

Diesel emissions and their mitigation approaches

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1 Introduction

Throughout history, the expansion of human civilisation has been supported by steady growth in our use of high-quality exosomatic energy. This growth has been driven by an increasing population and increasing levels of activity. As we learned to harness the energy sources around us we progressed from horse-drawn ploughs, hand forges and wood fires to our present level of mechanisation with its wide variety of high-density energy sources. As industrialisation has progressed around the world, the amount of energy each one of us uses has also increased, with the global average per capita consumption of all forms of energy rising by 50% in the last 40 years alone (Rizwanul Fattah et al. 2013). Historically, fossil fuels have played a vital role in global energy demand. The diesel engine, named after its inventor Rudolf Diesel, was patented in 1892 and catered for this energy demand substantially ever since (Cummins 1976). Being the powerhouse of heavy-duty and commercial transport vehicles, both on land and at sea, has been the most important use of diesel engines, and the importance is increasing consistently. The diesel engine is the most efficient type of internal combustion engine, offering good fuel economy and low carbon dioxide (CO₂) emission (Imtenan et al. 2014). The diesel engine converts the chemical energy contained in the fuel into mechanical

power. High-pressure diesel fuel is injected through injectors into the engine cylinder, where it mixes with air, and the combustion occurs due to the lower Self-Ignition Temperature (SIT) of diesel fuel. While diesel engines are arguably superior to any other power-production device for the transportation sector in terms of efficiency, torque, and overall driveability, they suffer from inferior performance in terms of emissions. Due to their mode of operation, involving stratification and presence of fuel-rich, soot-prone regions and simultaneously lean nitrogen oxide prone regions in the flame vicinity, a number of challenges are posed, necessitating further research effort into pollutant reduction technologies.

As far as emissions are concerned, diesel engines, especially heavy-duty vehicle engines, have been subjected to progressively stringent emission control standards. The adoption of emission standards was initially launched by the USA, followed by the European Union and Japan, and, subsequently, by other countries, like Australia, Brazil, China and India, among others. These standards have led to the current strict emissions limit, transpired by US EPA 2010 and Euro VI and their other variants and provided huge emission reductions of criteria emissions viz. hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM) and smoke. Nevertheless, due to climate change and air quality concerns, more stringent emission control is still a regulatory demand. One prominent example of emission control regulation is the US 2010 standard which required PM and NO_x emissions reduction by at least 90%, compared with initial standards (Barbosa 2020).

This chapter first discusses the diesel combustion process, which results in emissions in gaseous and solid forms. The criteria emissions, i.e. NO_x, soot/PM, HC and CO have been discussed next in detail to have a clear idea of characterising those emissions. After that, some of the salient pre-combustion and post-combustion technologies have been explored, which are in no way a complete list of available technologies. The simultaneous reduction of NO_x and

PM is also highlighted here. Finally, a quick review of the strategies and the available technological pathways for emission reduction is discussed.

2 Diesel combustion

The diesel engine is the most fuel-efficient commercial combustion engine ever built for transportation purposes. These engines operate on the principle of compression ignition (CI), unlike spark-ignited (SI) engines in which a spark plug initiates combustion. These engines rely on compression in the cylinder to raise the air temperature and pressure such that upon injecting fuel, the resulting combustible mixture auto-ignites. In conventional diesel combustion, spray droplets are formed from each hole of the fuel injector when liquid fuel is injected through multiple holes at high pressure. The spray penetrates the combustion chamber entraining in-cylinder or ambient gases into the jet, forming a roughly conical jet with volume increasing with downstream distance from the injector. The increasing entrainment downstream causes the equivalence ratio (ϕ), defined as the "ratio of the local fuel-ambient charge mass ratio to the stoichiometric fuel-ambient mass ratio" (Musculus, Miles, and Pickett 2013a), to vary along the jet axis approximately inversely with the downstream distance. The liquid fuel is vaporised by the entrained gases, and vaporised fuel-ambient mixture is then carried downstream of the liquid length by momentum and continues to entrain more ambient gases. First-stage ignition reactions then commence (Dec and Espey 1998, 1995), which is followed by a highly exothermic second stage reaction that leads to a "premixed burn" phase of the diesel combustion. As the temperature rises, soot-precursor species like polycyclic aromatic hydrocarbon (PAH) quickly form in the hot (~ 1600 K), fuel-rich combustion products of the premixed burn (Siebers and Higgins 2001, Dec 1997). Soot is formed afterwards, which fills the entire downstream jet cross-section (Pickett and Siebers 2004). Any of this soot that is not oxidised in the later phases of combustion becomes engine-out particulate matter (PM). The diffusion flame is formed on the periphery of the fuel-rich, high-temperature downstream

