Dean&Francis

ISSN 2959-6157

Diesel Engines Under Emission Pressure: Performance, Challenges, and Technological Solutions

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Abstract:

In 2015, the Dieselgate of Volkswagen diesel emission brought the emission problem of diesel engines into light, highlighting the gap between test results and real-world practice. The scandal draws international attention to environmental implications in terms of diesel engines, which are predominantly nitrogen oxides. However, diesel engines are still irreplaceably applied in some critical fields such as heavy-duty transportation, agricultural machinery, construction equipment, marine propulsion, military vehicles, and backup power generation, due to their high performance when it comes to torque, fuel efficiency, and durability. The essay reviews the basic structure of the diesel engine and its working mechanisms. With its imperative role, this essay focuses on the causes of pollution during combustion and potential emission filtration technologies, like Selective Catalytic Reduction (SCR), Exhaust Gas Recirculation (EGR), and Lean NO_x Traps (LNT), that make it possible to significantly improve the quality of exhausted gas without harming its fundamental strengths. This essay also aims to determine whether diesel engines can continue to develop with the applied cleaning technology.

Keywords: Diesel gate; NO_x emissions; SCR; diesel engine; emission control.

1. Introduction

Diesel engine has been the cornerstone of the modern economy since its invention in 1890s by Rudolf Diesel. Nowadays, according to International Energy Agency, more than 90% of engines in freight trucks and cargo ships globally rely on diesel engines. Despite the recent progress in electrification, diesel engines are still irreplaceable because diesel provides outstanding energy density and other clear advantages. For example, in remote construction sites or off-grid communities where electricity is not available, diesel engines remain essential because they can offer stable and sufficient power supply. Moreover, diesel engines are still dominant in heavy-loaded shipped on land or on sea because the energy density of diesel fuel, which is 45.5MJ/kg, remains far superior compared to lithium-ion batteries with an energy density of solely 0.72MJ/kg [1]. So, a lithium-ion battery with the same amount of energy will be 60-time heavier and, hence, drastically constraining the vehicle weight and economic efficiency. Similarly, diesel engines generate a greater torque at low rpm, outperforming gasoline engines. For instance, the torque could be up to 400 Nm at 1750 rpm for a 2-L diesel engine [2]. Gasoline engines of the same size, on the other hand, could just generate 320 Nm [3]. And an average heavy-duty truck can generate 25000 Nm of torque at 1200 rpm, making it possible to carry heavy goods without decreasing the working range or cargo capacity. These main advantages make diesel engines still essential in the modern world.

However, a series of environmental problems are caused by diesel engines mainly because of emissions. Especially, nitrogen oxide, a group of chemicals, which imposes a risk both environmentally and physically, is generated during high-temperature combustion. In 2015, the US Environmental Protection Agency made public allegations that Volkswagen Group had designed and installed over 10 million defective diesel engines worldwide [4]. They maliciously installed an erroneous software system that was intended to monitor emissions and activate cleaning system under certain circumstances. As a result, the control systems were discontinued to improve performance and fuel efficiency in normal driving. The aftermath of this was significantly harmful. Related vehicles emitted a vast amount of nitrogen oxides, which was 40 times above the regulated limit. The scandal was known as Dieselgate, and it shocked the world and led to backlash, billions of fines were issued, and public image of diesel engines were undermined. More importantly, stricter emissions laws were introduced, and they stimulated the shift toward cleaner energy and technology since such emission is detrimental for the environment and human body [5, 6].

In response to growing concerns about nitrogen oxide emissions, a variety of technological efforts have been made to mitigate pollution. These measurements focus on the mechanisms of the engines and the fuel. Notable emission-cleaning technologies such as Selective Catalytic Reduction (SCR), Exhaust Gas Recirculation (EGR), and Lean NO_x Trap (LNT) systems, have emerged to substantially lower pollutants. However, there is ongoing research that still addresses the balance between efficiency, performance and maintenance with the complex application of the systems mentioned.

This paper aims to assess the diesel engines mechanisms, clean diesel, existing cleaning technologies as well as their practical implications. Furthermore, the study explores the sustainability and the viability of the cleaner diesel engines with tightening regulations and their traditional advantages.

2. Results and Discussions

2.1 Basic Mechanism of Diesel Engine and Problems

Diesel engines, unlike gasoline engines, utilize compression ignition instead of spark ignition. Diesel engines are internal combustion engines. There are several key components of diesel engines which include an intake system, fuel injection system, combustion chambre, piston-cylinder assembly, turbocharger, and exhaust system [2].

