A Review of After Treatment Systems for State of the Art Advanced Engine Applications

Nivedha Karigiri Madhusudhan
Department of Mechanical and Civil Engineering
Florida Institute of Technology
Melbourne, Florida, USA
nkarigirimad2019@my.fit.edu

Gerald J. Micklow, PhD, PE
Department of Mechanical and Civil Engineering
Florida Institute of Technology
Melbourne, Florida, USA
gmicklow@fit.edu

***Abstract*—Due to the continual rise in the number of automobiles used throughout the globe today, the control of pollution emissions to minimize the negative effects on the environment is of paramount importance. Thus, the Environmental Protection Agency (EPA) standards set to control the emissions will demand more advanced technology with more efficient ways to control these emissions. Typical constituents in exhaust gases are oxides of nitrogen, carbon dioxide, soot, carbon monoxide and other particulate material. These vehicle pollutants have a serious detrimental effect on the environment. Completely omitting these emissions and implementing a zero-emission effect is still a challenging aspect in this field. But the ways to control these emissions is improving. One of the ways to do this is to introduce several catalytic reactions to the exhaust gas emissions. This is introduced by installing after-treatment systems to the vehicles, which uses several filters to comply with the pollutant emissions regulations and meet EPA standards. These systems would also need to be effective for use of alternate fuel systems such as bio diesels. Therefore, the development of different after-treatment systems is considered very important. This paper is focused on giving a detailed introduction to after treatment systems, its use, and its current advances to meet the more stringent EPA standards. These include the use of diesel particulate filters, oxides of nitrogen traps and catalysts that encourage the process of oxidation. The main aim of these systems is to implement a zero-emission technology, as it will be the most demanding feature in the near future. In this process of improving the after-treatment systems, factors such as cost, thermal efficiency, which includes exhaust heat recovery, must be considered. This paper will be focused on the overview of these systems, various combustion processes, recent advances related to exhaust pollutant emission reduction from after treatment systems, reduced fuel consumption and the role of gasoline direct injections on it, product formations, and ways to improve this technology.**

Keywords—pollutant emission control; regeneration; particulate matter; catalysts

I. INTRODUCTION

Exhaust gas treatment to control pollutant emission formation is considered a key feature towards the development of all new vehicles. Some of its major applications are the use of traps/ filters for particulates, introducing catalytic reactions in the exhaust gas system and the idea of increase in temperature of the exhaust gas to add in these reactions. It is important to note that these might affect the fuel efficiency of the system. Spark ignition engines, normally operate in a lean condition, with excess oxygen in the exhaust gases, have temperatures in the range of about 400 to 500 degrees Celsius. Oxidation of particles such as hydrocarbons and nitrous oxide however, require temperatures to be above 600 ° C. Achieving higher temperatures can be done by providing insulations to exhaust ports but this could compromise on thermal efficiency. Another viable option to this would be the use of catalytic reactions. This helps in the removal of exhaust particles with temperatures in the range of 250 – 300 °C. One such efficient way of removing nitrous oxide in SI engines is with using hydrocarbons, i.e., hydrogen and CO to produce nitrogen. Particulate filter traps are used to remove other particulate matters. The load accumulated in the filters and the difference in pressure are the two main factors to be considered for the efficient working of a diesel particulate filter. The removal of particles from the filter can either be done by using a filter which has catalysts or by an oxidation process with an increase in temperature. Oxidation catalysts can be used to oxidize the hydrocarbons and CO and produce carbon dioxide and water along with a composition of NO, CO, SO_2, O_2 and so on. But hydrocarbons that are at saturated levels are challenging to oxidize. With higher molecular weights and with excess oxygen, this process can be possible. As diesel engines run lean most of the time, the excess oxygen will help with the oxidation process of hydrocarbons. Diesel particulate filters are one of the devices used to control particulate emissions. They are used to trap the particulate matters and a technique called regeneration is used to burn off these substances. This is used to reduce the burden/load of soot formed in the filter and to maintain back pressure. The operation of a regeneration cycle is very important for the efficient working of the engine. Since soot needs temperatures greater than 500 °C, the regeneration process can be done by increasing the temperature in the filter to oxidize, which is termed as an active regeneration process. Another method to oxidize is by catalytic reactions in the filter, which is called passive regeneration. The surface area and other structural considerations are critical in the oxidation catalysts to provide effective reactions. The filters with coated catalytic particles are called catalytic particulate filters. This functions at low temperatures for the oxidation of soot particles.

