Advanced Diesel Engine Emission Control: Current Technologies and Future Alternatives

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Abstract. In an era increasingly focused on decarbonization and electrification, diesel engines, known for their high emissions, are being phased out in certain sectors, such as light and heavy-duty vehicles. However, the high thermal efficiency, durability, and superior power and torque output of diesel engines remain indispensable in various applications. As governments worldwide implement stringent emission standards, it is crucial for diesel engines to control their emissions to comply and stay relevant. This paper reviews recent advancements in diesel emission control, detailing the composition of diesel emissions and their detrimental effects on the environment and human health. It explores the operating principles and effectiveness of current emission control technologies, including water injection, post-injection, multiple injection, selective catalytic reduction (SCR), lean NOx traps (LNT), and turbocharging. Additionally, the paper examines the future of diesel engine development by evaluating the principles and potential of alternative fuel technologies such as hydrogen-diesel dual-fuel engines and dimethyl ether as a fuel. This comprehensive analysis aims to provide insights into sustainable diesel engine advancements that align with global emission reduction goals.

Keywords: Diesel emissions, water injection, fuel Injection, emission control, alternative fuel.

1. Introduction

Diesel engines are known to have better thermal efficiency, durability, superior power and torque output compared to gasoline spark-ignition engines. The above is mainly the result of diesel being denser and having a lower ignition point. These strengths allow diesel engines to remain prevalent in many fields of application in both light and heavy-duty applications to this day even with the trend of decarbonization and electrification. The common fields of applications include heavy-duty marine applications, powering many vessels, road applications in light-duty vehicles such as family cars and heavy-duty vehicles such as semi-trucks and lorries, railroad application in railroad locomotives and power-generation applications, powering generators to from powering lights to back-up generators in nuclear power plants.

However, diesel engine emissions are also known to contain significantly higher levels of Nitrogen Oxide, compared to gasoline engines and significant levels of Carbon Dioxide, Carbon Monoxide, Particulate Matter and Hydrocarbon Emissions. These emissions have significant negative health and environmental effects, being known to cause respiratory diseases and have environmental consequences such as acid rain and global warming. This is why governments around the world have regulations in place to control diesel emissions, such as the Clean Air Act imposed by the US EPA, the European Emissions standard, and the China standards.

In order to meet these increasingly strict emission standards, there have been many approaches to reducing diesel emissions, all being either active control, where the emission is being reduced as the engine where it is being produced, or passive control, which refers to methods that capture pollutants and reduces the amount of pollutants released to the atmosphere. Some current diesel emission control methods that will be discussed include water injection, alternative fuel injection methods such as post-injection and multiple-injection, turbocharging, lean NOx trap and selective catalytic reduction methods. Future emissions control technology will also be discussed, including dual fuel engines, Dimethyl ether fuel, and different types of biofuel.

2. Emission Characteristics of Diesel Engines

2.1. Composition of Diesel Emissions

NOx consists of a significant percentage of diesel emissions at 59.25% from f, compared to petrol vehicles, the average NOx emissions are on average higher than the NOx emission from petrol vehicles [1]. The other 3 pollutants are carbon monoxide (CO), hydrocarbon (HC) and particulate matter (PM), consisting of 11.53%, 8.59% and 20.63%, respectively. The compounds above are usually categorized as diesel pollutants and consist of less than 1% of total emissions. Carbon Dioxide consists of 9.41% of total emissions [1].

2.2. Harmful Effects of Diesel Pollutants

It is widely known that NOx can have many adverse health and environmental effects. NOx can cause acid rain, which is damaging to structures and soil acidity, which can affect crop yield, it is known alongside particulate matter (PM) and hydrocarbons (HC) to cause many respiratory diseases. It can create smog, which is why diesel emissions are so heavily regulated. CO and NOx are both greenhouse gases that contribute to climate change.

