Iranian (Iranica) Journal of Energy & Environment
Journal Homepage: www.ijee.net
IJEE an official peer review journal of Babol Noshirvani University of Technology, ISSN:2079-2115

NOx Emissions Control for Small Single-cylinder Diesel Engine Using Exhaust Gas Recirculation Strategy

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PAPER INFO

Paper history:
Received 07 November 2020
Accepted in revised form 19 Febreury 2021

Keywords:
Emissions reduction
Exhaust gas recirculation
Intake port Swirl
Intake valve opening
NOx emission
Small diesel engine

ABSTRACT

Small Diesel engines pose a very tough challenge of simultaneously meeting NOx and particulate matter (PM) emissions, without hampering performance and fuel consumption. Frequent revision in small diesel engines pose a very tough challenge of simultaneously meeting NOx and PM emissions, without hampering performance and fuel consumption. Frequent revision in emission norms for small diesel engines makes it further difficult, as they need to be upgraded in design and for combustion. These small, low-capacity engines are predominantly used in specific regions/countries where cost plays a major role and hence these engines lack a clear emission reduction strategy. It is required to develop an emission reduction strategy considering available technologies and cost implications. Current research work aims to develop a cost-effective emission reduction strategy by modifying the engine using conventional technologies. The present work is an experimental study of the effect of cylinder head Swirl, static injection timing (SIT), intake valve opening (IVO), and Exhaust gas recirculation (EGR) on a 0.4 l single-cylinder diesel engine's performance and emission. Baseline vehicle has HC+NOx and PM emission levels are 0.61 g/kM and 0.04 g/KM, respectively; which is higher considering existing and upcoming emission norms. The lower Swirl cylinder head, advanced IVO timings with retarded injection timings shows an 18% reduction in NOx emission with a 3% improvement in performance at the engine dynamometer. Different EGR rates were also studied and effects were analyzed on emission and fuel consumption and emissions. EGR rate of 25% with advanced IVO of 16° with SIT of 5° and 1.9 Swirl cylinder head had shown 48% improvement in HC+NOx emissions, 20% improvement in PM emission, and 11% improvement on CO emissions at the Chassis dynamometer.

***doi**: 10.5829/ijee.2021.12.01.04*

NOMENCLATURE

CO	Carbon Mono Oxide	HSDI	High-speed Direct Injection
HC	Hydrocarbon	IVO	Intake Valve Opening
NOx	Oxides of Nitrogen	EGR	Exhaust Gas Recirculation
DI	Direct Injection	IDC	Indian Driving Cycle
PM	Particulate Matter	CA	Crank Angle
Abbreviations		3W	3 Wheeler
BS	Bharat Stage Emission Norm	NA	Naturally aspirated
TDC	Top Dead Centre	*BSFC*	Brake Specific Fuel Consumption
ID	Internal Diameter	CA	Crank Angle
HPP	High-Pressure Pipe	LCV	Light Commercial Vehicle

INTRODUCTION

Diesel engines are the most reliable and best available power source for all domestic, industrial, agricultural, and transportation applications in the world. The reason for their wide application is high power density, fuel economy, and robustness under all operating conditions. The size of these engines varies from the small single-

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Please cite this article as: A. Jain, P. Ekambaram, S. S. Thipse, 2021. NOx Emissions Control for Small Single-cylinder Diesel Engine Using Exhaust Gas Recirculation Strategy, *Iranian (Iranica) Journal of Energy and Environment,* 12(1), pp.23-33. Doi: 10.5829/ijee.2021.12.01.04

cylinder engine used for commercial applications to large engines used to propel ships. The need for greater fuel economy, enhanced performance, and drivability expectation from customers for these engines are progressively increasing along with stringent emission norms from the Indian government [1]. The major issue with these engines is the efficiency of these engines. Furthermore, they are also known for high smoke and NOx emissions [2-4]. Attempts have been made and are still being made around the world, to achieve the maximum possible efficiency [5]. Owing to the lack of throttling losses, higher compression ratio, and lower equivalence ratios, diesel engines have low specific fuel consumption. This helps in lower CO_2, CO, and HC emissions [6]. However, diesel engine suffers from relatively high nitrogen oxides (NOx) and particulate matter (PM) emissions [7, 8].