Active regeneration is performed by increasing the temperature of the filter and maintaining the load on the filter. Excess fuel is added to the exhaust gases for the combustion process. This process compromises on the efficiency, fuel consumption and high carbon dioxide formation. Studies have shown[1] that the temperature can be effectively increased by the introduction of CO along with H2. Some engines also put load on the electrical system by introducing an electric heater to increase the temperature. Considering a main injection delay and introducing injections in the exhaust gas is also one of the methods to increase the temperature. Once passed through the diesel particulate filters (DPF), the diesel oxidation filters placed above DPF are used for the oxidation process. Maintaining of temperatures is also considered crucial as the filter must be able to withstand it to prevent any cracks or stresses on the surface. The highest allowable temperature should be considered such that it is below the melting point of the substance used. The collection of soot on the filter also plays a major role in terms of the surface area. A parameter named specific filtration area is considered to determine the efficiency given by the filtration area and the volume of the diesel particulate filter. Therefore, the temperature inside the filter and the filtration area are the two main parameters to be considered for a proper working of a DPF after treatment. Back pressure is also considered a major parameter to reduced fuel consumption and maintain a lower value can contribute towards it. The structure of the cells in the filter determines the load to be carry and the mechanical strength. The overall efficiency of the filtration process to avoid the passing of soot into the surroundings is called the filtration efficiency. Studies have shown the effect on fuel consumption with the DPF load on three different substrates show that the back pressure increase contributes to a significant rise in the fuel consumption.[2]

One investigation for soot formation reduction consisted of the introduction of a cooling stage in the exhaust gas regions which helped in the reduction of the formation near the walls by causing local rich mixtures and thereby reducing soot emissions up to 48 percent [3]. As temperature is considered the major parameter, diesel oxidation filters can be used for the removal of carbon monoxide, hydrocarbons, and nitrous oxides. Nitrous oxide can be challenging to reduce and therefore selective catalytic reactors and a lean NOx trap will help with its reduction. One of the major challenges faced in the after-treatment systems is the treatment of oxides of nitrogen and soot formation. Exhaust gas recirculation with a reduced pressure helps in reducing the NOx formation with a reduction in temperature, but this in turn does not help with the oxidation of soot particles accumulated in the filter due to the reduction in the level of oxygen, therefore becomes inefficient.

Though there are several advantages using a regeneration cycle for soot oxidation, it is very important to know the drawbacks associated with the fuel consumption. Therefore, it is necessary to include a frequency at which the regeneration cycles can occur. It is mainly based on the substrate the maximum amount of load that it can withhold. This is defined with a parameter called the maximum mass limit. One of the experimental investigations using Silicon carbide as the substrate introduces a factor called the safety limit, which is given by the ratio of the mass limit at which the filter cracks and the mass limit at which the regeneration cycle occurs. This parameter helps in determining as target limit and to set a frequency for different substrate materials, taking into account the permanent damage of the substrate being used.

The introduction to NO_x trap after treatment systems is another major consideration [3] which helps in the reduction of NO_x to nitrogen through adsorption process in the catalyst. Some noble metals are generally preferred for the reduction in the amounts of NO_x and the oxidation process of nitrous oxide. To improve the performance related to the reduction of NO_x, a process called selective catalytic reduction is employed. Ammonia is used in the reduction process of NO_x, which is set up in the exhaust line. This is the main reason why there is a presence of water at the end of the tail pipe, as this process helps in the conversion of NO_x to water, carbon dioxide and nitrogen, through a few catalytic reactions. The structure of the cells used in the filter determine the efficiency of this process and a large surface area is usually preferred for even distribution of the particles. It is important to note that there are several systems put together in a meaningful order for the efficient working and the removal of exhaust particles and to meet the standard requirements for different emissions.

II. EMISSION CONTROL DEVICES

A. *Diesel oxidation filter*

Emission control devices are considered important, particularly in diesel engines. While diesel engines have many advantages, one of its drawbacks is the emission of particulate matters and oxides of nitrogen. Companies developing new strategies for emissions control face more challenges as the standards of emissions control increase. Some of the strategies include retrofit, repower, rebuild, refuel and replace. The application of emission control devices falls under the retrofit category.

The use of diesel oxidation filters (DOF) helps in reducing carbon monoxide, hydrocarbons and PM emissions. DOFs have been in use for over 50 years in various internal combustion engines and have proved effective in emission control. The overall reduction rate shows about 40 to 50 % of the total emissions. Its main function is to oxidize the gases coming out of the exhaust into particles that do not harm the environment. This is done by using a set of catalysts in built on the filter[1] Therefore, particles like CO and HC are oxidized through catalysts to form CO_2 and water along with other particles. There are three main reactions that take place in this process.[1]