3. Emission Reduction Methods

3.1. Water Injection

By introducing water into the combustion chamber, the peak temperature of the combustion process can be reduced. One process in which NOx is produced is through the oxidation of nitrogen in the air at temperatures above 1300˚C, a process known as thermal NOx [2]. By reducing the peak temperature of the combustion chamber, there will be a reduction in the amount of NOx produced. Currently, there are 3 approaches to how the water is introduced into the cylinder.

3.1.1 Low-Pressure Supply of Water

This method refers to when water is introduced to the combustion chamber by injecting water at low pressure into the air intake, which then mixes with air and fuel as it travels into the combustion chamber. This method can be done with two separate approaches if the diesel engine has a turbocharger installed. Experimental result shows that by adding 20% mass of water to air before a turbocharger, at a rotational speed of 2150 rpm, there can be a reduction in the NOx produced by close to 20% but an increase in PM emissions of close to 20% [3]. If the water is introduced after the turbocharging, the reduction of NOx emissions is close to 18% with no measurable effect on PM emissions. In the case that no turbocharging is used, this method can lead to a reduction in total NOx emissions of 8.9% and reduce thermal NOx production by 34.85%. In summary, this method is the most effective overall when applied to an engine with turbocharging after the turbocharger.

3.1.2 In-Cylinder Water Injection

This method refers to when water is injected directly into the engine using an electronically controlled injection valve. This method is the most difficult to implement due to the technical complications involved with installing an extra valve to an engine cylinder. As a result, existing research on the effectiveness of direct water injection is limited. Experimental results show that the ideal quantity of water is 60% of the mass of the fuel. This has been shown to reduce NOx emission by 61% while also resulting in a power increase of 3.7% [4].

3.1.3 Water-Fuel Emulsion (W/F)

This method refers to when water is mixed in with the diesel fuel at a certain ratio in the fuel tank. In different experiments and simulation models, it has been shown that when 20% mass of water is added to diesel fuel prior to combustion, results show total NOx emissions were reduced by around 21% and up to 26% in some cases, reducing the thermal NOx production rate by 53%, and reduces

PM emissions by close to 58% [3]. This method has the most significant result in reducing emissions compared to the previous two methods. One reason for this is that besides the function of lowering the peak combustion temperature, the emulsion of water and diesel has also been observed to cause multiple micro explosions during the combustion process. This appears to allow the fuel and air to mix more thoroughly and thus result in more complete and efficient combustion, reducing overall emissions [3].

3.2. Fuel Injection Methods

3.2.1 Post injection

Post-injection is an active reduction method that works by having a short injection after a longer main injection, thus separating the combustion process into two processes. The primary function of post-injection is to reduce the soot produced from diesel engines, thus reducing the need for exhaust treatment along the exhaust manifold thus maintaining the power output to the largest extent. Experiments consistently show post-injection to be an effective method of reducing soot output from diesel engines, with some post-injection schedules leading to a 62% reduction in the smoke produced from a diesel engine at 1500 RPM [5]. The After Interval, which refers to the time between the first main injection and the second post-injection, measured by the degree by which the crank turns in this time, can also have a significant impact on the result. Experiments have shown that delaying the injection from 5 to 10 degrees can lead to an increase in smoke(soot) and HC emissions, with 5 degrees being the Interval that demonstrated the most significant reduction in HC and soot output at around 23% (60/260) and 50% reduction respectively. However, post-injection does not appear to have a significant impact on the reduction of NOx emissions, and in some cases will increase the NOx emissions. In the case of Fig. 1, the reduction of NOx emission is negligible compared to the soot reduction. When the After interval is 5 degrees to 10 degrees, it can lead to an increase of NOx production of 50% to 10%, respectively [5].