Currently, research around the world is focused on oil extraction, transportation, recovery, fuel consumption, and emission reduction on multi-cylinder engines with the latest technologies. This includes the latest simulation technologies, automation, high-pressure common-rail fuel injection systems, multiple injection strategies, combustion optimization, low-temperature combustion (LTC), HCCI, PCCI, VVT/VVA, new boosting technologies like twin-turbo, supercharging, and advanced exhaust after-treatment systems.

Bahrekazemi et al. [9] developed a simulation tool to strengthen the oil recovery from the reservoir and its performance prediction. Arkawazi et al. [10] studied and analyzed the influence of signalized intersection delay on fuel consumption, emission reduction, and operation cost. Gas engine-driven heat pump performance was studied by Zhang et al. [11] for space heating and colling at various engine speeds, modes, and operating conditions.

Diesel engine combustion is the most prominent way to improve fuel efficiency for global CO_2 emissions reduction [12]. Combustion optimization is a technological way for improvements in the combustion process, wherein optimization is carried out from incoming air and fuel to the outgoing exhaust gases as emissions. This process includes optimization of parameters like fuel injection system (including injection rate and timing), fuel-air mixing, intake port Swirl, squish, cam timings, nozzle tip protrusion, piston bow geometry, turbocharging, intercooling, EGR, and design of peripheral components related to these parameters [13]. All research work carried out is with the opinion that fuel and air mixing processes, fuel injection strategy and associated components were key elements in reducing emissions.

Fayed [14] studied the effect of different injection strategies on performance and emission and observed that increased injection pressure enhances combustion pressure and retarded injection timings help in NOx emission reduction. The effect of cooled EGR with injection pressure strategy was studied by Gautamendra [15] for light-duty diesel engines and observed that a higher EGR rate reduces thermal efficiency, in-cylinder pressure, and NOx emissions. It also helped in the reduction of exhaust gas temperature [16].

Rakopoulos et al. [17] studied the effect of EGR on combustion and emission for a laboratory diesel engine. Using a simulation tool, they predicted NOx smoke trends for various EGR rates, injection timing, and temperature. They concluded that retarded injection timings with EGR helped in lower in-cylinder pressure, temperature, and NOx reduction with a penalty of smoke. The introduction of an 8% EGR rate reduces the NOx emission by 25% at high loads for ship engines [18]. High and low-pressure EGR on a 6 cylinder engine was studied by Mao et al. [19] for combustion, emission, and thermal efficiency. They observed increased BSFC with EGR rate and 22.5% NOx reduction with LPL at middle operating speeds. At low loads, lower NOx and PM emission is observed by Maiboom [20] with higher EGR due to delayed combustion.

Mobasheri et al. [21] studied the effect of injection timing and EGR strategy for heavy-duty diesel engines and observed that split injection with 10% EGR rate substantially reduces NOx emission. However, the delay in timing didn't affect the soot emission and BSFC of the engine. They concluded that EGR is effective for reducing the NOX emission due to lower in-cylinder temperature. Zammit et al. [22] studied the effect of advance IVC timings on fuel consumption and emission for diesel engines and observed that effects are significant only after advancing IVC by 30° or more. For fixed NOx levels, soot emission was reduced with higher exhaust gas temperature. Parvate et al. [23] studied the valve openings and closing combination for 8 different combinations and concluded that early intake valve opening helped in the reduction of NOx emissions. Higher Swirl helped in rapid mixing of fuel-air mixture [24] and reduction of Soot emission [25]. Reduction in Swirl helped in the reduction of NOx emission [26].

The Indian government's view on Climate Change is to promote clean, efficient, and sustainable mobility with a focus on environmental protection and affordability. The Indian government aims to provide a long-term, stable, and consistent roadmap for the automotive industry to make India a global manufacturing hub with green mobility, increased local R&D with a focus on commercially viable innovations towards indigenous research, design, and engineering [27].