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \quad (1)$$

$$C_3H_6 + \frac{9}{2}O_2 \rightarrow 3CO_2 + 9H_2O \quad (2)$$

$$NO + \frac{1}{2}O_2 \rightarrow NO_2 \quad (3)$$

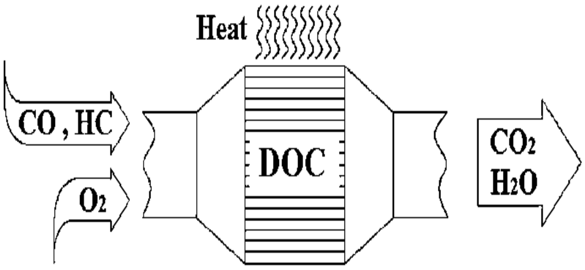

Fig.1.DOC Oxidation Process

The idea of thermodynamic equilibrium plays a major role in eq (3) regarding the oxidation of NO. This reaction very important because the ratio of NO_2 and NO_x is the one which determines the efficiency in the overall emission reduction process. A high ratio is needed to have a good output as these gases pass on to diesel particulate filters and a few catalytic reductions at the end. The light-off temperature in a DOF is the temperature at which the reactions start in the catalyst and temperatures above light off is necessary to perform efficient oxidation process. DOF plays a major role for further reduction processes happening downstream like the DPFs. The high temperature produced in DOF can be used to function the DPF process. Therefore, DOF acts as a catalytic heater. The structure of DOF is a honeycomb structure with a coating of a catalyst relating to a platinum group of metals. The quantity of the catalyst material added is referred to as loading. The honeycomb structure can either be a metal or a ceramic material. It also consists of a wash-coat substance besides the noble metals catalysts which helps in the oxidation process. The oxygen from the diesel exhaust is taken by this filter to perform the oxidation process. At high temperatures, a phenomenon called catalyst sintering occurs, which causes the particles to be stuck or welded together with high pressures. This can be avoided by creating a high surface area in the wash-coat layer. The value of loading in the catalyst and the type of catalyst used (Platinum, Rhodium, Palladium), exhaust gas temperature and mass flow rate, the dimensions of the filter used play a major role in determining the conversion efficiency of the process. The conversion efficiency can be given by the ratio of the mass rate removal of a particular constituent in the catalyst to the mass flow rate of the constituent towards the catalyst. Let $\dot{m}_c$ be the mass flow rate of any constituent considered (HC, CO, NO etc.), the conversion efficiency is given by the following.[3][1]

$$\eta_{conversion} = \frac{\dot{m}_{c,in} - \dot{m}_{c,out}}{\dot{m}_{c,in}} \quad (4)$$

To attain steady state conversion efficiencies, the temperature of the catalyst should be around 250 to 300 °C. The particles of these noble metals increase with an increase in temperature. DOFs also contribute towards a significant reduction in the mass of particulate matters as shown by Mohammed Et Al [4] by conducting experimental and modeling analysis with and without DOF. It showed that the increased amount of NO_2 in DOF helps in an efficient oxidation of PM downstream the filter. Overall reductions in CO and PM are around 60 to 90 percent using DOF and are being used in almost all types of diesel vehicles. One of the limitations here which causes harm to the emission controls is the oxidation conversion of SO_2 to SO_3. This leads to the creation of oxides of sulphates which causes negative effects on the environment [1]. Oxidation of aldehydes and polymers are also possible using diesel oxidation catalysts. One major parameter in these filters is the thermal stability, which can be achieved through Pt or Pd based catalysts which contains Alumina. This combination along with H_2 in the diesel exhaust not only provides thermal stability, but also improves the oxidation process of nitrous oxide. The use of Al_2O_3 helps in the reduction of metal contact and control sintering. Studies show that H_2 addition helps in improving the local area temperature to enhance the combustion process. Diesel Oxidation Filter also complies with alternate fuel choices such as biofuels or various fuel blends[1] A factor called space velocity, which gives the ratio of volumetric rate of exhaust and the volume of the catalyst is used in the design of DOFs. Therefore, the volume of the filter is proportional to the swept volume of the cylinder. This value typically ranges between 0.6 to 0.8. [1]

B. Diesel Particulate Filters

Diesel particulate filters help in trapping the particulate filters from the exhaust of the engine. The structure of DPF is similar to a honeycomb structure with silicon carbide or cordierite for effective filtration process. The three main components of a DPF are the filter, regeneration and the control devices.[5][6] As soot is trapped in the filter, temperatures around 600 °C is necessary to oxidize it. But diesel engines operate in the range of 250 to 500 °C. One of the ways to oxidize soot in this condition is to decrease the oxidation temperature of soot using catalysts or by increasing the temperature of the diesel particulate filter. The former method is termed as passive regeneration, which improves the performance of filters at low temperature. One of the potential methods is by employing Ceria based catalytic filters, which has a high contact efficiency with the soot leading to the formation of CeO_2 and its redox reactive properties helps it further to decrease the temperature. Active regeneration is the method of increasing the temperature necessary to perform oxidation. Active regeneration is used to remove the soot through a process called soot incineration, where the load and temperature of the filter play a major role. As passive regeneration and regeneration of filters used cannot be done in all applications, soot incineration is employed. This process comes with a cost of adding additional fuel to the exhaust to increase temperature and also additional amounts of CO_2. This is crucial as the heat and energy supplied can sometimes reach the melting point of the filters. Extensive research in the regeneration process shows that addition of NO_2 as a catalyst decreases the temperature of soot to around 200 °C. This is a called catalyst-based regeneration process. Regeneration processes are crucial and necessary as the filters will fill up over time and accumulation of these soot particles causes adverse negative effects on the engine such as an increase in back pressure. To maintain a high exhaust temperature during regeneration, the engine must be operated at high load. Therefore, it is important to conserve the energy and fuel in the engine used in this regeneration.[4] Sometimes, an increase in the amount of sulphur can cause adverse poisonous effects in the filter. Therefore, a passive regeneration technique is fuel efficient and continuous oxidation of these soot particles can take place smoothly with the addition of NO_2. Also, this source of NO_2 is obtained through the process taking place in diesel oxidation filter. It is important to note that several emission control devices play together a major role in the overall reduction of emissions. Silicon carbide filters are the most popular filters worldwide.[2] It is also shown that additional of hydrogen along with CO upstream of regeneration will help increasing the filter temperature and oxidize soot. Some of the reactions taking place in a DPF are as follows.[2]

$$C + O_2 \rightarrow CO_2 \quad (5)$$

$$CO + NO_2 \rightarrow NO + CO \quad (6)$$

Regeneration techniques can also use electric heat supply as a source of increasing the temperature. Also, to burn the particulate matter, this electric heat energy supply from the engine is used.[7] This process is comparatively simple as a source of electric heater is required to increase the temperature. However, this puts a load on the battery efficiency of the vehicle. This method can be implemented in two ways, the filter internal heating method, which might likely develop uneven transfer of heat and the front-end method which can consume large amounts of power.

