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Impacts on No_x Emission Control Measures to Achieve EURO VI Limits - A Review

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ABSTRACT

The intention of this review study is to investigate the control measures of NO_x emission. Even though the diesel engine sector plays a pivotal role in economic growth, it brings an unavoidable environmental deterioration. The current work reviews the effect of EGR, boost pressure variation, fuel modification, advanced engine combustion concepts, and after treatment processes for reducing NO_x emission to EURO VI level. The outcomes of bio-diesel performance and other emission characteristics are too highlighted. In addition to this, specific attention is given to Porous Medium Combustion (PMC) technology adopted in diesel engines and a separate section is devoted. In order to facilitate a better understanding of PMC technology, simulation and experimental results of NO_x emission are reported. Through this porous medium experimental study, it was found that NO_x, HC and CO emissions were reduced significantly. Reducing the NO_x and PM emissions might simultaneously increase the chance of usage of diesel and biodiesel blends fuelled CI engines in near future. The findings of this research work serve as best possible ways for achieving ultra-low NO_x emission subjected to EURO VI norms level is suggested in future directions to give the reader insight and the track for the future investigation.

1. INTRODUCTION

Over the past few decades, there has been a tremendous increase in the vehicle population. According to the worldwide survey, over 4.2 million people died due to outdoor air pollution in the last year 2017 [1]. The only way to protect biodiversity and human being from automotive pollution is by implementing stringent emission norms. Most countries have implemented stringent regulations on engine out emissions based on European Emission Standards (EURO). The emission standard for commercial vehicles in India is proposed to attain EURO VI level. These newer emission norms have brought new diesel engine technologies in the country. So, Several developing countries have banned the operation of old diesel vehicles [2] and encourage the use of biodiesel combined with progressive engine combustion concepts. The combination of advanced engine combustion concepts and biodiesel adoption might reduce the emissions compared to a conventional diesel engine.

Biodiesel is a renewable fuel which is produced by the transesterification process of feedstock, vegetable oils, animal fats, and biowastes, etc. Jatropha, Pongamia, Palm, and Sunflower oil are some of the most commonly used raw materials for biodiesel production [3]. Biodiesels can be delivered at a lower cost when produced in large scale. It is less hazardous, has less storage risk, has a high cetane number and high flash point properties. The most commonly used biodiesel in India is ethanol. Typically sugarcane is used as a raw material to produce ethanol. Crop harvest, material softening, breaking down the sugar – hydrolysis and finally fermentation are the respective processes produce ethanol. India as 125 ethanol production plants producing around 1.25 billion liters of ethanol [3]. However, usage of fertilizers, water and agricultural land used of domestic food crop production are some of the disadvantages of producing biodiesels. Diesel engines are designed to run on diesel, not for direct biodiesels. Even though biodiesel's calorific value is closer to diesel fuel other properties like viscosity, density has a stronger impact on mixture formation and proper auto-ignition. The overall efficiency and depreciation of the engine running on continuous biofuels are the challenging tasks to be faced when implementing them directly in diesel engines.

In order to achieve the same auto-ignition conditions of biodiesel near to diesel, researchers focused their ideas to operate it as same as diesel combustion. So, fuelling of biodiesels directly in diesel engines requires some additional changes in fuel lines, injection pressure, and injection timings. Still, these variations might reduce HC, CO and smoke emissions but increases the NO_x emissions. However, HC and CO emissions can be reduced more efficiently by the three-way catalytic converter and smoke emissions might be reduced by DPF. Reducing NO_x emission is the must one to achieve EURO VI emission level. Hence, the importance is given to NO_x emission compared to other emissions.

The combustion of fossil fuels with nitrogen in atmospheric air under high pressure and temperature forms N_2O, NO and NO_2. Out of these, the biggest contributor is NO. NOx reacts with moisture in the lungs to form nitric acid, affects respiratory systems causing bronchitis, pneumonia, lung infections and visibility reduction. Many strategies are developed to reduce NOx emission and these are classified into a few major technologies as shown in Figure 1. NOx formation in CI engines is directly proportional to the combustion temperature. The following sections will briefly summarize the above-said parameters and its effects on diesel and biodiesel-diesel blended diesel engines performance and emission characteristics.