region (in excess of 2600 K) of the jet where nitrogen oxides are formed. Thus, traditional mixing-controlled diesel combustion contributes to undesirable engine-out NO_x and PM emissions because of its inherent nature.

3 Diesel exhaust emissions

Diesel engine exhaust contains a wide range of gaseous and particulate phased organic and inorganic compounds with higher amounts of aromatics and sulphur compared to gasoline engines. The particles have hundreds of chemicals adsorbed onto their surfaces, comprising many recognised or suspected mutagens and carcinogens. The gaseous phase also contains many toxic chemicals and irritants. These have a serious adverse effect on human health and environmental impact (Ackerman et al. 2000, Reitmayer et al. 2019).

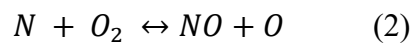
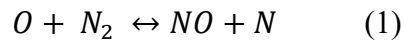
3.1 Diesel gaseous emissions

Diesel gaseous emissions primarily comprised of, but not limited to, nitrogen oxides (NO_x), unburnt hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO₂) and sulphur dioxide (SO₂). Out of these, as discussed previously, NO_x, HC and CO are regulated by most emission standards.

3.1.1 Nitrogen Oxides (NO_x)

Nitrogen oxide is the generalised term for NO and NO₂ given with the formulae of NO_x. NO_x is the most harmful gaseous emissions from diesel engines; the reduction of it is always the target for engine researchers and engine manufacturers. As discussed, during typical mixing-controlled diesel combustion, a diffusion flame is formed at near stoichiometric fuel-air mixtures where NO_x formation is high due to the very high temperatures at typical diesel operating conditions (exceeding 2600 K) (Ahmad and Plee 1983, Dec and Canaan 1998). NO_x, primarily NO is typically formed by three main mechanisms viz. thermal (Zeldovich), prompt (Fenimore), and fuel-bound nitrogen mechanisms (Sun, Caton, and Jacobs 2010).

The thermal mechanism is based on the Zeldovich mechanism, represented by Reactions (1) through (3) involving the breakdown of strong triple bond of atmospheric (molecular) nitrogen and occurs during combustion or shortly thereafter in the post-flame gas region (Bowman 1975). Residence time and concentration of nitrogen and oxygen also play a vital role in the production of thermal NO (Ban-Weiss et al. 2007).



The presence of a second mechanism leading to NO formation was first identified by Fenimore and was termed as "prompt NO" (Fenimore 1971). In this mechanism, the formation of free radicals in the flame front of hydrocarbon flames leads to rapid production of NO_x. Prompt NO_x is prevalent in some combustion environments, such as in low-temperature, fuel-rich conditions and where residence time is short (Fenimore 1971).

The fuel NO_x is formed by the combustion of nitrogen chemically associated with the fuel (as apart from the molecular nitrogen) (Cofala and Syri 1998). The production process is complex because this includes the order of 50 intermediate species and several hundred reversible reactions and the true value of rate constants are still unknown. However, this is not as prevalent as the other two since diesel fuel has very low nitrogen levels. The addition of additives containing nitrogen atoms, e.g. pyridine, pyrrole, etc., may lead to fuel NO_x formation.