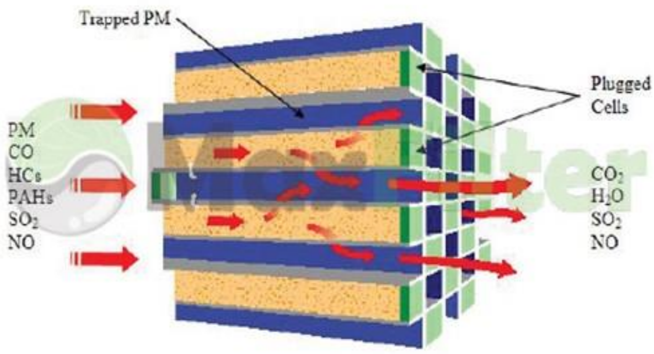

Fig.2.DPF Process

There are several techniques used for the regeneration process in diesel particulate filters. With oxygen-based oxidation of soot, the catalysts called fuel borne catalytic substances are used to decrease the temperature of soot.[8] The concept of combining DPFs with the emission control systems helps in the reduction of emissions above 90 percent. Several types of filters such as ceramic fiber filter, wire mesh filter, wall flow and foam ceramic filters are proven to be efficient for different types of applications. Wall flow filters are the most extensively used and with cordierite and silicon carbide materials.[9] The major parameter in these filters is the structural strength as it should be able to withhold the mechanical shocks and the vibrations occurring in the vehicle with a long-lasting life and at an affordable cost.[10]

C. Developments in after treatment technology

Several studies have been conducted to study about the impact caused by soot loading occurring before the regeneration process in the DPF. An optimal soot loading value for the substrates in the filter is a major parameter to be determined and should occur before the regeneration process begins in the DPF. This process helps in the lowest fuel consumption amount. However, it is accompanied with a reduction in filter regeneration and an increase in the back pressure. This situation was addresses in [11]. Three different kinds of substrate materials with different soot loading levels were experimentally analyzed. A one-dimensional engine model was used to analyze the increase in fuel consumption as a function of back pressure. Only under certain driving conditions, an appreciable amount of fuel consumption was noticed. Regeneration tests helped in concluding the different levels of soot loadings for the respective substrates used. This study led into understanding the major characteristics to be present in the substrate that is being used [11]. As previously discussed, the specific filtration area helps in attaining the maximum soot loading efficiency. This might not occur in all cases especially when the maximum limit temperature is attained. As there is an increase in temperature in the process, a thermal gradient forms in the filter, which implies that one end is hotter than the other.

Eventually, thermal expansion takes place in the hotter side, thereby putting a high thermal and mechanical stress in the filter material being used. The thermal expansion coefficient determines the thermal expansion taking place in the material. A higher value of this coefficient introduces micro cracks that might eventually propagate through the structure. Here, the tensile strength of the material should be high enough to overcome the thermal stress. Some materials may possess a higher melting point value and therefore a very high operating temperature may be achieved. However, the highest temperature in the combustion process must always be less than the maximum operating temperature of the substrate. This is because exceeding a particular temperature value will not melt the substrate but leads to the formation of certain surface particles which block the pores and therefore leads to increasing the back pressure. This also affects the filtration efficiency as the smaller pore diameters gets blocked. It was found that Silicon carbide was allowed was able to withstand approximately 1300 °C despite its high melting point at 2200 °C. [11]

These above-mentioned filtration characteristics and the composition of particulate matter affects the filtration efficiency. A reliable filtrate is the one which can withstand high temperatures, trap the particulate matter and prevent it release into the atmosphere. Another important characteristic of a DPF filter is its ability to better integrate with downstream after treatment systems. Studies show that filtrate materials such as Cordierite and Aluminium Titanate are suitable in terms of integrating with the Selective Catalytic Reduction (SCR) system and also helps the control of heat loss.

D. Selective Catalytic Reductions

Selective catalytic reductions play a major role in converting harmful oxides of nitrogen gases into natural mixtures of air. It is one of the most advanced emission control systems used in heavy duty diesel engines and in gas turbine engine applications. Heavy or light duty cycles with an SCR system requires periodic supply of DEF (Diesel Oxidation Filter) to the vehicle in to keep the vehicle running. These periodic intervals include the miles travelled and other load and operating conditions of the vehicle. It is also important to have heating devices for the DEF fluid stored to prevent it from freezing below 12 degrees. It helps to meet the stringent emission requirements and also helps in increasing the efficiency of the fluid to around five percent. Therefore, it provides an increase in substantial fuel economy. This system uses a catalyst which is specially designed through which a diesel exhaust fluid is passed. The exhaust particles that are noted at the tailpipe of the engine are the natural particles like water droplets, nitrogen and small amounts of carbon di oxide. These particles emerge from the special catalytic reactions that occur with the diesel exhaust fluids. Reductants like urea or ammonia are well mixed with the exhaust gases before they pass into the catalyst chamber for the catalytic process. Therefore, the diesel exhaust fluid that is being used can be reduced rapidly into ammonia. The ammonia that is being used here can be either anhydrous or aqueous in nature.[12] Aqueous ammonia can be less toxic in nature and easy to handle. Results show that SCR is an advanced technology which reduces the NOx emissions around 90%. There are three important reactions that define the process of reduction of nitrous oxides. They are as follows.[4]