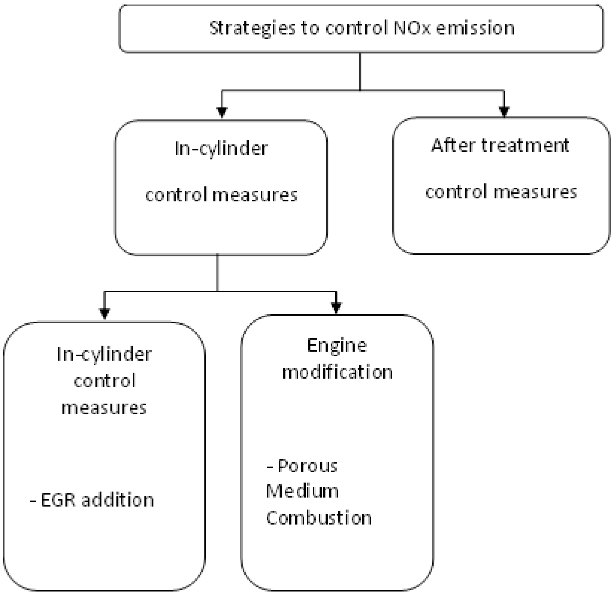

Figure 1. Strategies to control NO_x emission

2. IN-CYLINDER CONTROL MEASURES

2.1 Effects of intake charge modification

2.1.1 EGR addition

EGR, an additional heat sink replaces some part of the fresh air mainly to reduce NO_x emissions. Diluents lower the combustion rate and reduce peak combustion temperature thus the NO_x formation reaction diminishes. However, EGR improves combustion efficiency. In some cases, before inducting EGR is cooled close to atmospheric temperature and used up to 60 % with fresh air. Appendix A shows the combined and individual effects of EGR on emissions with other strategies like varying fuel injection pressure, injection timing, and a number of injections. Some additives like DME and CH_2O can also be combined with the fuel to attain homogeneous charge. The increase in additive percentage might increase ignition quality. Yao et al studied the control strategies to attain homogeneous combustion in diesel engines. The engine selected was a single cylinder water cooled diesel engine which was modified to operate in dual fuel mode. The DME and methanol dual fuel is port injected separately at the pressure of 2.5 bar. Since the engine is mechanical governor controlled the remaining required diesel is conventionally injected through the main injection.

From the literature, it is found that the researchers varied EGR from 0 – 80 %. Amongst most of the results approved that 30 % EGR shows better performance and emission characteristics. In the research work of Yao et al, the EGR ratio was varied from 0, 25, 40 and 65 % and DME ratio 60 to 76 % respectively. On conducting experiments, controlling the DME ratio and EGR percentage improved the homogeneous ignition with increased thermal efficiency. The results reveal that the increase in the percentage of DME reduces the HC and CO emissions. Increase in EGR ratio reduced the NOx emissions significantly [4]. Though EGR is capable to reduce NO_x emission it raises HC, CO, and smoke emissions. However, the above experiment didn't report about smoke emissions. EGR reduces more than 30 % of the NO_x emissions and on the same side, it reduces the available intake oxygen. The reduction in the oxygen level reduces the combustion speed and power output of the engine. Simultaneously PM emissions will be increased. In order to achieve the same performance and simultaneous reduction of NO_x and PM emissions, the EGR technique is combined with optimized boost pressure and high fuel injection pressure. The boost pressure can be increased by means of a turbocharger or a supercharger in CRDI diesel engines. An empirical study was carried out by Usman Asad et al to find the influence of fuel injection pressure and boost pressure in combination with EGR. The EGR was cooled and used from 30 – 57 % to replace fresh air. The tests were carried out on a four-stroke, CRDI engine. The boost pressure was varied from 1.5 to 3 bar and the fuel injection pressure was varied from 600 to 1800 bar. It was reported that NO_x and PM emissions were decreased by cooled EGR and increasing intake boost pressure, fuel injection pressure respectively [5].

Olsson et al tried to achieve ultra-low NO_x emissions and thermal efficiency. The two different fuels namely ethanol and n-heptane were chosen on the basis that it will aid to gain homogeneity of the charge. The test engine chosen was a modified six-cylinder Scania DSC12 turbocharged diesel engine operating at 18: 1 compression ratio. The increase in inlet pressure by turbocharger allows the engine to operate at higher loads. As a result, the highest efficiency of 41.2 % is achieved with less than 0.1 g/kWh of NO_x emission [6] at full load. But the CO emissions were increased significantly due to the lack of oxygen at lower loads which can be reduced by slight heating of the intake air. As a result, the dilution required to control the NO_x emission necessitates the use of higher boost supply compared to the conventional mode of operation. When high boost is required, turbocharger efficiency is shown to be very important in order to reduce the pumping losses. For high load applications, two-stage turbocharging with inter-cooling was recommended. Better control of the turbocharger avoids unnecessary pumping work throughout boost. Appendix B shows the experimental outcomes of using variable geometry turbocharger.