3.1.2 Hydrocarbons (HC)

Diesel engines run on an overall fuel-lean equivalence ratio ($\phi < 1$) whereas the gasoline engine tends to run on near stoichiometric ratio ($\phi \approx 1$). As such, diesel engines generally produce about one-fifth of the HC emissions of a gasoline engine (Ganesan 1996). In general,

a CI engine has a combustion efficiency of 98%, which means only about 2% of the HC fuel being emitted after combustion. The prevalent reasons for HC emission include over-mixing of fuel with air which leads to over-leaning, thereby making it difficult to support combustion, especially at low temperature, low load and idle; under-mixing of fuel and air causing an over-rich mixture which is difficult to ignite; and flame quenching at low-temperature walls which causes partial burning (Alozie and Ganippa 2019). In addition, other causes, including low velocity and late fuel injections such as post-injection, can also be significant (Rizwanul Fattah et al. 2013).

3.1.3 Carbon monoxide (CO)

CO is a poisonous gas, and when inhaled, this replaces the oxygen in the bloodstream, which causes the metabolism to function improperly. Small amounts of CO concentration slow down physical and mental activities and produce headaches, while large amounts can kill. CO is generally formed due to incomplete combustion of diesel fuel in the absence of a sufficient air supply. However, combustion in most diesel engines is practically lean beyond stoichiometric. Therefore CO emission is normally low except for during transient operations. In general, CO emissions in the exhaust represent lost chemical energy that is not fully utilised in the engine (Ozsezen and Canakci 2010).

3.2 Solid-phase emissions

The solid phase emissions, known as particulates in broader terms, are the combination of soot and other liquid- or solid-phase materials that are collected when product (exhaust) gases pass through a filter (Agarwal, Gupta, and Kothari 2011).

3.2.1 Soot

Particulates are often separated into a soluble and an insoluble or dry fraction. The fraction of particulate, which is soot, is often estimated by finding the insoluble portion of the particulates (Ullman 1989, Lee, Pedley, and Hobbs 1998). Soot is not a clearly defined substance. In general, soot is a solid substance consisting of roughly eight parts carbon and one part hydrogen (Tree and Svensson 2007). Soot is formed from unburned fuel, which nucleates from the vapour phase to a solid phase in fuel-rich regions at elevated temperature without sufficient oxygen concentration. In engine-out emission, soot primarily consists of fractal-like carbonaceous agglomerates and adsorbed material in the size span of 30–500 nm (Kittelson, Watts, and Johnson 2006). Liquid phase materials and hydrocarbons are adsorbed on the surface of soot, depending on engine operating conditions. The fraction of soot in particulate from diesel exhaust varies but is typically higher than 50% (Tree and Svensson 2007). Soot is of particular interest to researchers studying spray combustion because it can be quantified using advanced combustion diagnostics such as optical and/or laser diagnostics (Fattah et al. 2019, Chan et al. 2011). Soot is often deposited on combustion chamber walls in diesel engines. Smoke opacity is an indirect indicator of soot content in the exhaust gases of a diesel engine (Agudelo, Benjumea, and Villegas 2010). As such, this parameter can be correlated with the fuel's tendency to form soot during engine operation.

3.2.2 Particulate Matters

As mentioned previously, particulate is often separated into a soluble and an insoluble or dry fraction. The soluble portion is generally termed PM which a mixture of solid and liquid particles that differ in surface area, solubility, number, size, shape, chemical composition, and origin (Sakurai et al. 2003, Pope and Dockery 2006). Soluble fraction present in particulates mainly consists of aldehydes, alkanes, alkenes, aliphatic hydrocarbons, PAHs and its

derivatives (Mohankumar and Senthilkumar 2017). Other PM constituents include: un/partially burned fuel/lubricant oil, bound water, wear metals and fuel-derived sulphates (Ullman 1989, Lee, Pedley, and Hobbs 1998). Researchers studying engine combustion are predominantly interested in PM because it can be quantified using exhaust gas measurement devices (Khalife et al. 2017). The aerodynamic diameter has been recognised as a simple means of defining the particle size of PM (Bhat and Kumar 2012), as these particles exist in different shapes and densities in the air. Those are:

- PM₁₀: inhalable particles, with diameters that are generally 10 micrometres and smaller; and
- PM_{2.5}: fine inhalable particles, with diameters that are generally 2.5 micrometres and smaller.

