using other techniques. Filter regeneration is the term used for this. Periodic maintenance also includes cleaning, which needs to be done carefully without harming the filter. Cleaning may also be required if the filter becomes contaminated with engine oil or raw diesel due to fuel injector or turbocharger failure. Vehicles driven exclusively at low speeds in urban traffic may occasionally need to make journeys at higher speeds in order to clean up the DPF. This is because the regeneration process takes place at greater road speeds which are not often possible on city streets. However, the DPF may not regenerate correctly if the driver disregards the warning light and drives the car above 60 km/h (40 mph) for an extended period of time. Driving the car after that point may fully destroy the DPF; therefore it must be swapped out. A feature of some more recent diesel engines, namely those found in combination cars, is the ability to carry out a process known as "Parked Regeneration," in which the engine raises its rev limit to roughly 1400 when stationary in order to raise the exhaust's temperature.

Because of incomplete combustion, diesel engines emit a variety of particles when the fuel and air mix burn. Depending on the kind of engine, its age, and the emissions standards it was built to satisfy, the particle makeup varies greatly. As the two-stroke engines burn the fuel-air mixture less thoroughly compared to that done by four-stroke diesel engines, they emit more particulate matter per unit of output.

Soot (black carbon) particles are produced by incomplete combustion of diesel fuel, which results in diesel particulate matter. The minuscule nanoparticles in these particles are smaller than micron, or one micrometer. In addition to being unhealthy, soot and other diesel engine particulates exacerbate air pollution. Up to 95% of the hazardous soot can be captured by new particulate filters, ranging from 30% to higher. Diesel particulate filter (DPF) efficiency can reduce soot emissions to less than 0.001 g/km.

VIII. SELECTIVE CATALYTIC REDUCTION

By using a catalyst and selective catalytic reduction (SCR) shown in Fig. 4, nitrogen oxides (NO_x) can be converted into diatomic nitrogen (N_2) and water (H_2O). A stream of flue or exhaust gas is mixed with a reductant (usually anhydrous ammonia (NH_3), aqueous ammonia ($NH_4(OH)$), or urea ($CO(NH_2)_2$) solution and reacts onto a catalyst. In the case of urea, nitrogen (N_2) and carbon dioxide (CO_2) are produced as the reaction progresses toward completion.

The Engelhard Corporation received a patent in 1957 for the selective catalytic reduction of NO_x utilizing ammonia as the reducing agent in the United States. In the early 1960s, SCR technology development proceeded in the US and Japan with study concentrating on catalytic agents that are more robust and less costly. IHI Corporation implemented the first large scale SCR in 1978.

Large utility, industrial, and municipal solid waste boilers are common installations for commercial selective catalytic reduction systems, which have been demonstrated to reduce NO_x by 70%–95%. Diesel engines used in big ships, gas turbines, diesel locomotives and even cars are examples of more modern usage.

Heavy trucks as well as autos and light commercial vehicles are now required to fulfill Tier 4 Final and EURO 6 diesel emissions requirements where SCR systems are the recommended solution. As a result, compared to engines operating without SCR, the amount of NO_x, particulates, and hydrocarbons released have been cut by up to 95%.

IX. RESULTS and DISCUSSION

9.1 Simulation Findings for Prostar and WordStar Vehicles

a. Two system designs for a Prostar vehicle and a packaging design for a WordStar vehicle were simulated.
b. The Prostar vehicle simulation included a configuration with a long inlet cone to the fuel reformer, demonstrating compliance with EPA 2010 emission regulations.
c. Based on simulation results, a small package design resembling the long inlet cone was created for the Prostar vehicle.
d. The outcomes of the small packaging were extended to a WordStar vehicle for situations requiring compact packaging.

Table 1 Dependability Examination of After-treatment Systems

Aspect Examined	Discussion
Dependability Examination	The work provides a rigorous examination of after-treatment systems' dependability, offering a comprehensive understanding of interrelated reliability concerns.
Analytical Approaches	Analytical approaches and strategies used to resolve and prevent reliability problems in all after-treatment system's subsystems have been methodically considered.
Systemic Assessment	The review addresses shortcomings of previous research by providing a reference perspective of the state-of-the-art in after-treatment system reliability.
Future Challenges	The section summarizes main points raised by the systematic assessment and indicates future challenges in after-treatment system development.

9.2 Challenges and Advances in Specific After-treatment Components

9.2.1 Selective Catalytic Reduction (SCR) Systems

a. Control and chemical reaction management are complex tasks, with focus on improving control, NO_x conversion efficiency, and NH_3 slip prevention.
b. Future use of high performance, computationally intensive techniques is anticipated as computer technology advances.
c. Strong control techniques like Model Predictive Control (MPC) and integrated control approaches are desirable.

9.2.2 Diesel Particulate Filters (DPF)

a. Reliable regeneration control schemes and accurate soot quantification are primary issues**.**
b. High-efficiency DPF and SCR technologies are needed to comply with future emissions requirements.
c. Guaranteed NO_x sensor reliability is essential.

9.2.3 Dependability Modeling and Design

Physics of failure modeling is employed to improve system reliability, particularly effective with complex nonlinear structures like SCRs.

9.2.4 Fault Diagnostics and Software Dependability

a. Technology for fault diagnostics has advanced, incorporating computer networks, databases, control theory, and artificial intelligence.
b. A novel protocol is needed to keep up with contemporary fault diagnosis techniques.

9.2.4 Interdependency of Multi-Component Systems

a. The assumption of independence for reliability and failure prediction models is unrealistic for multi-component systems.
b. Stochastic dependency is crucial for understanding how a component's condition affects the lifetime distribution of others.

9.2.5 Software Dependability

a. Stochastic and dynamic nature distinguishes software dependability from hardware dependability.
b. It reflects flawless design and incorporates principles of fault tolerance.

This discussion provides insights into the challenges and advancements in after-treatment system development, focusing on reliability, control, and compliance with emissions regulations.

X. CONCLUSION

It seems that while regulations for vehicle emissions have reached a plateau in some regions like the EU and the US, there's still pressure on aftermarket shops to comply with existing regulations, especially concerning off-road use. This loophole exploitation by some shops has led to penalties from the EPA, indicating stricter enforcement despite the absence of new tier requirements. Exactly, the stagnant regulations in some regions don't lessen the scrutiny on aftermarket shops regarding emissions compliance. The EPA's penalties demonstrate a commitment to enforce existing regulations, even if new tier requirements haven't been introduced yet. This suggests a focus on maintaining emission standards and preventing loophole exploitation.

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