On concluding the effect of adding EGR, it increases the heat capacity of the intake charge and displaces the fresh oxygen. So flame temperature becomes lower resulting in NO_x emission reduction while HC, CO and soot emissions rose due to insufficient oxygen. Increased EGR level increases the engine wear, degradation of lubricating oil, knocking and increased fuel consumption [7]. So, to reduce the BSFC the authors tried to work with varying the compression ratio. The compression ratio of an engine has a direct impact on efficiency and at the same time ignition delay of an engine. Increasing the compression ratio produced more power output and increases the thermal efficiency of the engine. Lowering the compression ratio reduces the self-ignition spots thus increases the ignition delay. The results of varying compression ratio and fuel injection timings in an HCCI engine was investigated by Arjan Helmantel et al. [8]. Tests were performed on a Ricardo Hydra single cylinder engine. In this work, a toroidal piston bowl region is enlarged to lower the compression ratio. In addition to the bowl enlargement, the timing of the intake valve closing was altered by camshaft modifications to change the compression ratio. By conducting the experiments, NO_x and PM formations drastically reduced while HC and CO emissions were increased. In the same experiment configuring injector nozzle to an angle of 60^{o} showed excellent choice for HCCI while 140^{o} orientation increased the PM and reduced the engine efficiency. On the overall analyzation of results are shown in Appendix A and B, lowering the compression ratio in the presence of diluted EGR with the combination of higher intake boost pressure and fuel injection pressure extends the operability limit of an HCCI engine. In addition, HC and CO emissions reduced with a minor drop in thermal efficiency. Thus the combination of EGR and compression ratio has the potential for reducing NO_x and improving thermal efficiency respectively. However current emission norm EURO VI requires low NO_x and PM emission level. So, researchers focused their ideas on advanced engine combustion concepts like PCI, HCCI, and PMCI via fuel modification techniques.

2.1.2 Fuel modification

The above-mentioned techniques are used to reduce the NO_x emission while the forthcoming technologies experiment to a simultaneous reduction of NO_x and PM emission. Attaining homogenous charge will help to reduce the PM emission. To get the air and fuel mixed well, PCI mode tends to help more in achieving homogeneous combustion. This mode of operation prepares premixed charge outside the combustion chamber. A premixed charge is obtained by an auxiliary injector placed near the intake manifold which is termed as port fuel injection [9]. Early injection, multiple injections, and late injection are the three different types of approaches that have been taken to experimentation. This mode of operation paid more attention to the formation of the homogeneous mixture before autoignition. There is no PM producing fuel rich zones since it reduces local fuel rich zones and high-temperature regions. However, these advanced engine concepts are limited to low and medium load operations. It may be extended by fuel controlled multiple split injection strategies and they are discussed below. Advancing the injection timing reduces the formation of fuel stratification [10]. This mode of combustion reduces NO_x and PM emissions with a slight increase in HC and CO emissions. It is quite obvious that changes in SOI, air temperature and mass flow rate of the fuel have a great impact on particulate matter reductions [11]. Too early injection leads to wall dousing due to over penetration of the fuel and misfire and so this mode of operation is controlled by chemical kinetics and governed by fuel injection and mixing rate.

Multiple Injections technology for advanced engine concepts.

The effect of misfiring in early injection promotes researchers to work in multiple injections. Studies were carried out in an experimental setup consisting of one main injector and two auxiliary injectors at the sides by Takeshi et al. The engine chosen was single cylinder four stroke diesel engine. The fuel injection timing, quantity, and pressures are controlled separately. The main fuel injection pressure was kept constant as 2500 bar and the auxiliary injector pressure is maintained at 1000 bar. The first stage injection is set at 150º bTDC and the second stage from 2º bTDC to 30º aTDC. Looking at the results from the experiment, retarding the second injection from 2º bTDC to 30º aTDC gradually reduces 50 % of NO_x and PM emissions compared to the conventional mode with improved thermal efficiency. NO_x emissions were reduced due to the reduction of cylinder temperature at the end of the second stage injection [12]. To support these experiments, research conducted by Halysun et al proved the same i.e. multiple injection strategies will reduce the NO_x and PM emissions [13]. After a great deal of research, Sanghoon et al evaluated the adverse effects of injection pressure, injection timings, EGR rate, swirl ratio, and several injections approach in a diesel engine to achieve clean as well as efficient combustion. The combined effect of high EGR and triple injection reduces NO_x and PM emissions [14]. To investigate more about multiple injections, Lemongrass oil was tested in PCCI mode under the basis of the premixed ratio on an energy basis. An auxiliary injector is used which is placed close to the intake manifold (injection pressure - 2 bar) and controlled by an electronic unit, where the main injection is kept at 23° bTDC under 220 bar. The experiments were conducted with two different premixed ratios 5 % and 10 %. Due to the increased ignition delay period and reduced combustion duration, the NO_x and PM emissions are reduced. Even though the prospective benefits are achieved in emissions, its performance is lesser compared to diesel but the experiment was mainly conducted in PCCI mode to reduce the NO_x and PM emissions [15].