A standard diesel cycle includes four steps: intake, compression, power, and exhaust. First, air is first drawn to the combustion chambre during the intake stroke. Then, in compression stroke, the air is compressed by the piston to a high pressure and temperature environment contributed by the high compression ratio which is typically between 16:1 to 20:1. After that, fuel is injected into the hot and compressed chambre. The ignition is natural because of the elevated temperature and pressure. The combustion propels the piston to travel downwards in power stroke, converting chemical energy to mechanical energy. Consequently, temperature and pressure drop. Eventually, during the exhaust stroke, gas produced by combustion exits the chambre and exhausted into atmosphere [2].

The toxic nitrogen oxides produced by diesel engines are mainly caused by the high temperature and pressure during combustion. Nitrogen and oxygen in the atmosphere easily react when the temperature goes beyond 2000 degrees, creating monoxide and nitrogen dioxide. Normally, the highest temperature in chambre during combustion ranges from 1800 to 2500 degrees and the peak pressure ranges between 40 to 80 bars [7], offering an ideal condition for such reaction. Typically, concentrations of nitrogen oxides in diesel exhaust gas range from 100 ppm (parts per million) to 2000 ppm. This varies under different loading and combustion conditions and the efficiency of the cleaning systems. In some extreme cases [8], the concentration can be as high as 4000 ppm. For example, in Diesegate, on-road tests revealed that the related vehicles emitted gas with 800 ppm to 4000 ppm of nitrogen oxides [9], which is 10 to 40 times higher than the permitted by EPA and Euro 5 [4].

2.2 Possible Cleaning Technologies

2.2.1 Selective catalytic reduction

Selective Catalytic Reduction (SCR) is by far the most effective cleaning technology applied in order to decrease nitrogen oxides in diesel engines exhaust. This system works by injecting a urea-based solution, known as Ad-

ISSN 2959-6157

Blue, into a catalytic converter in the exhaust system. With the heat of the exhaust gas, the temperature is typically above 200 degrees. Therefore, urea breaks down to ammonia and carbon dioxide [10]. Then, ammonia will react with nitrogen monoxide and nitrogen dioxide on the surface of a vanadium-, zeolite-, or copper-based catalyst, turning harmful gases into common and harmless gases nitrogen and water vapor through the following reactions (1) and (2).

$$4NO+4NH_3+O_2 \rightarrow 4N_2+6H_2O \quad (1)$$

$$6NO + 8NH_3 \rightarrow 7N_2 + 12H_2O \quad (2)$$

SCR systems can greatly improve the quality of the exhaust gases, decreasing the concentration of nitrogen oxides by over 90% [11]. This makes it preferred by industry to meet Euro VI and EPA 2010 regulation for heavy-duty application because the filtration is achieved after the combustion unlike some other technologies, meaning that the engines retain the inherent advantages in terms of fuel efficiency.

However, there are still challenges for this technology related to engineering, because SCR systems need to accurately measure the exhaust temperature and properly control the amount and rate of ammonia injected. Furthermore, this system is also sensitive in cool conditions, where crystallization process could be problematic. And clogging can contribute to catalyst inefficiency. In addition, refilling the liquid after a period can be hard for operation in remote areas where infrastructure is underdeveloped.

With all the shortcomings, SCR remains to be the most popular and dominant solution for exhaust control in high-load diesel applications like long-distance truck, buses and agricultural machinery. Effectiveness and scalability play critical roles in this modern diesel emissions control system.

2.2.2 Exhaust gas recirculation

Exhaust Gas Recirculation (EGR) is another widely used technology applied in cylinders of the medium diesel engines to reduce nitrogen oxides produced. In short, the working principle of EGR is to recirculate part of the exhaust gas back to the intake system of the engine, which consequently decreases the concentration of incoming air. This can significantly lower the temperature of the combustion. And in return, it suppresses the creation of nitrogen oxides during combustion.

EGR systems are classified broadly into two categories: High-Pressure EGR (HP-EGR) and Low-Pressure EGR (LP-EGR). For HP-EGR, a part of takes exhaust gas before the turbocharger and sends it back into the intake, working best at low to medium engine loads. It works optimally in medium diesel engines under medium or low loading conditions. On the other hand, low-pressure EGR (LP-EGR) uses exhaust gas after the particulate filter and returns it after the turbocharger, making it more effective for high engine loads.