There have been deep concerns about public health because of particulate emissions in the atmosphere. This is mainly because of the nature of particles in emissions being very small (more than 90% are less than 1 mm by mass) which makes them readily breathable.

4 Methods of mitigation

As discussed previously, traditional mixing-controlled diesel combustion contributes to undesirable engine-out NO_x and PM emissions, reduction of those is often the primary objective of many studies.

4.1 NO_x emission mitigation

This section summarises the developments regarding NO_x mitigation in CI engines. NO_x can be mitigated through several techniques depending on when it is implemented. Various pre-combustion and after-treatment technologies are employed to control NO_x emission. The complete layout of NO_x control techniques is shown in Fig. 1.

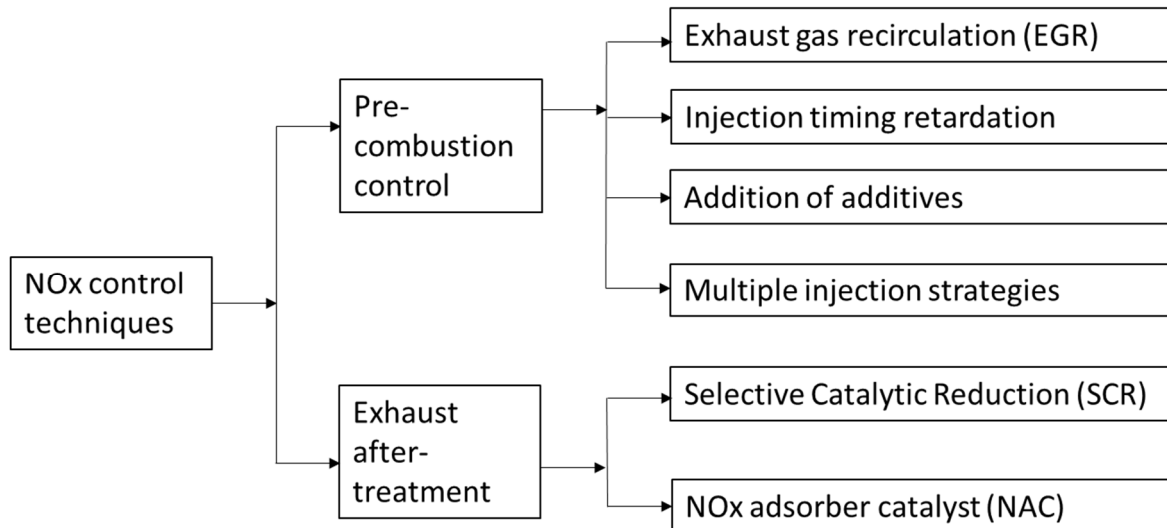


Figure 1: Schematic layout of NOx control techniques

4.1.1 Pre-combustion techniques

Exhaust gas recirculation (EGR) is an engine-out (i.e. prior to exhaust after-treatment) emission control technology allowing significant NOx emission reductions from most types of diesel engines: from light-duty engines through medium and heavy-duty engine applications. EGR can be achieved by diluting the intake stream with combustion products, thereby reducing both the intake-oxygen concentration and thereby the flame temperature (Ladommatos, Abdelhalim, and Zhao 2000, Alriksson, Rente, and Denbratt 2005). However, this benefit of EGR comes at costs viz. increase in fuel consumption, higher emission of PM, HC, and CO, higher engine wear and reduction in engine durability (Abd-Alla 2002). In particular, EGR exacerbates the trade-off between NOx and particulate emissions at high loads. The percentage reduction of NOx depends on EGR level with intake oxygen concentrations in the range of 10–15%, engine speed and load condition, intake air condition, etc. (Pandurangi et al. 2014, Musculus, Miles, and Pickett 2013b).