Recent literature suggests that to meet the stringent emission legislation imposed by the Indian government, diesel engines need to be upgraded in design, manufacturing, and combustion for the lowest possible emissions with performance. Considerable development work has been carried out on the multi-cylinder diesel engines with conventional and advanced technologies to reduce engine-out emissions. Furthermore, these strategies are restricted to the turbocharged, intercooler, CRDI / higher injection pressure engines with EGR strategy. However, the small, naturally aspirated diesel engine industry needs concurred solutions to keep emission under control with minimum modifications on the existing design. This paper is an experimental work that deals with the study of the conventional technology for emission reduction for the small naturally aspirated single-cylinder diesel engine. Modifications are carried out on Cylinder head Swirl, IVO timings, Injection pressure, and Injection timings. Various EGR rates are tried and the effect is analyzed on engine-out emissions at the engine dynamometer. The optimum combination is analyzed for vehicle level trials and shows improvements at IDC on chassis dynamometer tests.

MATERIAL AND METHODS

Experimental test setup

Initially, baseline testing of vehicle and engine is carried out for the study of emission and performance with a focus on emission reduction strategy. The baseline engine is an HSDI single-cylinder diesel engine of a cubic capacity of 0.43 liter, mounted on a 3W light commercial vehicle. The engine dynamometer and chassis dynamometer are used for evaluating the baseline and upgraded performance of the engine and vehicle with variable speed tests using the Indian driving cycle (IDC) [8]. Modifications are carried out considering conventional technologies on components namely cylinder head, fuel injection system, Valve timing, with exhaust gas recirculation (EGR) technique for the reduction of NOx emissions. Modification work on the cylinder head is carried out by modifying the intake port profile for lower Swirl and higher flow coefficient. IVO timings are advanced and lower internal diameter (ID) high-pressure pipe (HPP) is used to increase fuel line pressure along with different EGR supply strategies for reducing emission. The measurement system and its uncertainty levels are the same as discussed by Jain [13]. The schematic view of the engine testbed is shown in Figure 1 wherein design modifications are highlighted. Figure 2 shows the flow chart of the experimental strategy carried out for emission reduction of the vehicle.

Design modifications in cylinder head

The specifications of the baseline engine are given in Table 1. Intake port performance is carried out on a steady- Swirl test-rig for study and optimization of the cylinder head.

The Swirl ratio and mean flow coefficient of the baseline engine cylinder head were 2.59 and 0.279. Swirl and flow is measured at steady state swirl rig. Swirl is calculated by the AVL paddle wheel method shown in Equation (1); it is ratio of paddle rpm by fictitious engine rpm for different intake valve lifts. Flow coeffiicent is ratio of actual flow to theoritical flow at minimum valve seat area measured at different valve lifts which is shown in Equation (2).

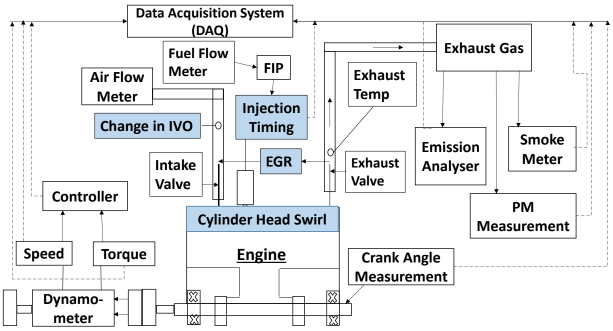

Figure 1. Schematic view of the experimental setup with varied state parameters

$$Swirl\ Ratio = \frac{n_p}{n} = \frac{n_{paddle}}{n_{motor}} = \frac{\rho.A.S}{30.m} n_{paddle} \tag{1}$$

$$Flow\ Coefficient = \frac{Q}{A\,Vo} = \frac{\frac{m}{\rho}}{A\,Vo} \tag{2}$$

where,

n_p: Rotational speed of paddle wheel

n: Rated engine speed

ρ: Air density

A: Valve seat reference area at minimum seat dimeter

S: Stroke of the engine

m Mass flow rate of air

Q: Actual flow measured at seat reference area

Vo: Velocity head

Cylinder head Swirl affects NOx emission and has to be reduced for lower emission and better efficiency. It is also observed that the flow coefficient of the baseline head is on the lower side and hence, needs to be improved to feed more air into the combustion chamber. To reduce the Swirl ratio and to increase the flow coefficient intake port profile is modified. With reduction of intake port swirl, there is increase in flow cofficient due to reduction of port resistance to flow. The Swirl ratio and flow coefficient of