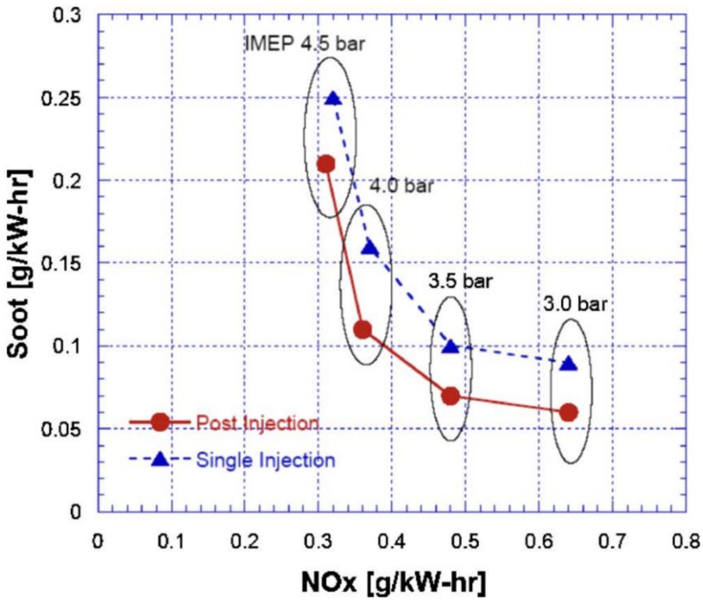

Figure 1. Soot and NOx emission of post-injection compared to single injection [6]

The operating principle behind the post-injection method has been disputed in research. One popular explanation is that the secondary injection allows fuel and air to mix more thoroughly since it can be visually observed with a “split flame” profile created by the post-injection. This increased mixing results in a more complete combustion. It also allowed for a larger soot-oxidization zone, which, at the same time as reducing soot, also produces NOx, which explains why the emission of soot and HC is reduced as the After Interval decreases while NOx increases at the interval is prolonged, and other results that show a limited change to the NOx emission [5]. The second explanation that the increased temperature caused by the delayed injection causes the reduction also supports the aforementioned results since NOx forms more easily at higher temperatures [5]. In summary, this method requires a balance between the NOx formed from soot oxidation and the reduction in soot and HC brought on by the more complete combustion.

3.2.2 Multiple injection

Similar to post-injection, multiple injection involves injecting the fuel over 2 more separate events in an experiment done with a three-injection method in a low-compression ratio, heavy-duty engine. In the three-injection method, Results show a decrease in the amount of NOx emission of 58.7% and a decrease in the amount of soot emissions of 25% [6]. The double injection method is similar to post-injection since both have two injections, but with double injection, the pilot injection, which is a small injection of fuel followed by a larger main injection, is the opposite of post-injection. As can be seen from Fig. 2, this method is able to reduce max soot output by up to 68%, much higher than the three-injection method and the post-injection method. There was also a 24.16% reduction in the NO output, whereas CO_2 emissions were 7.85% higher [6]. Since the principle of multiple injections is similar to post-injection, both are intended to increase the thoroughness of the fuel and air mixture, thus increasing the temperature and the completeness of the combustion. CO can easily oxidize under higher temperatures and form CO_2.

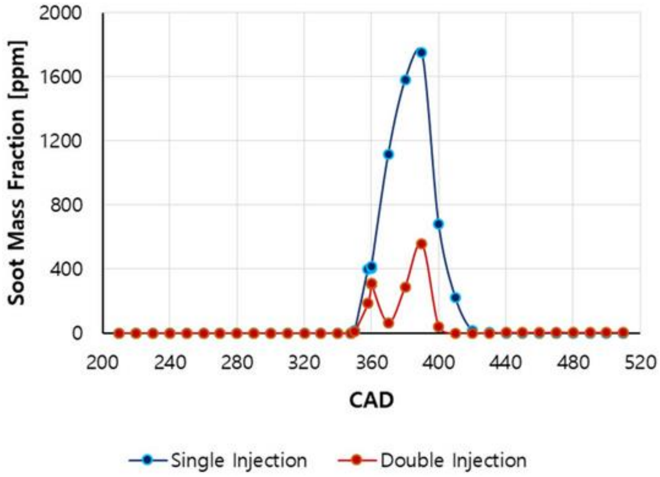

Figure 2. Soot emission of single injection compared to double injection [6]