Yet another assessment to advancing and retarding second injection work was carried by Takayuki Fuyuto et al [16]. The results of varying second injection timing are shown in table 1. Extensive research has been done in Diesel-PCCI mode as a single post injection and double post-injection strategy by Youngsoo et al. [17]. The single post injection has longer ignition delay and reduced 33 % of NO_x emissions, whereas HC and CO emissions increased compared to conventional diesel injection. In the same study, the author tried to achieve double post injections through a split injection strategy. By conducting trials at various injection timings, it is concluded that when the second injection is retarded more than 30° crank angle after the main injection, NO_x levels reduced. The experimental outcomes prove that double post injections lead to the best NO_x and HC reduction compared to single post injection. The combined effect of the reduced compression ratio and retarded injection timing greatly reduced the PM and NO_x emissions by the lean homogenous mixture and low flame temperature. Being interested to know the effects of combustion efficiency and other emissions of multiple injections, Naoto Horibe et al. conducted an experiment to analyze the influence of injection parameters in an 857 cc diesel engine. The engine is modified from conventional mode to Diesel-PCCI mode [18]. The progressive result of this work is presented in table 2. A retard in the fuel injection improves pressure to rise and combustion efficiency also lowers CO and HC emissions.

Table 1. Influence of second injection timing

PCCI	Injection Timing	Effect
Single injection	Advanced	↓NO_x and noise; ↑ HC, CO, and SFC
	Retarded	Steep ↑ HRR, NO_x, and noise where ↓HC and SFC
Second Injection	Advanced	↑ PM and CO
	Retarded	↑ PM, ↓ CO, and noise

Table 2. Influence of first and second late injection

Influence of	Engine at low speed		Engine at high speed	
	Quantity	**Timings**	**Quantity**	**Timings**
First injection	Increase	Retard	Decrease	Advance
Second injection	-	Retard	-	Advance
Effect	↓maximum pressure rise		↑ PM and CO, improved efficiency	

Retarding injection timing with high compression ratio reduces the NO_x and PM emissions, compared to multiple injections [19]. This trend is principally due to the longer ignition delay. The late injection is better than early injection for reducing NO_x emissions, but it increases HC and CO emissions. However, HC and CO emissions can be reduced by cheap and efficient after-treatment processes. Similarly, a single retarded injection has the same performance effect compared to multiple injections but a slight increase in NO_x as stated in the literature [20]. A single cylinder diesel engine was chosen to analyze the effects of changing injection pressure and timing on NO_x and PM emissions. From the experimental results, it is concluded that increasing the injection pressure (from 600 to 1000 bar) alone decreases PM with little penalty in NO_x while retarding injection timing (2° bTDC) with increased injection pressure simultaneously reduces the NO_x and PM emissions. So advanced injection timing provides homogeneous fuel distribution inside the cylinder. This trend is principally due to the longer ignition delay [21]. The combined effect of the reduced compression ratio and retarded injection timing greatly reduced the PM and NO_x emissions by the lean homogenous mixture and low flame temperature.

2.2 Effects of engine modification

2.2.1 Porous medium combustion

The performance and emission issues discussed so far in previously mentioned modes are positively influenced by the PMC. For simultaneous reduction of these aforementioned pollutants, fuel properties and combustion chamber modifications are vital. Higher burning rate, reliable lean burn ignition, ultra-low emissions, higher cycle efficiency, and equalized temperature mode are some of the potentials of PMC. Porous ceramic materials are made as a high-density wire packed grid structures. It has a large number of hotspots distributed throughout the entire structure with the properties of transparency of liquid and gas flows, capable of transferring single spray into multiple sprays and improves fuel vaporization to make the charge homogeneous. It has a higher heat accumulation, convection, and radiation capacity. The disciplined procedure associated with PMC is shown in Figure 2. The most commonly used porous materials are Silicon Carbide (SiC), Zirconia (ZrO_2), Alumina (Al_2O_3) and Yttria-Stabilized Zirconia due to their properties of high compression strength, thermal resistance, and hardness. The combination of the large heat capacity and large specific surface area might form an excellent heat transfer characteristic which achieve quick fuel vaporization and homogeneous mixture [22].