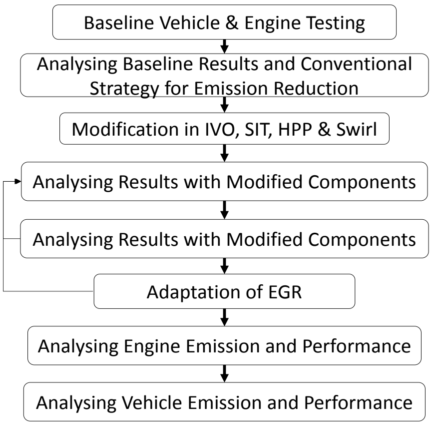

Figure 2. Flowchart of the work carried out

the modified cylinder head is 1.91 and 0.310. The modified cylinder head intake port has a 26% lower Swirl and 11% higher flow coefficient compared to the baseline cylinder head. The baseline and modified port profiles of the cylinder heads are shown in Figure 3; while Figure 4 shows the comparison of the Swirl and flow coefficient performance for the two cylinder heads.

Modification in IVO timing

It is required to have good air-fuel mixing for lower emission and fuel consumption. Intake valve opening timing governs the quantity of the air coming into the combustion chamber and consequently combustion and emission. It is required to have proper opening and closing timing to regulate the airflow. Intake valve opening timing is advanced by 5° and 9° from baseline intake opening timings as shown in Figure 5. This provides a slightly wider valve overlap period and allows exhaust gases to come into intake the intake manifold. This reverse flow of exhaust gases dilutes the fresh air availability in the intake manifold thus controls oxygen availability and helps in curbing the emissions [28].

Modification in the fuel injection system

Modification in Fuel injection timing and lower ID high-pressure pipes are used to attain higher injection pressure with retarded static injection timing. High-pressure pipes of ID of 1.25 and 1.5 mm are used to get higher line pressure thereby utilizing the advantage of higher injection pressure and control. Unit injector with fuel cam is the baseline injection method, different shim thicknesses are used to get different injection timing options. Baseline shim thickness is 0.5 mm and the option tried to vary from 0.3 mm to 1.3 mm thickness. This gives NTP variation of 2.5 mm to 4 mm. The SOI timing is advanced by 3° and retarded by 2° to 6° with these shims of different thicknesses.

Table 1. Brief engine specification

Parameter	Specification
Engine Type	Single Cylinder Naturally Aspirated
Combustion	DI – Diesel
Rated Power	5.5 kW
Rated Speed	3,600
Rated Torque	18.0 Nm
Cooling System	Air Cooled
Valve Mechanism	Push Rod operated
Bore / Stroke Ratio	1.146
Number of Cyl.	Single
Displacement, Liter	0.43
Compression Ratio	19:1
Fuel Injection Pump	PF Type
Fuel	Diesel
Bore/Stroke	1.146
Injector	P-Type, VCO hydro eroded
Engine Dynamometer	Eddy-Current Type [Saj AG 150]
Vehicle Type	Light Commercial Vehicle
Gear Box	Four Speed
Emission complaints	BS-III
Fuel used	BS-IV Diesel