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O \quad (7)$$

$$4NH_3 + 2NO + 2NO_2 \rightarrow 4N_2 + 6H_20 \quad (8)$$

$$8NH_3 + 6NO_2 \rightarrow 7N_2 + 12H_2O \quad (9)$$

Reaction c tends to be slower in nature and implies that the ratio of NO_2 to NO is greater than 1: 1 ratio. A quick catalytic reaction occurs when the ratio of these constituents is exactly equal to 1. While the main aim of the SCR system is to reduce NO emissions, it tends to produce abundant amounts of NO_2. This might pave a way for the production of secondary emissions. The following reactions show that abundant amount of NO_2 can react with oxygen in the surroundings to produce nitrous oxide, N_20. Therefore, partial oxidation of the ammonia fuel used tends to produce nitrous oxide and complete oxidation of ammonia produces NO.

Catalyst damage can also occur due to the formation of ammonium nitrate, which can be explosive from the reaction of ammonia and nitrous oxide. The 1:1 mole ratio of ammonium nitrate and ammonia, a stoichiometric ratio, would help in preventing the formation of NH_4NO_3 along the catalyst. Maintaining the temperature above 200 °C can also prevent the formation of ammonium nitrate. There are also other harmful reactions that can take place due to the increased amounts of NO_2 and tends to form a chain reaction producing substances like SO_3 and H_2SO_4.

A phenomenon called ammonia slip causes drastic effects on the atmosphere which leads to the leakage of ammonia through exhaust. This occurs when the ratio of ammonia to NO_x is not stoichiometric. To avoid this, a guard catalyst downstream of SCR is placed which acts as an oxidation catalyst that reduces the ammonia slip to 5 to 10 ppm, which is undetectable in environment. There are several factors that affect the performance of SCR. It is to be noted that the temperature at which SCR operates is about 250 – 430 °C. [12]

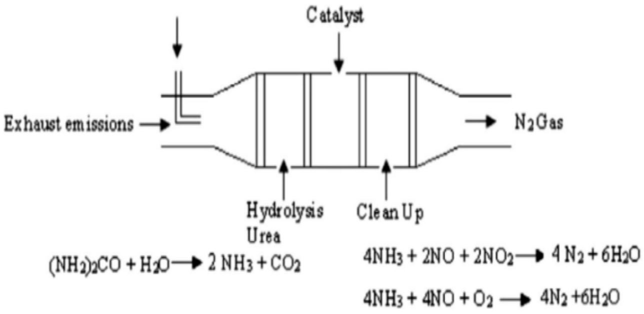

Fig.3.Main SCR Reactions

The optimum temperature in this operating range depends on the flue gas compositions and the type of the catalyst being used. Studies were performed to note the NOx removal efficiency using a metal oxide catalyst. The following graph shows the optimum temperature range where the highest efficiency occurs. At temperatures above 400 °C, the NOx removal efficiency starts to drop.[12]

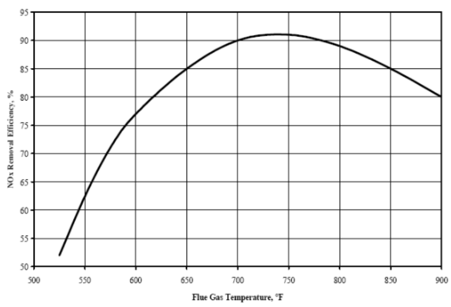

Fig.4.NOx Reduction efficiency Vs flue gas temperature

The application of SCR systems is mainly used where there is a significant release of oxides of nitrogen. Therefore, it is considered a critical design as the amount of NOx, composition of flue gases and its temperature, types of catalysts and the catalyst volume are inter- related. This led to the definition of major performance parameters to optimize the design of SCR systems. To determine the amount of NOx removed from the system, the rate of reduction reaction is determined. There are various operating parameters as the SCR operates with a different set of catalyst and a reaction chamber other than the combustion chamber. Catalyst activity and the pressure drop across it, catalyst loading, formation of SO_2 and SO_3, residence time, regeneration and management are the main performance parameters. The duration for which the reactants stay in the reaction chamber is the residence time. The duration and temperature determine the residence time. NO_x removal and residence time are directly proportional to each other. The degree to which maximum efficiency occurs also depends on the extent to which mixing occurs between the flue gases and the DEF. Parameters such as liquid penetration, momentum ratio, viscosity and surface tension of the fluid, injection spray velocity and angle, number of injectors and nozzle design are crucial. Various numerical modeling results determine the mixing parameters. One of the approaches to improve the mixing is to spray air/steam as a carrier fluid along with DEF which increases the penetration depth.