Molecular transport and adiabatic combustion are the two mechanisms that control the propagations of combustion waves in the porous medium [23]. Using transient approach, the excess specific enthalpy achieved during porous medium combustion is given in the below relation

$$\int_{T_0}^{T_f} C_p dT = q_c + q_a = h_f - h_0 \qquad (1)$$

where, T_o and T_f are the initial and final temperature, q_c is the heat released by chemical energy, q_a is the energy added, and h_o and h_f are the enthalpies of initial and final states [24]. At the end of combustion, the residual enthalpy of the combusted gas gets accumulated in the porous medium. This residual enthalpy is used to increase the enthalpy of the forthcoming fuel mixture in the next cycle [25]. At a bird's eye point of view, liquid fuel fired porous medium combustion chambers are characterized into fuel vaporizing type PM and fuel spraying type PM.

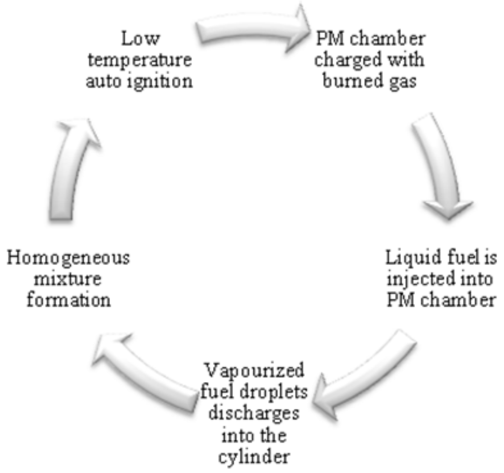

Figure 2. The porous medium ignition process

Fuel vaporizing type PM. Fuel vaporizing type concept is used to make the diesel vaporize quickly in compressed air [26]. For of all before experimenting Liu et al developed models to study the degree of sophistication attained for predicting problems. Some of the expected issues are fuel flow, velocity, temperature, flame speed, mass fraction, combustion efficiency and emissions. The PMC analysis is carried through one dimension and two-dimensional models [27]. In that two unique models of configuring porous medium have been recommended and tried. To be specific they are named as open and closed chamber configurations. The porous medium chamber that has a perpetual contact with the cylinder content is named as an open chamber and the porous medium chamber has intervallic contact with the cylinder content named as a closed chamber. Based on these two configurations, three locations for mounting porous medium in the combustion chamber were chosen commonly and they are cylinder head, cylinder wall and in the piston head. SiC is selected as the porous medium and it is assumed to be placed in the cylinder head between the intake and exhaust valves as an open chamber system without any damage to the porous medium material. A series of tests were conducted and the results showed an obvious reduction in peak pressure compared to conventional mode of diesel operation. Also, it revealed very low CO, NO_x and PM emissions with better fuel economy. One more test was carried on permanent contact PM engine with porous SiC reactor mounted in the piston head. The experimental result shows decreased NO_x emission with a slight increase in CO and HC emissions. From this above literature, it is concluded that the location of PM in the chamber either moving or stationary have a direct influence on emissions. Heat accumulation in the porous medium reduces the flame temperature and thus NO_x emission is reduced. Susceptibility of the valve exposed to combustion products and high thermal stress can cause damage to valve and piston tops [28]. Saravanan et al attempted simulation study to control NO_x using PMC technique in a diesel engine. The software chosen was Converge 2.0 and the same conventional engine operating parameters are considered for simulation. Silicon carbide is selected as the porous medium due to its significant properties of thermal conductivity, porosity, and ppi, etc. The simulation is devoted to NO_x reduction and the NO_x results were found reduced. The authors observed that the NO_x emission was reduced by 77 % while HC and CO emissions were increased by 80 % significantly. However, HC and CO emissions can be controlled by simple after treatment processes, the main objective of the simulation study was achieved via PMC [29].

Fuel spraying type PM. The fuel spraying type porous medium is a concept of making porous nozzles to inject diesel fuels. A new type of porous injector nozzle was reported and investigated experimentally by Reijinders et al. [30]. Fuel spray interface with a porous medium is given in figure 3. In this pioneering research, it is quite new that the nozzle with an orifice diameter has less than 50 µm was taken. The advantage of the new concept was further sophisticated by porous nozzle tip designed to achieve a spray angle nearly by 180 º. A model is created using Darcy-Forchheimer equation in COMSOL Multiphysics to predict the direction and velocity of the fuel. The simulation was analyzed by varying parameters like mixture formation, high-pressure fuel injection, different hole and sizes configuration under different loads. The results showed technical and profitable perspectives like shorter ignition delay and more homogeneous distribution compared to the conventional injector.