Different types of additives such as metal-based additives viz. ferric chloride (FeCl_3), magnesium oxide (MgO); nanoparticles viz. Cerium oxide (CeO_2), alumina nanoparticle, carbon nanotubes (CNT); oxygenated additives viz. dimethyl ether, ethanol, and methanol;

antioxidants viz., cetane number improver viz. 2-Ethylhexyl nitrate (EHN), di-t-butyl peroxide (DTBP), etc. in conjunction with biodiesel are generally used to reduce the NO_x emissions (Rizwanul Fattah et al. 2014, Soudagar et al. 2018, Hosseinzadeh-Bandbafha et al. 2018). Biodiesel is an alternative fuel commonly described as fatty acid methyl ester derived from vegetable oils and animal fats (Ong et al. 2014, Ong et al. 2019, Silitonga et al. 2020). It is renewable, biodegradable and oxygenated fuel consisting of triglycerides of long-chain saturated and unsaturated fatty acids that can be converted into monoglycerides by the transesterification process.

Retarding main injection timing is always found to reduce NO_x emission due to the fact that it reduces combustion temperature in the cylinder, as well as the residence time of high-temperature burned gas in the combustion chamber where NO_x is actively formed (Qi *et al.* 2011).

The multiple injections viz. pilot-injections, split-injections and post-injections are the three most commonly used multiple injection strategies (O'Connor and Musculus 2013). Among these two strategies, pilot-injection and split-injections are used to mitigate NO_x emission. Pilot injection strategy is initialised with a pilot injection that precedes the main injection, whereby the quantity of fuel injected in the pilot injection is typically lesser than that of the main injection (Tow, Pierpont, and Reitz 1994). Pilot combustion raises the in-cylinder temperature prior to the main combustion event, which allows for a reduced ignition delay, limiting the amount of premixed combustion and lowering the rate of combustion (Sahoo et al. 2013). As a result, the peak heat release rate is reduced and consequently, so is the NO_x produced. Split-injection, on the other hand, is often used for splitting the overall heat release which alleviates wall-wetting of long injection pulses achieved through splitting that into few pulses thereby interrupting their maximum stabilised length (Pickett, Kook, and Williams 2009) and reducing emissions. The number of pulses into which the single injection is split is

vital for emission reduction. Ehleskog *et al.* (Ehleskog, Ochoterena, and Andersson 2007) found that splitting the main injection into three and four pulses was found to result in a reduction in NO_x emissions.

4.1.2 Exhaust after-treatment techniques

There are two main after-treatment technologies available to reduce NO_x emissions from diesel engines (Hoekman and Robbins 2012). The first one involves the use of Selective Catalytic Reduction (SCR) catalyst. In the SCR system, reductant (e.g. ammonia in the form of aqueous urea) is injected into the engine exhaust line ahead of the SCR catalyst, and a different catalyst bed is used to directly reduce NO_x to N₂. SCR technique has a high NO_x conversion efficiency of about 90%. SCR with hydrocarbon reductant is known as a lean-NO_x trap (LNT) (Alozie and Ganippa 2019). The second one involves the use of a NO_x adsorber catalyst (NAC). A NAC system utilises catalyst containing a basic oxide viz. Pt/Ba/Al₂O₃ catalysts to convert all NO to NO₂, which is then trapped in an adsorbent bed i.e. Ba surface. Once the adsorber is saturated with NO₂, the exhaust stream is forced into a fuel-rich condition and the trapped NO₂ is reduced to N₂ on the Pt surface, which is exhausted (Tripathi, Dhar, and Sadiki 2018). A NAC is also called a NO_x Storage Reduction Catalyst (NSRC/NSC) in the literature (Liu and Gao 2011). NAC has up to 80% reduction efficiency.