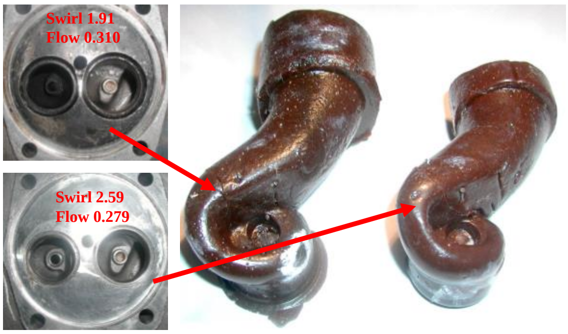

Figure 3. Modification on the engine cylinder head

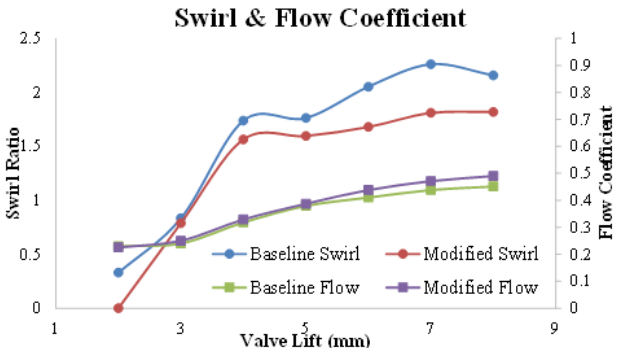

Figure 4. Comparison of Swirl ratio and Flow coefficient for baseline and modified cylinder head

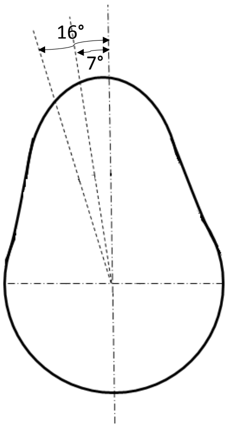

Figure 5. Advanced IVO timings option compared to baseline engine

Adaptation of EGR system

Hot exhaust gases are directly supplied to the intake manifold with a flexible pipe and are controlled by the ID of the plate mounted just before the intake manifold. Initially, an ID of 3 mm is used and thereafter increased to 10 mm. With these different plate orifice diameters, the EGR rate supplied to the engine is also varied; hence, the effect of EGR is analyzed on engine performance and emissions [3]. EGR rate is varied between 4% to 25% with help of these different ID plates. This Orifice is attached to an ON-OFF type EGR valve. The strategy for emission reduction is developed based on the testing results of the above iterations and in combination with other modifications.

RESULTS AND DISCUSSION

Baseline performance tests on engine/chassis dynamometer

Baseline vehicle emission measurement is carried out as per the Indian driving cycle (IDC) (Figure 6) for CO_2, CO emission as shown in Figure 7. Vehicle emission results for HC and NOx emission with vehicle speed at IDC are shown in Figure 8. Baseline Vehicle is a BS-III Vehicle and doesn't meet existing and upcoming emission norms. It is also observed from CO and HC emission pattern that emission is higher due to the cold starting of the vehicle and this effect continues for the first two-cycles; thereafter this effect is wiped out. NOx emission from the vehicle is higher throughout the cycles. It is required to optimize the engine to reduce engine-out pollutants and meeting upcoming emission norms with minimum load on after-treatment devices. The engine is removed from the vehicle and baseline engine testing is carried out for variable speed load combination performance tests on the engine dynamometer. Emissions and performance parameters like NOx, HC, CO, power, torque, and bsfc are analyzed for the baseline engine. The peak engine Torque measured is 19 Nm@2000 rpm with engine out Exhaust gas temperature as 672˚C. Furthermore, a strategy using conventional technology is developed for emission reduction with a minimum penalty on performance parameters is developed on an engine dynamometer and vehicle emission and performance is measured on Indian Driving Cycle (IDC) at the chassis dynamometer.

Effect of Swirl, IVO, and SIT

The baseline engine has higher NOx and CO emissions. The primary focus was to target the source of this emission and modification started from the parameters affecting the combustion and are responsible for higher NOx emissions. While doing this we had to consider that it should be without hampering the engine performance. The intake port Swirl is an important parameter affecting the air-fuel mixture inside the combustion chamber and lower Swirl values have a direct impact on engine-out emission. A lower Swirl intake port is useful for NOx emission reduction, they reduce the axial velocity and kinetic energy of the incoming air. This further delays the fuel-air mixing and thus the mixing is more heterogeneous. Furthermore, it also gives an edge of a higher flow coefficient which helps in feeding more air into the combustion chamber. The cylinder head of 1.91 Swirl helped in reducing the engine NOx emission, however, it should be supported by other parameters for reducing the emission. The effect of a lower Swirl Cylinder head on NOx emission is shown in Figure 9, wherein NOx emission is lower than the baseline engine.