3.3. Selective Catalytic Reduction (SCR)

SCR is a passive control method that is primarily aimed at reducing NOx emissions from vehicles. It works by having NOx travel through a heterogeneous catalytic bed containing reducing agents in the presence of oxygen, usually ammonia or urea, hydrocarbon (HC), and hydrogen [7]. Below are the chemical equations describing the reduction process using ammonia and urea, respectively.

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

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O \quad (2)$$

$$NO + NO_2 + 2NH_3 = 2N_2 + 3H_2O \quad (3)$$

The chemical equation for the process with ammonia as a reducing agent [7]:

$$4NO + 2CO(NH_2) + 2H_2O + O_2 \rightarrow 4N_2 + 6H_2O + 2CO_2 \quad (4)$$

$$6NO_2 + 4CO(NH_2)_2 + 4H_2O \rightarrow 7N_2 + 12H_2O + 4CO_2 \quad (5)$$

The chemical equation for the process with urea as a reducing agent [7]. The catalyst is also very important for the effectiveness of the SCR method. Common catalysts include metal oxides of titanium, vanadium or iron, active carbon and zeolites. These elements can be formed into many shapes that serve to maximize the surface area the flue gas is in contact with, such as layers of mesh or a honeycomb structure. Selective catalytic reduction methods used today can consistently reduce

NOx emission by 60 to 90%, with some catalysts, such as the zeolite catalyst, reducing NOx emission by close to 100% [7].

3.4. Lean NOx Trap (LNT)

Lean NOx trap works by using a catalyst made from Pt/Rh group metals to catalyze the reduction/oxidation process of the flue gas [8]. Followed by a base-metal oxide or basic absorbent that acts to store the reduced/oxidized NOx. Said absorbers are usually composed of barium oxide (BaO) and barium oxide [9]. The chemical process is as follows: after the oxidization catalyst oxidizes the NO produced by the engine into NO_2, it reacts with the absorber material to form barium nitrate during lean operation of the engine where it is stored. This also means the LNT will eventually fill and, therefore, needs to be regenerated periodically. Regeneration occurs when the engine is running fuel-rich. In the fuel-rich exhaust environment, H_2, CO and HC replace oxygen and reduce the NO and NO_2.

One persisting limitation of LNT is the occurrence of NOx slip during fuel rich regeneration process. It has been shown to occur the most during the regeneration process when the temperature is 150˚C, with a NOx slip of anywhere from 36% to 78%. However, at higher temperatures of 350˚C to 450˚C, the regeneration efficiency can be around 100% [10].

3.5. Turbocharging

Turbocharging works by direct pressure of the exhaust gas through a turbine, which serves to funnel air into the air intake at a greater pressure and greater temperature compared to naturally aspirated engines. This allows for more air at higher temperatures to be mixed in with fuel in every engine cycle, thus reducing fuel consumption. This reduction in fuel consumption is the primary principle behind the reduction of emissions. The most prominent reduction of CO, experimental results have shown a reduction of 47% (Fig. 3) compared to naturally aspirated diesel engines, and NOx emissions have also seen a decrease of 27%. For this reason, turbocharging is now widely adopted across most diesel vehicles sold in order to meet emission standards.