The concentration of NO_x at the inlet has a direct effect on the rate of reaction that shows the efficiency of the conversion rate. The more the NO_x concentration at the inlet, the higher the rate of reaction, for which the catalyst volume plays a major role. The volume of the catalyst should usually be higher than the amount of NOx in the inlet. Studies show that higher than 150 ppm in the inlet can decrease the conversion efficiencies in the catalyst[12] The reduction rate is accelerated by the catalyst and is determined by a factor called the catalyst activity. The temperature of the gas and its composition, the structure of the catalyst and its composition play a major role in determining the catalyst activity. Reduction in reaction rates reduces the removal of NO_x and thus increases ammonia slip. It is important to calculate the deactivation time of a catalyst.[12]. It is given by the following equation. The regeneration or installation of a new catalyst must be done when the ammonia slip reaches a maximum level intended for the design.

$$K = K_0 \, e^{\frac{t}{\tau}} \quad (10)$$

Here, K_0 is the catalyst activity, t is the lifetime of the catalyst. As the catalyst operating time increases, the catalyst activity value decreases. This deactivation of catalysts came occur due to many causes. Catalyst poisoning is a serious issue that leads to blockage of active pores in the catalyst due to certain chemicals occurring through combustion. The temperature of the flue gases also leads to a change in the structure of the pores leading to catalyst inactivity.[12] Physical changes to the catalyst can also occur due to aging. Pressure drop across the catalyst occurs which leads to the deposition of other particulate matters on the surface of the catalyst. This is because as the flue gases pass through the catalyst, its pressure decreases as a function of the length of the catalyst. Introduction of draft fans is one way to improve the pressure in the catalyst.[12] To reduce the number of particulate matters loading on the catalyst, the pitch of the catalyst must be designed efficiently. Pitch is the width of the catalyst along with the thickness. This also ensures an optimum velocity values in the interstitial spaces in the catalyst. An exponential curve that shows the variation of catalyst activity with duration is referred from[12]

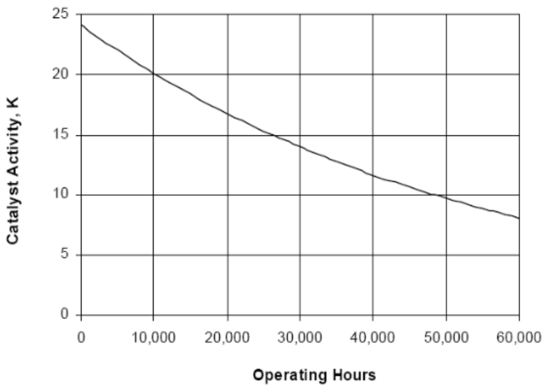

Fig.5.Depiction of Catalytic activity with duration

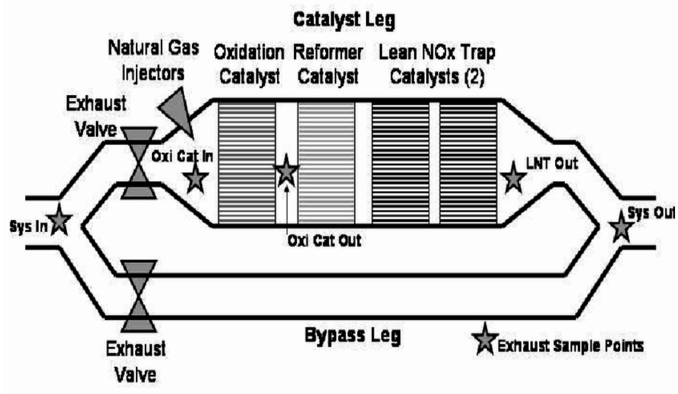

Fig.6.Lean Nox Process

One of the studies show that using a honeycomb-squared structure of a catalyst coated with vanadium shows about 95% conversion efficiency with an optimum temperature around 400 °C for a proper absorption of DEF.[12]. Several patents that show improved design and methodologies for SCR applications have been developed and can be referred from [6]

The application of SCR is proven to be a very effective method to reduce the NOx reductions. However, one main disadvantage in this system is the formation of sulphur and other components with a combination of ammonia and sulphur. Ammonia reacts with sulphur below 300 degrees Celsius and leads to the formation of sulphur oxides.[13] This can be mitigated by introducing certain oxidation catalysts. Therefore, application of SCR is a crucial and complex mechanism, and its operational conditions should be very accurate for a better efficiency and to prevent adverse effects on the environment.

E. A reduction method for NOx in Diesel Engines

Of the strategies in after treatment systems to meet the Euro 6 standard emissions was the implementation of the Lean NO_x trap, LNT. It is one of the well-known after treatment systems that results in a marked reduction of the NO_x emissions to a high percentage. A schematic of the working of a lean NOx trap is shown.[6] The process takes place in alternate conditions of the engine during lean and rich mixture conditions which works with oxidation and reduction reaction mechanisms.