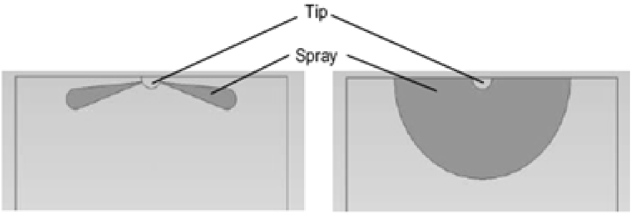

Figure 3. Fuel distribution of a conventional and porous injector [30]

Table 3. An average lifetime of the tested porous materials [32]

Material	Average injections
Stainless steel (316L)	58,000
Hastelloy X	1,35,535
Inconel 600	3,13,500

The sample of the injector with three different porous materials mounting on conventional injector tip is tested at atmospheric pressures under a pressure of 100 MPa, 5ms duration, and 15 HZ injection frequency. The results obtained from the test concluded that increasing the strength of the porous material increases lifetime (average injections) as given in table 3. High injection pressure has more additional capacity to scatter rapidly than low injection pressures [31]. Despite these potential advantages, the normal lifetime is not yet met.

Shanhangian and Ghojel et al. [33] explored the effect of injection pressure on porous media with the help of high-speed imaging technique. The combustion chamber volume was reduced with an increase in size, heat capacity, pore density and specific surface area of the porous reactor. An experimental setup was systemized in a 150 mm diameter and 135 mm depth, eight windows stainless steel constant volume chamber. The PM was centrally positioned across the entire vessel. Thermocouple and static pressure transducer were used to measure the temperature and pressure of the chamber. In addition to this a common rail diesel fuel injection system, high-speed camera, trigger circuit, and illumination circuits are connected in series. The camera used here is Shimadzu Hyper Vision HPV-1 fitted Micro Nikkor lens to capture the injection and impingement events. The high-resolution charge-coupled device camera with exposure time was adjusted to achieve the frame integrated time of 2 µs for the 125 and 63 kfps framing rates. The experiment is carried out with an Al_2O_3 porous sphere and repeated for a different number of layers of porous spheres. The results showed that there is a significant reduction in NO_x and PM emissions with increased combustion efficiency. Looking at results from the literature, it is accomplished that the temperature of the combustion medium is reduced, which paves the way for NO_x reduction. Lower oxygen concentration and uniformed hot spots may also reduce the NO_x formation.

Navid Shahangian [33] et al investigated the influence of injection pressure and pore density on a porous medium. To access the technical viability high-speed imaging technique was employed and images are processed with the help of Matlab code to analyze the spray impingement. For the experimental analysis three different SiC types of 10 ppi, 20 ppi, and 30 ppi are chosen. As the injection pressure rises, the numbers of secondary spray increases. From the investigation, it is decided that the injection pressure of 1000 bar increases the amount of fuel penetration. Increased air entrainment and improved homogenization resulted from the experiment outcomes. Porous medium combustion technology is furthermore efficiently achieved by varying the parameters like compression ratio, swirl ratio, equivalence ratio, injector nozzle tip diameter, etc. Since HC, CO and NO_x, smoke emissions have a tradeoff to rise or decrease vice versa HC and CO emissions can be reduced by a combination of porous medium combustion and by implementing after-treatment processes like Three Way Catalytic converter, Lean NOx Trap (LNT) and NOx Storage Reduction Catalysis (NSR).

3. AFTER TREATMENT CONTROL MEASURES

Though many techniques are employed for emission reduction in automotive industries, the use of catalytic converters is considered as the best way of reducing the emissions without any modification in the engine and its performance. The harmful pollutants discharged from engines such as carbon monoxide, unburned hydrocarbons and NO_x can be changed over to safe ones utilizing a three-way catalyst through balanced oxidation-reduction responses. A three-way catalytic converter has principally three responsibilities:

Reduction of nitrogen oxides to nitrogen and oxygen

$$2NO_x \rightarrow xO_2 + N_2 \quad (2)$$

Oxidation of carbon monoxide to carbon dioxide

$$2CO + O_2 \rightarrow 2CO_2 \quad (3)$$

$$4\ HC + 5\ O_2 \rightarrow 4\ CO_2 + 2\ H_2O \quad (4)$$

$$C_nH_{2m} + (n + m/2)\ O_2 \rightarrow nCO_2 + mH_2O \quad (5)$$

To advance this technology furthermore led to the development of multi-component LNT catalysts to abolish the shortcoming of the traditional TWCs and urea-SCR system [34]. LNT technology is the most feasible and potential technique to reduce the NO_x emission from the diesel engine exhaust. These challenges led to the development of multi-component LNT catalysts to abolish the shortcoming of the traditional TWCs and urea - SCR system. LNT technology also acknowledged as NSR is the most feasible and potential technique to reduce the NO_x emission from the diesel engine exhaust. But there is an unclear hypothesis on the chemistry and process mechanism of reduction of the stored NO_x. In recent times, it has been suggested that ammonia is intermediate in the reduction of the stored nitrates by H2 [35]. The NSR catalytic system composed of noble metal is the most promising alternative for the removal of NO_x from the exhaust of diesel engines because it does not need any additional equipment and infrastructure. Since NO_2 and NO gases are acidic, various oxides of alkali and alkaline earth metals can be used for the NO_x storage. The goal of this investigation was to provide analysis of the pathways operating during both lean and rich operating conditions particularly to study the behaviour of the combined NSR/SCR catalytic systems on the basis of the proposed pathways for the reduction of the stored NO_x with NH_3 as an intermediate species which can be used in SCR bed to further improve the total efficiency of the system [36].

4. CONCLUDING REMARKS AND FUTURE RECOMMENDATIONS

Internal heat recuperation, fuel injection, fine vaporization, homogenization, and self-ignition are the processes followed to attain homogeneous charge in porous medium combustion. Several simulation works have been made to focus the eye of current research workers in the progress of a porous medium combustion process. But, the experimental works carried out were found to be very few due to the complexity in the setup construction or modifying the existing one. Experimental optimization of adding porous medium inside the combustion chamber is difficult, due to the physical limitations of the porous material. Fracture, and degrade upon continual thermal cycling is one of the demerits to be assured in porous media. SiC is the best porous medium to use in a combustion chamber and mainly reported in all literature. Amongst this, a large specific surface area and heat capacity of Sintered silicon carbide may be utilized for excellent interphase heat transfer, because other porous materials are feasible, but not applicable to high-temperature processes. For a very good heat transport properties, foam structure should have a mean pore diameter of 0.1 to 5 mm. A wide range of low calorific fuels can be used in dual fuel mode with main diesel fuel.

(1). Porous medium combustion has superior thermal efficiency and a major reduction in NO_x and PM emissions

(2). It is concluded that the temperature of gas trapped in the porous medium is less dependent on the air-fuel ratio of the engine

(3). Multipoint fuel injection with electronic control unit enables to achieve efficient fuel economy

(4). Having an optimized compression ratio lowers the combustion chamber pressure

(5). Even though substantial numerical modeling research has been dedicated to porous medium combustion still there is a lack of satisfactory experimental verification owing to its intricacy in the process

(6). Investigations can be attempted on the combination of diesel fuel with onboard generated hydrogen

(7). Investigations on porous medium combustion can be done on multi-cylinder diesel engines and high-speed engines

(8). Investigations can be done on more fuel modifications

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NOMENCLATURE

aTDC	after Top Dead Centre
bTDC	before Top Dead Centre
CI	Compression Ignition
CN	Combustion Noise
CO	Carbon monoxide
CRDI	Common Rail Direct Injection
DE	Diesel Engine
DI	Direct Injection
DME	DiMethyl Ether
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
EURO	European Emission Standards
FV	Free Volume
HC	Hydro Carbon
HCCI	Homogeneous Charge Compression Ignition
HRR	Heat Release Rate
HSDI	High-Speed Direct Injection
ID	Injection Duration
IPR	Ideal Porous Reactor
LNT	Lean NO$_x$ Trap
NO$_x$	Oxides of Nitrogen
PCCI	Premixed Charge Compression Ignition
PM	Particulate Matter
PMC	Porous Medium Combustion
RPR	Real Porous Reactor
SCR	Selective Catalytic Reduction
SFC	Specific Fuel Consumption
SiC	Silicon Carbide

APPENDIX

Appendix A: Experimental results on varying EGR ratios, injection timing, and pressure

Engine type	Operating conditions	Test fuel	Injection timing (Injection pressure)	Performance	Emission	Ref
Kirloskar -7.4 kW rated @ 1500 rpm	EGR – 8, 15 & 30 %, CR – 19.5	CNG–intake manifold inj, Diesel-Main inj	(250 bar)	↑BTE. Upto 15 % EGR @ 37 % CNG energy share	↓ NO$_x$ – 94 %, ↑PM with ↑ EGR; CO & HC ↓ for 15 % EGR & ↑ for 30 % EGR c.t. D	[37]