Static injection timing (SIT) of the baseline engine is too advanced and hence is retarded by 6° by adjusting the shim thickness. A lower diameter high-pressure pipe (1.25 mm) also helped in increasing the line pressure.

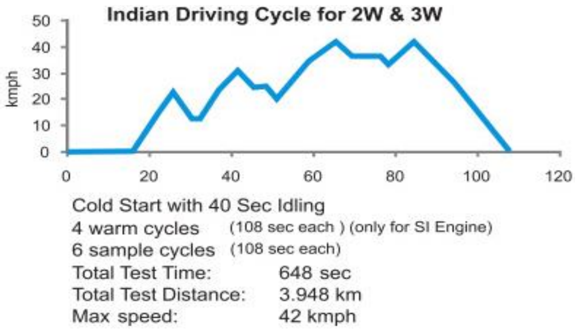

Figure 6. Indian driving cycle for 2wheelers and 3wheelers

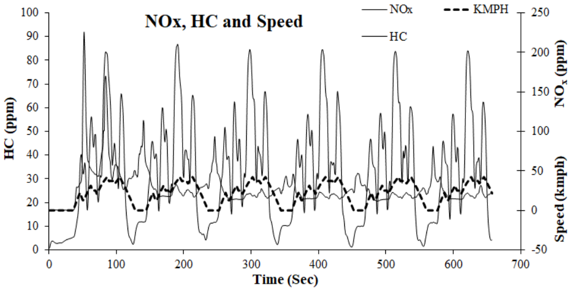

Figure 7. NO_x and HC emission (in ppm) for baseline engine vehicle

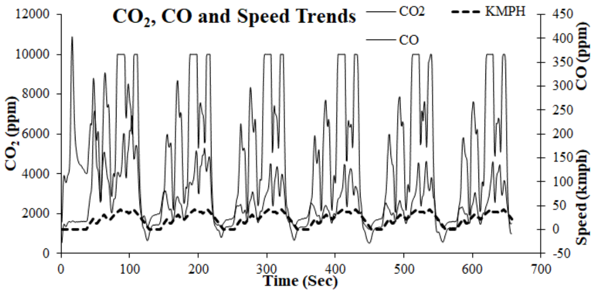

Figure 8. CO and CO_2 emission (in ppm) for baseline engine vehicle

Retarded injection timing delayed the combustion and thus increased the rate of combustion, and hence combustion pressure and temperature inside the combustion chamber increased abruptly. Even though this abrupt increase in pressure and temperature is favorable for the formation of NOx emission, the NOx emission values are still low due to retarded timings [14]. The effect of SIT on NOx emission is shown in Figure 9. Change in NTP has minimum or negligible effect on engine performance, however, it has more effects on combustion and emission parameters like HC and CO.

Advanced IVO timing technique is used for the internal EGR effect. Advance IVO timing allows higher valve overlap and this overlap allows a portion of hot exhaust gases to go back into the intake side. During suction stroke, these exhaust gases come with fresh air, thus dilutes the incoming air quality. This reduces fresh oxygen availability and thus controls combustion and emission. The effect of advanced IVO on NOx emission is shown in Figure 9.

By combining these modifications, there is a slight increase in engine power and torque values. This is due to better combustion with a higher quantity of fresh air because of higher flow coefficient, advanced IVO, and retarded SIT. As SIT is retarded with the same fuelling, it has a penalty in fuel consumption and thus bsfc of the modified engine is higher than the baseline engine [21]. With a lower Swirl and advanced IVO, the NOx emission is reduced with a penalty in HC emissions [13]. The modified engine has an unchanged combustion package with a slight change in fuel. The benefits achieved in performance are helpful during EGR adjustment. The comparisons of performance and emission parameters of the baseline and the modified engine are shown in Figure 10.