The efficiency of EGR can change due to load, speed and tuning strategies. In general, the concentration of nitrogen oxides can drop by 20% to 40 % [12]. Compared with SCR, EGR focuses on addressing this issue of emissions before combustion and reduces nitrogen oxides from the source. Hence, it is the economic solution for applications where supply conditions are restricted, and simplicity of operation is the key.

However, the recirculation of exhaust gas decreases oxygen in the combustion chambre, resulting in insufficient combustion where more particulate matter will be generated [12]. Moreover, the efficiency of the engine decreases. Additionally, over time carbon buildup becomes a problem and degrading components can affect durability.

Despite all the limitations, EGR is adopted widely in areas with limited access to urea-based solutions and poor infrastructure. And for the particulate matter, it can be alleviated by combining technology like Diesel Particulate Filter (DPF) and other fuel injection systems.

2.2.3 Lean NOx trap

Lean-burn operation is a common condition where there is excessive oxygen in mixed gas in diesel engines. Lean NO_x Trap (LNT), also known as adsorber catalyst, is an exhaust aftertreatment technology that aims to reduce nitrogen oxide during that process. The theory of technology is to temporarily store nitrogen oxides for a certain period of time, and when extra fuel is injected and a reducing environment is created, it will automatically reduce within an intense burn-rich event [13].

There is a storage material for nitrogen oxides in LNT systems, which is usually based on barium compounds built on platinum metal catalysts. Nitrogen oxide is stored as nitrates by the trap during lean conditions. Periodically, the engine enters rich phase with more fuel when NO_x is released and initiate the process of being transformed into nitrogen and water by catalytic reduction [13].

The performance of the engines is heavily influenced by the sulfur content in the fuel and the catalyst can be poisoned and blocking the storge [13]. Therefore, it is required to eliminate the sulfur in the catalyst by heating it under high temperature, which subsequently increases the risk of thermal stress. But the system is relatively compact compared to other technologies discussed and it makes it suitable for small engines and light-duty trucks.

Generally, LNT reduces the nitrogen oxides by 40% to 70% [13], and it offers a simpler option without any external fluid assistance. In many cases, LNT is used in combination with diesel oxidation catalysts or particulate filters to meet stringent emission standards [14].

2.3 Fuel and Energy

Quality of fuel is critical regarding emissions control.

Most modern systems require ultra-low sulfur diesel because sulfur oxides can react with catalytic materials like barium [15, 16], forming stable solids that reduce the ability of catalysts to transform nitrogen oxides [17]. In addition, other renewable fuel such as biodiesel and synthetic diesel offers benefits of cutting carbon footprints.
However, some alternative fuels can increase NO_x emissions or have compatibility issues with aftertreatment systems [18]. For example, some biodiesel contains more oxygen when combusting and therefore higher temperature, promoting NO_x emissions. Plus, the composition of the fuel matters, because it may react with the surface of the catalyst. Diesel fuel also remains far more energy-dense than batteries, making it more practical for long-haul and off-grid applications. Therefore, improvements in fuel formulation, along with engine calibration and aftertreatment technologies, are essential to balancing performance, emissions, and energy efficiency.

3. Conclusion

Diesel engines remain to be imperative in some key sectors in future due to their high efficiency, torque output and durability. However, the danger of nitrogen oxides emissions and particulate matter pose potential risks and concerns on environment and public health. Especially after Dieselgate, the gap between laboratory performance and realistic emission results.
A variety of emissions control systems have been developed to solve this problem.
Selective Catalytic Reduction (SCR) has proven to be the most effective for NO_x reduction in heavy-duty vehicles, while Exhaust Gas Recirculation (EGR) offers a cost-effective solution for smaller engines. Lean NO_x Trap (LNT) systems serve niche applications in light-duty vehicle. These technologies, often used in combination, have significantly improved the environmental performance of diesel engines.
There are still challenges in spite of all the advancements. Increased system complexity, cost, fuel requirements and requirements for periodically maintenance Moreover, tightening global emission standards continue to raise the bar for compliance.
Looking forward, the future of diesel engines will depend on their ability to balance performance, regulatory compliance, and public perception. With cleaner fuels, advanced control systems, and integrated aftertreatment technologies, diesel engines can remain a viable option in applications where electrification is not yet practical. Continued innovation will be essential to ensuring that diesel remains part of a cleaner, more sustainable energy landscape.

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