6 Cylinder, 24-valve DE	CR – 16, EGR – 15 & 45 %	PFI – N-butanol, Diesel – Main inj	DI CRDI – 8° CA bTDC	At 10 % EGR- P & HRR ↑, 45 % EGR- ↓ P& HRR	↑ HC & CO for ↑ PFI, ↓ NO$_x$ & ↑PM as ↑EGR	[38]
4 Cylinder DIDE, 2 PFI	CR – 18, EGR – 0 & 50 %	Biogas & hydrogen-PFI; Diesel- Main inj	Main inj - 10°bTDC, PFI - 60°bTDC, CRDI (1200 bar)	↓ID	At 50% EGR, NO$_x$ ↓, ↑PM as ↑EGR	[39]
6 cyln heavy duty DE	CR – 16, EGR – 0-45 %	40 % Butanol + D	-3° aTDC CRDI (1400 bar)	↑P for B40 c.t. D	↑ NO$_x$ for B40, ↑ HC & CO as ↑EGR	[40]
Single cyln, DE	CR – 18, EGR – 5, 10, 15 %.	20 % soybean + D	(180 bar)	↑P & HRR with ↑ EGR with B20, ↑BSFC, ↓ BTE	↑ EGR→↓ NO$_x$, slight ↑ smoke.↓ HC & CO c.t. D	[41]
Petter PH1W diesel engine	CR – 16.5, EGR – 5, 10, 20 %.	CNG – main inj; diesel – PFI	(200 bar)	↓P w.r.t.↑ EGR	NO$_x$, HC and CO ↓w.r.t. ↑EGR	[37]
Single cyln, DE	CR – 17.5, EGR – 10-30 %.	1-Hexanol (blends by vol. 10, 20 & 30 %) + D	21, 23 & 25 °CA bTDC (210 bar)	For 30% blend ↑P & HRR	↓ PM & CO but ↑ NO$_x$ & HC	[42]
Kirloskar TAF1	CR – 17.5, cooled EGR – 10, 20, 30 %	n-Pentanol + D (blends by vol.10, 20, 30 & 45 %)	23.4 °bTDC (200 bar)	↑ID, ↓BSFC & BTE for all blends	↓ NO$_x$ @ 45% blend & 30% EGR, ↓ PM for all blends, ↑HC & CO for all trials but not significant	[43]
GW4D20 diesel engine	CR – 16.7, EGR (0-70 %)	Gasoline (37-66 %) – Diesel	SOI 1-35° aTDC, SOI2-5° aTDC CRDI (650 bar)	↑P & HRR	↓ NO$_x$ & PM as ↑gasoline ratio	[44]
Ford “Puma”	CR – 18.2, EGR (0-60 %)	Ethanol, Diesel	CRDI(1600 bar)	↓ BTE with ↑ EGR	↓ NO$_x$ as ↑ EGR, where ↑ PM	[45]

* D-Diesel, P-Pressure, PFI-Port Fuel Injection, inj-injection, CNG- Compressed Natural Gas

Appendix B: Experimental results on variable geometry turbocharger

Engine type	**Operating conditions**	**Test fuel**	**Injection timing**	**Performance**	**Emission**	**Ref**
4S DE	Turbocharged, CR-16.8	Biodiesel-D	12° bTDC – 215 bar	↑BTE & BSFC c.t.D	↑NO$_x$ & ↓CO c.t.D	[46]
XLD 418 Ford Diesel	Supercharger, CR-21.5, EGR – 27, 29, 32 %	D	-	↑P	↓NO$_x$ & PM, ↑CO and SO$_x$	[47]
HSDI diesel passenger car engine	Steady state pre-turbo, DPF, CR-18	D	-	↑P	↑NO$_x$,↓CO & HC, ↓Opacity for pre-turbo while ↑Opacity for post-turbo;	[48]
4-cyln diesel engine	Turbocharger, DOC, POC, CR-17.1,	DMDF	-	-	↓PM by 25% for D after DOC, 96% reduction after DOC & POC treatment for DMDF	[49]
6-cyln diesel engine	inter-cooled turbocharger,CR-18.1	D(DI) + methanol (PFI)	(PFI - 4 bar)	↑ P	↓ NO$_x$ & PM; ↑ HC & CO,	[50]

* D-Diesel, P-Pressure