With modification, there is a reduction in NOx emission by 50-90 ppm along with performance improvements of 2-6% with retarded injection, advanced intake valve opening timing, and lower Swirl cylinder head. Along with performance improvements, there is a penalty of 15-20 ppm in HC emission also observed, with a spike at rated speed. There are improvements in smoke emissions as well. These results are in line with the results of Kaleemuddin and Rao [3]. Further reduction will be analyzed with an adaptation of EGR.

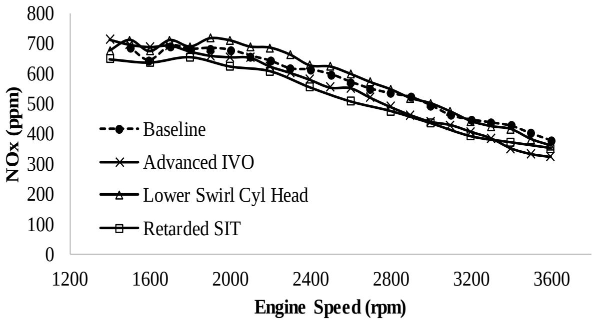

Figure 9. Comparison of effect of IVO, Swirl and SIT on NO$_x$ emission

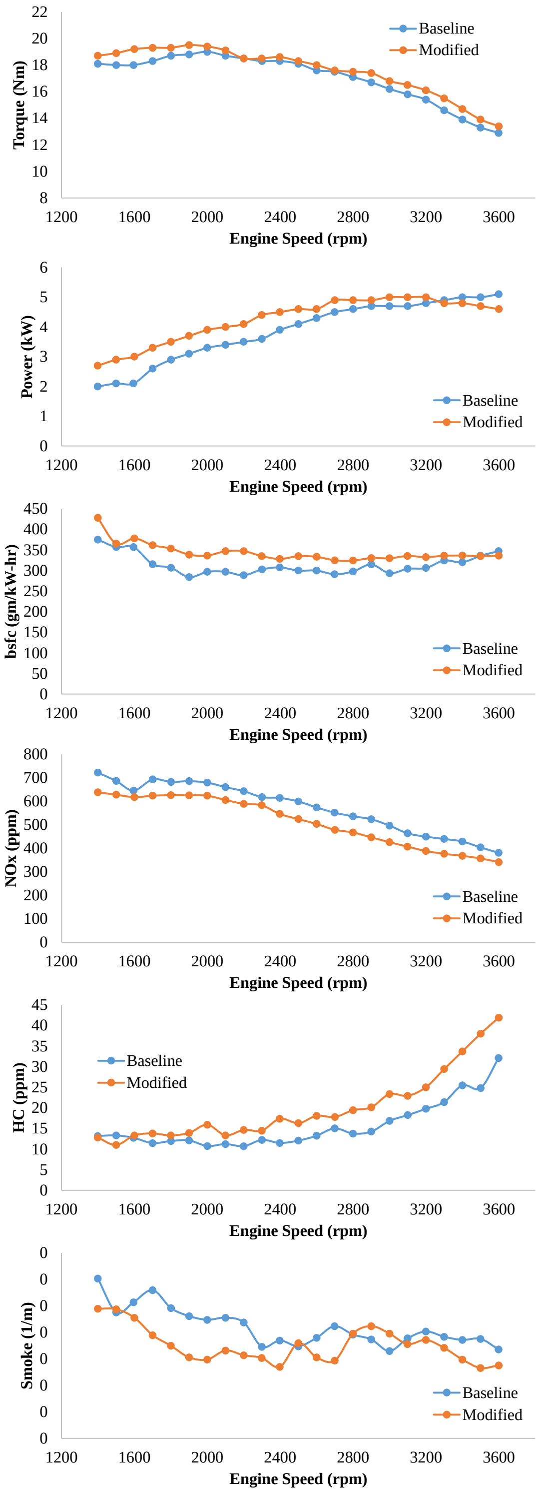

Figure 10. Comparison of performance characteristics for baseline engine under the full-load condition

Effect on engine in-cylinder pressure measurement

With the lower ID high-pressure pipe and retarded injection timings, the injection pressure and in-cylinder pressure increased by 23 bar and 5.5 bar respectively at full load condition compared to the baseline engine. This improvement helped in performance and emission improvements. Figure 11 shows the in-cylinder Pressure vs crank angle and line pressure Vs crank angle for baseline and modified engine for in-cylinder pressure and line pressure.