4.2 Particulates emission mitigation

This section summarises the developments regarding soot/PM mitigation in compression ignition engines. Soot can be mitigated through several techniques depending on when it is implemented. Various pre-combustion and post-combustion technologies are employed to control particulates. The complete layout of the particulates control technique is shown in Fig. 2.

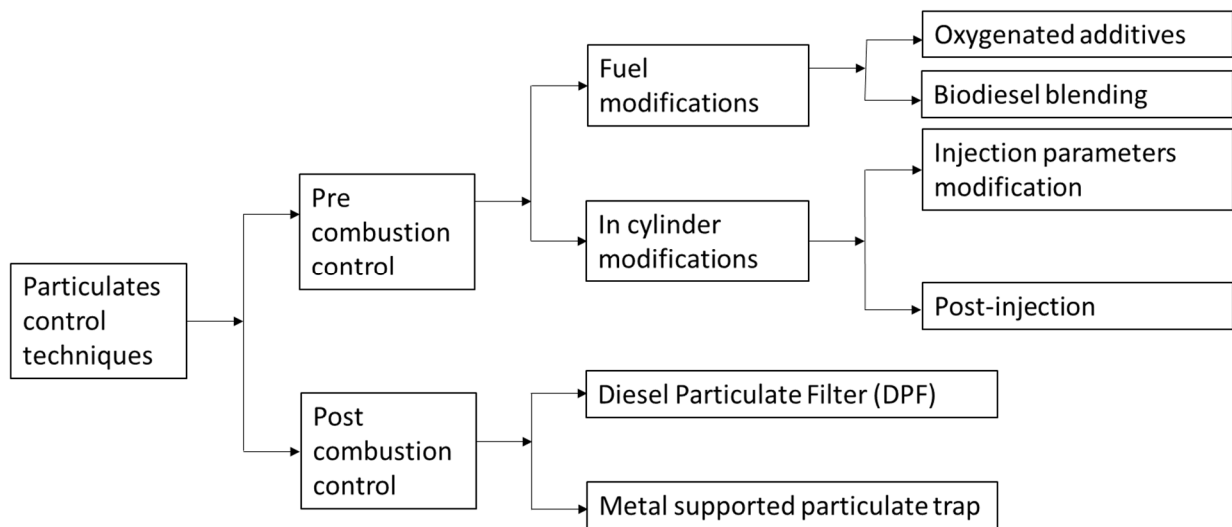


Figure 2: Schematic layout of particulate control techniques

4.2.1 Pre-combustion techniques

The addition of oxygenated additives is a well-documented technique for soot/PM mitigation. These chemicals have fuel bound oxygen in their structure and typically possess a very high cetane number which enhances combustion and the ignition quality of fuel, thereby increasing the likelihood of oxidation of particulates (Mohankumar and Senthilkumar 2017). Some of the oxygenated additives used in previous studies include methanol, ethanol, butanol, diethyl ether, diphenyl ether, diethylene glycol, dimethyl ether, and nitromethane, dimethyl carbonate, etc. (Wang et al. 2009, Mueller and Martin 2002, Górski et al. 2013).

Biodiesel blending with diesel at various proportions (~10-50%) has been reported to reduce particulate emissions significantly. The presence of long-chain saturated and unsaturated fatty acids, low sulphur and aromatic content, nearly 10% fuel bound, etc. has been advantageous in the reduction of PM (Mahlia et al. 2020, Silitonga et al. 2013).