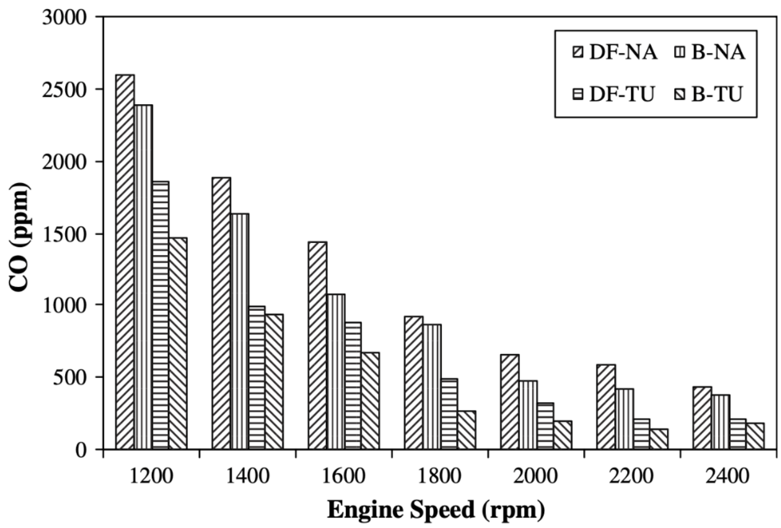

Figure 3. CO emission of turbocharged (TU) engine compared with the naturally aspirated engine at different engine speeds [11]

4. Future Development of Diesel Engines

4.1. Hydrogen/Diesel Dual Fuel Engines

Unlike diesel fuel, hydrogen is one of the most abundant elements on earth. In experimental setups of hydrogen/diesel dual-fuel engines, hydrogen is injected into the engine in gaseous form in separator fuel injectors as diesel fuel. Experimental results show that at 80% H_2, experimental results a decrease of soot emissions of 88% with a 58% of H_2. This is because the combustion of H_2 is not able to produce any soot or carbon. The increased percentage of H_2 also means less diesel combustion and, therefore, a reduction in CO and CO_2 emissions [12]. At 58% H_2, the reduction in CO and H_2 is the most significant, there is an 85% reduction in CO and a 62% reduction in CO_2 emissions [10].

4.2. Dimethyl Ether

Dimethyl ether (DME) is a gas at room temperature and pressure but can be a liquid at moderate pressure [13]. The energy density of DME is significantly lower than conventional diesel fuel. Due to its physical properties, DME can be used in direct-injection diesel engines without any modifications. Although experimental results show a combined NOx and HC reduction of around 40% compared to regular diesel fuel and PM and soot emissions of close to 0, there was roughly a 64% increase in the CO produced (Fig. 4) [13].

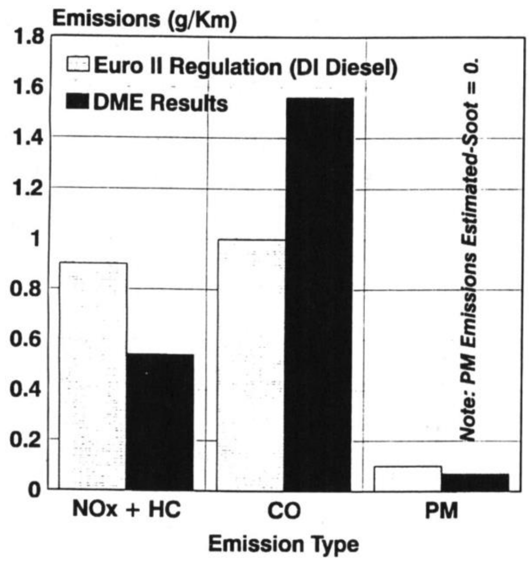

Figure 4. Different emissions of DME fuel compared to standard EU diesel [13]

5. Conclusion

In conclusion, diesel engines remain relevant in today's increasingly stringent emissions standards from world governments due to their reliability, high torque output and higher thermal efficiency. However, as was established, diesel engines produce significantly more NOx compared to gasoline engines and high levels of other emissions, including HC, carbon dioxide, PM and carbon monoxide. Methods of emissions reduction can be categorized into active and passive reduction. The first active reduction method explored was the water injection method. In this method, there are three ways in which water can be injected: at low pressure through the air intake, direct injection into the cylinder and water-fuel emulsion. The third and second methods both showed a significant reduction in emission at 58% reduction in NOx with water emulsion but the water-fuel emulsion method is significantly simpler to achieve compared to the direct injection method. The second method is the injection method. This method also yields significant results at a 50% reduction of soot but shows an increase in NOx production.