The NO_x produced during the lean condition of the engine gets adsorbed by the substrate material in the catalyst. The adsorbed NO_x gets oxidized into nitrogen when the rich cycle (excess fuel) occurs in the engine. This catalyst is also efficient in the oxidation of HC and CO. Therefore, this can be used in light and heavy-duty engines and other operational cars. The catalysts and the storage medium for NO_x have selective materials for an efficient conversion and storage capability. Since the storage of NO_x take place in the system, it can also be referred to as a storage reduction catalyst. Noble metals have been a conventional choice for years for the storage medium. However, the high-cost factor with the choice of noble metals led to the transition of other metals which are noble free catalysts.[6]

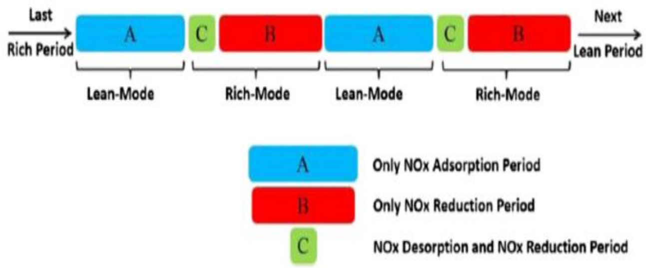

Fig.7.Lean and Rich cycles of NO_x trap

Platinum is one of the materials that is used in this system as it offers high conversion rate of NO to NO_2 and for the reduction process of nitrates to Nitrogen. Typically, on a high surface area layer, which is generally preferred, LNT comprises of alkali and alkaline earth metals. It helps in trapping the NO_x during the lean operating conditions and during periodic releases of rich conditions, where the overall air-fuel ratio is altered, the trapped NO_x is released, which is the regeneration process of the catalyst that serves as an NO_x reduction mechanism. Diesel engines in particular possess a major challenge in reducing the NO_x emissions due to the excess oxygen present in the exhaust gases. Even though systems like SCR and EGR are in use, it is challenging for these systems to meet the current stringent EPA emission standards. EGR will require a continuous supply of reductant which can be tedious under certain conditions. A lean NO_x trap can help in reducing the emissions with minimal effort. It uses an adsorbent like zeolite, which traps the NO_x content to its maximum level. Several techniques for the regeneration of this trapped content are proposed throughout the years. This can be fast and a cost-effective technique and also has a low light-off temperature. However, these traps can be prone to poisoning by sulphur components and would need periodic high temperature regeneration which could put a burden on the operating life of the catalyst. This issue leads to different approaches of performing the regeneration technique.

Two main approaches called the active and passive regeneration techniques are practiced. The regeneration process that occurs during the rich cycles where the adsorbed NO_x is oxidized is generally the active method. This process is also used in gasoline engines where the three-way catalytic reactions are replaced by an active regeneration process. In the case of a heavy-duty vehicle, the exhaust temperatures can reach high levels, and the conversion efficiency of this active system tends to decrease. Therefore, this system can be limited in the use of a certain light duty vehicles. However, this can also become challenging to the current and future modern vehicles. The challenges faced in active regeneration process can be mitigated using passive techniques. Passive techniques have the ability to adsorb NO_x during a cold start and can release the trapped NO_x content to oxidize it downstream the Lean NO_x trap catalyst. This is where the Selective Catalytic reactants are functional. It is to be noted that passive systems do not completely mitigate the NO_x from the system and depends on SCR placed downstream for the reduction reactions to take place. Typical catalyst materials used by LNT are precious metals like Platinum, Palladium or Rhodium to provide active sites for the conversion of NO to NO_2 and using Barium oxide as a storage container material. Once oxidized over Platinum, the resulting NO_2 gas gets adsorbed as Barium nitrate. The following reactions show the adsorption process and the products formed from the oxidation catalyst.[14]

Ba

$(NO_2)_2$ -> Ba + N_2 + $2O_2$ (11)

Ba $(NO_3)_2$ -> Ba + N_2 + $3O_2$ (12)

The barium nitrate on the surface of the catalyst is then released to oxidize it as barium oxide. The constituent in the trap gets restored after the regeneration process. The constituent CO and HC help in the conversion to nitrogen along with the Pt/Pd catalysts. One of the drawbacks associated with this selection of precious catalysts is the presence of sulphur which forms sulphur di oxide in the combustion process and in the presence of Platinum, leading to the formation of sulphur trioxide. There are several ways to run the periodic rich conditions in an engine for the regeneration process. Some of it can include throttling the air intake, fuel injection after combustion (post combustion injection) and exhaust gas recirculation. Therefore, this technology does not require a reductant tank or the use of reductant and can produce good fuel efficiencies and conversion efficiencies for engine displacement values less than two liters[14] High temperature and the LNT capacities limit its use in engines with a high displacement value. Due to formation of Sulphur components, a desulfation process is to be performed periodically. Sulphur can be easily exhaust in gasoline engine where the temperatures can range up to 900 °C. Diesel engine do not operate at such high temperatures and therefore needs additional processes to oxidize it. Ammonia is another harmful and unwanted emission constituent that occurs in the LNT which requires another catalyst to oxidize and limit it to 10 ppm[14]. The SCR located downstream can make use of the ammonia from the LNT system has use it for further conversion efficiency. Hybrid LNT and SCR systems are used.