Increasing the fuel injection pressure greatly reduces particulates emission because of shortening ignition delay thereby improving spray atomisation and enhancing fuel-air mixing rate (Gao, Matsumoto, and Nishida 2007, Fang et al. 2010). In addition, the reduction of the injector nozzle diameter also produces the same effect (Kuti et al. 2013). The shortened ignition

delay advances the combustion and also the soot formation processes giving ample time to oxidation of soot. As such, increasing the injection pressure and reducing the nozzle hole diameter to a micro-hole size help in reducing particulate emission.

Post-injection is where a quantity of fuel (usually up to 20%) is allocated into separate portions in a way that the second injection duration is much shorter than that of the main injection. As discussed previously, a high level of EGR can cause an increase in the engine-out soot emissions when used in conventional diesel engines due to the suppression of soot oxidation (Idicheria and Pickett 2005, Tree and Svensson 2007). This unwanted increase can be countered by post-injection which is introduced early enough to interact with main combustion (Fattah et al. 2018, Yip et al. 2019). Another advantage of post-injection is that it increases exhaust temperature thereby helping the regeneration event of diesel particulate filter (DPF).

4.2.2 Post-combustion techniques

DPF is a type of monolithic filter which is used to trap particles of micron and sub-micron sizes carried with the exhaust gases (Salvat, Marez, and Belot 2000). The most commonly used one is wall-flow DPF which has the cells alternately plugged at each end where exhaust gas permeates through walls of the filter while the particles are trapped. Due to the continuous use of DPF, there is a chance of clogging, which requires periodic "regeneration" to oxidise the accumulated soot in the filter and keep its pressure drop at a reasonable level to ensure the fuel economy and the proper working of the engine. In general, DPF should possess high filtration efficiency, less pressure drop, high soot-storing capacity, and compatibility along with stability (mechanical, thermal, and chemical) with regeneration methods.

DPF technology cannot be applied to all applications since the filter regeneration is limited by engine-out NO_x to PM ratio as well as exhaust temperature. Thus, these cannot be

applied to older diesel engines like heavy-duty trucks with high soot/PM emissions. To overcome this difficulty, a passive PM control technology known as metal-supported flow through diesel filters employing continuously regenerating trap's principle has been developed for this type of engine (Jacobs et al. 2006, Pace, Konieczny, and Presti 2005). This technology is referred to as 'Partial Filter Technology (PFT)' which can reduce PM by up to 77%.

4.3 Simultaneous NO_x and particulate reduction

Simultaneous reduction of particulate matter (PM) and nitrogen oxides (NO_x) emissions from diesel exhaust is the prime focus of research and development of modern diesel engines.

4.3.1 Low-temperature combustion (LTC)

LTC is one of the methods to achieve a simultaneous in-cylinder reduction of NO_x and soot/PM reduction. LTC takes place at temperatures below the formation regime of NO_x and at local equivalence ratios below the formation regime of diesel soot (Imtenan et al. 2014). During LTC, a large fraction of the fuel burns in the premixed combustion phase and combustion of the homogeneous lean mixture takes place throughout the combustion chamber. This unique feature of LTC offers ultra-low NO_x (due to low in-cylinder temperature) and soot emissions (due to premixed combustion) simultaneously. LTC is generally achieved through two pathways viz. Homogeneous Charge Compression Ignition (HCCI) combustion and Reactivity Controlled Compression Ignition (RCCI). HCCI utilises volumetric autoignition and combustion in a lean or diluted mixture which is achieved by different methods including premixed, early direct injection, and late direct-injection (Juttu et al. 2007). The main problem is that the charge ignites too rapidly at higher loads which are addressed with RCCI, wherein stratification is introduced into the charge by using two fuels of differing reactivity (Splitter et al. 2011). In-cylinder fuel blending using port fuel-injection of a low reactivity fuel and

optimised direct injection of higher reactivity fuel is usually used to control combustion phasing and duration. The combustion is spread out over more crank angle degrees maintaining low NO_x and low PM.