Similarly, for the third method, the multiple injection method, reduction of emissions where observed in soot and NOx, but there was an increase in CO production. Lastly, for active reduction, turbocharging is very widespread at this point and is able to reduce many types of emissions and reduce fuel consumption. For the passive reduction methods, the selective catalytic converter appears to be the most effective, with a reduction of NOx of close to 100% in certain cases. However, it is not very effective in reducing other types of emissions. The same can be said about LNT, but it has problems with NOx slippage during regeneration. In the future development direction is in alternative fuels, including hydrogen and dimethyl ether. Hydrogen shows a significant reduction of many emissions, but for dimethyl ether, there is an increase in CO emissions. These are problems that still need to be solved in the future of compression ignition development.

References

[1] Istrate A, Bică M, Simion, M. Compression ignition engine-sources of pollution. IOP Conference Series: Materials Science and Engineering, 2020, 997 (1).

[2] Saadeldin Mahmoud Abdelnaser, Elgoharya M. M., Abdelnaby Maged, et al. Effects of direct water injection on the nitrogen oxide emission characteristics of marine diesel engines. Journal of Marine Science and Technology, 2023, 31 (2): 6.

[3] Kegl Breda, Pehan Stanislav. Reduction of diesel engine emissions by water injection, SAE Technical Paper Series, 2001.

[4] Sun Xiuxiu, Ning Junjie, Liang Xingyu, et al. Effect of direct water injection on combustion and emissions characteristics of marine diesel engines. Fuel, 2022, 309: 122213.

[5] O'Connor Jacqueline, Musculus Mark. Post injections for soot reduction in diesel engines: A review of current understanding. SAE International Journal of Engines, 2013, 6 (1): 400–421.

[6] Yun Hanho, Sun Yong, Reitz Rolf. D. An Experimental and Numerical Investigation on the Effect of Post Injection Strategies on Combustion and Emissions in the Low-Temperature Diesel Combustion Regime. Proceedings of the ASME 2005 Internal Combustion Engine Division Spring Technical Conference, 2005, 25-35.

[7] Seol Ju-Hwan, Pham Van Chien, Lee Won-Ju. Effects of the multiple injection strategy on combustion and emission characteristics of a two-stroke marine engine. Energies, 2021, 14 (20): 6821.

[8] Mladenović Milica, Paprika Milijana, Marinković Ana. Denitrification techniques for biomass combustion, Renewable and Sustainable Energy Reviews, 2018, 82 (3): 3350–3364.

[9] Alimin Ahmad Jais, Benjamin S.F, Roberts Carol. Lean nox trap study on a light-duty diesel engine using fast-response emission analyzers. International Journal of Engine Research, 2009, 10 (3): 149-164.

[10] Suzuki Yasumasa, Tsujimura Taku, Mita Takuro. The performance of multi-cylinder hydrogen/diesel dual fuel engine. SAE International Journal of Engines, 2015, 8 (5): 2240–2252.

[11] Schönebaum Simon, Dornseiffer Jürgen, Mauermann Peter, et al. Composition/performance evaluation of lean NOx trap catalysts for coupling with SCR Technology. ChemCatChem, 2023, 13 (7): 1787–1805.

[12] Karabektas Murat. The effects of turbocharger on the performance and exhaust emissions of a diesel engine fuelled with biodiesel. Renewable Energy, 2009, 34 (4): 989–993.

[13] Fleisch Theo, McCarthy Chris, Basu Arun, et al. A new clean diesel technology: Demonstration of ULEV emissions on a Navistar diesel engine fueled with dimethyl ether. SAE Technical Paper Series, 2009.