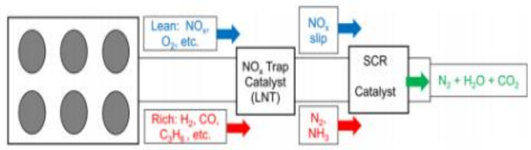

Fig. 8.Integration of SCR and LNT

The hybrid SCR-LNT system has a lot of advantages than the LNT system. The issue relating ammonia slip can be eliminated due to the presence of SCR downstream of the catalyst. The precious catalyst materials used in the LNT can be reduced thereby reducing its catalyst volume which in turn improves the cost efficiency.

III. FUEL ECONOMY STRATEGIES

Several strategies to improve the fuel economy conditions of the engine and to maintain the exhaust gas temperatures for conversion mechanisms have been developed throughout the years. One of the strategies to improve fuel economy and thermal management systems in after treatment systems is discussed in [14] Cylinder deactivation and intake valve closure modulation are some of the proposed strategies. To provide high exhaust gas temperatures, air flow reductions at the intake could be performed which helps in reducing the pumping work and increases fuel efficiency. It is well known that heavy duty vehicles mostly incorporate diesel fuel for better efficiency. However, a complex after treatment design comes along to reduce the tail pipe emissions. These systems were developed because the existing strategies like multiple fuel injections, late fuel injection techniques and high injection pressure were not enough to meet the current emission standards which would become complex in the near future. Conditions such as cold start makes the exhaust gas temperature very low and reduce the functioning of these after treatment systems. To make these systems operate over a wide range of temperatures, effective thermal management systems are to be developed. A variable valve actuation can be a potential development for this purpose and can be referred from[15] It is shown that the thermal management of after treatment systems and the fuel efficiency can be improved via variable valve actuators. This study was performed at 2200 rpm as more than 30% of fuel is consumed at these operating conditions. [15]Through experimental strategies, it was concluded that lower air flow strategies had several benefits of improved fuel efficiency with pumping work. A good maintenance of after treatment temperature can be achieved. This also tends to increase the warm-up rate of the components used in after treatment system. Also, this temperature can contribute towards the functioning of the diesel particulate filter active regeneration process. It is shown that fuel efficiency of around 30 % can be achieved depending on the break mean effective pressure of the engine.[15]. Cylinder deactivation can be performed to reduce the displaced volume in the cylinder and reducing the airflow which can contribute towards a reduction in pumping work. It is also important to maintain elevated temperatures in the aftertreatment components. Reduction in the air-fuel ratio is one of the direct methods to maintain the turbine outlet temperature.[15]. Reduction of air flow helps in maintaining a low air fuel ratio. The rate of heat transfer is considered an important approximation as it depends on the exhaust gas temperature and flow rate, the temperature of the gas from turbine. A positive rate of heat transfer is preferred as it tends to the flow of heat from the exhaust gases to the catalyst. Catalyst cools down requires a negative heat transfer. An experiment was performed considering loads higher than 2.54 BMEP value to conclude a strategy than could give better fuel economy results, and it was found that the Intake valve closure method provided better fuel economy results than the cylinder deactivation method. This is because of the higher in-cylinder heat loss occurring during the deactivation process thus reducing its efficiency. However, it is to be noted that applying a cylinder deactivation process helps in providing the required temperature for the DPF regeneration without much load on DOF. Therefore, fuel economy strategies depend on the application of the vehicle, its load and usage. A detailed method about the experiment performed can be found in [15]. To further improve the performance of the engine, strategies such as turbocharge electrification and super-charging and variable valve actuation strategies could be employed. Another experimental research [16] shows about 5 to 25% increase in the fuel efficiency value under various operating conditions using the cylinder deactivation process. It can also lead to exhaust temperature values that are capable of performing a passive regeneration process in the DPF filter. It shows that cylinder deactivation process can be an efficient fuel-efficient process for idle engine conditions and non-idle conditions and was experimentally demonstrated which resulted in the conversion efficiency of about 3.4%. Thermal performance plays a major role here.

IV. Summary and Discussions

This paper focusses on the various components and the processes involved to minimize pollutant emissions formation. It is important to note that the combination of various types of after treatment systems mentioned above with less expensive integration strategies is required for the maximum elimination of pollutants. Several regulations for emissions control and fuel economy standards have been implemented over the years and the standards increase as technology improves in the current vehicle designs. Current after treatment systems are much more refined than the previous ones and can also perform lesser regeneration cycles over a wide range of operation. Single module after treatment systems are one of the recent designs for emissions control. This has led to many improvements with respect to the complexities in the previous designs. The design was made lighter and smaller in size than the previous decade models and the conversion efficiency and prevention of failure modes were improved with the use of Urea emission solution. Advancements in the development of efficient fuels such as biofuels is an emerging field in emission reductions, where biofuels are used as a replacement to diesel fuel and is used as a solution to mitigate sulphur formation in the exhaust gas. However, it comes with some challenging aspects related to fuel injection which are currently being studied with intensive research and experiments. Development in engine simulations with advancements in the use of Computational Fluid Dynamics is considered a most important factor for the development for technological advancements in engines. Therefore, it is important to develop the efficiency of these systems by further research in this field to move towards a net zero pollutant emissions production and to create a sustainable environment.

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