4.3.2 Water injection

Water injection is one of the methods for introducing water to the diesel combustion chamber which helps in reducing the emissions of NO_x and particulates simultaneously. There are various ways of injecting water into a combustion chamber as inlet water injection, directly into the combustion chamber, and emulsifying fuel (Tauzia, Maiboom, and Shah 2010). The emulsion is the more practical way of injecting water into the combustion. The emulsion is created when water is dispersed throughout the fuel, usually in the form of spherical droplets. With the use of emulsions, an improvement in the mixing process is usually observed due to two confirmed phenomena. The first one is an added momentum in jet behaviour due to water addition (Andrews et al. 1988). The second one is the internal droplet micro-explosions of water induced by the volatility difference between the water and the fuel. This violent disintegration disperses the fine droplets, producing a secondary atomisation and consequently enhancing the fuel-air mixing in the combustion chamber (Kadota and Yamasaki 2002). This increases the premixed combustion duration as well as the ignition delay period, which in turn allows more time for fuel-air mixing leading to a reduction in particulate matter formation. In addition, water droplet evaporation also reduces peak cycle temperature, which leads to the reduction of NO_x emission.

4.3.3 After treatment technologies

Simultaneous particulate and NO_x reduction represent the next step in the reduction of diesel emissions. To achieve this target, the combination of two technologies already in use is utilised. There are a few combinations that have been reported in the literature. For example,

combined SCR and DPF (Conway et al. 2005), combined NSC and DPF (Ranalli, Schmidt, and Watts 2004), etc. Another standalone technology which has been developed is known as Diesel Particulate-NO_x Reduction (DPNR) system (Nakatani et al. 2002, Mizuno and Suzuki 2004). This is a type of catalytic converter consisting of a fine porous ceramic having a monolithic honeycomb structure coated with NO_x storage reduction catalyst.

4.4 HC and CO emission mitigation

4.4.1 Use of turbocharger

A simple way to reduce some of the potentially harmful emissions is to use turbocharger which increases the mass of air inducted into the cylinder. This also allows for a proportional increase in fuel injection to create additional power output compared to a naturally aspirated engine which helps in downsizing the engine (Tigelaar et al. 2017). Since the air velocity is higher through the intake, air-fuel mixing is enhanced. This leads to better fuel oxidation and reduction in emission of HC, soot/PM and CO. However, it can increase NO_x formation.

4.4.2 Diesel Oxidation Catalyst (DOC)

DOC assists in the oxidation of HC, CO, soot particles and PM to CO₂. To promote this oxidation, DOC consists of precious metals viz. platinum (Pt) and palladium (Pd) as a catalyst. This catalyst is covered in a wash-coat material of alumina (Al₂O₃) or silica (Si₂O₃). The layer of wash-coat and catalyst is spread on DOC substrate which can be either ceramic or metallic in honeycomb structure (Hora, Singh, and Agarwal 2018). DOC is highly durable in operation and can achieve a high conversion efficiency of up to 90% at a sufficiently high exhaust temperature. It can also remove diesel odour. The DOC is also used to generate the necessary exothermal energy for the regeneration of the wall-flow filters.

5 Conclusions

The diesel combustion process is a complex phenomenon, understanding which is required to comprehend the emission formation process. Engine systems design viz. air delivery, fuel delivery, mixing design; the interplay of relevant integrated technologies; and transient nature of combustion event due to load variation play a key part in this regard. Albeit, the efficiency of the in-cylinder combustion is central to the quality of emission occurring at the tailpipe. The efforts in reducing this emission have been transpired into a series of continuously evolving emission standards in the last thirty years. The emission control focus has been on the so-called criteria pollutants (HC, CO, PM and NO_x). Heavy-duty diesel engines have been scrutinised heavily due to their high NO_x and PM emission potential, intrinsic to their combustion process. Several pre-combustion and post-combustion technologies are available for emission mitigation such as EGR, additive addition, SCR, NAC, multiple injections, LTC, DOC and so on. These days, it is customary to incorporate a series of after-treatment devices, especially for automotive applications.

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