Due to retarded injection timing and lower internal diameter injection pipe, in-cylinder pressure is increased. This also increases the combustion temperature; however, advance IVO timing helped in the reduction of NOx emission [23].

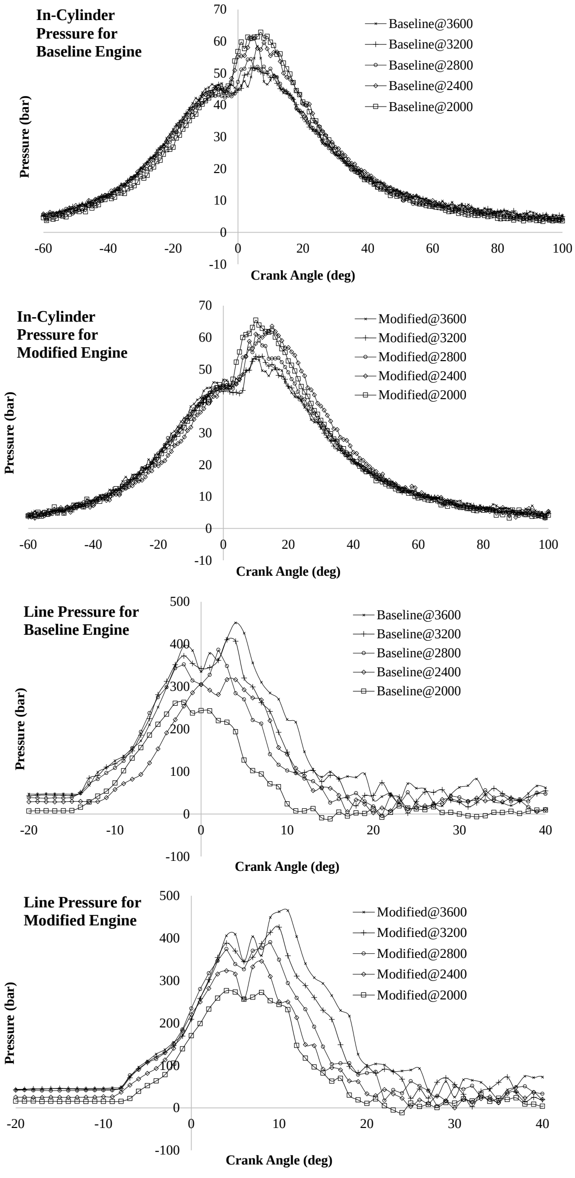

Figure 11. In-cylinder pressure and line pressure for baseline and modified engine at various speed and full-load

Effect of EGR on performance and emission

The baseline emission pattern of the vehicle showed that emissions are higher at cold soak and low initial temperature conditions. With modifications in Swirl, IVO, and retarded injection timings, significant reductions in NOx and smoke level on the engine are achieved; however, these modifications are not able to resolve low initial temperature conditions. A further modification is required to reduce emissions, meet upcoming emissions norms, and load on after-treatment devices. EGR technique is used for the reduction of NOx emissions as it is well established for a significant reduction in NOx emissions [16]. There is always a trade-off between NOx emission and PM emission. To reduce both the parameters we need to achieve the best possible combination of EGR along with swirl, IVO and injection strategies. Two strategies were used for EGR; in the first one, no EGR is supplied at full throttle condition and EGR starts with 80% throttle. The drawback of this strategy is, at lower speeds due to lower pressure difference the EGR quantity requirements are not sufficient. In the second strategy, EGR starts with 100% throttle condition with a drawback of lower BSFC and engine performance due to lower availability of oxygen at rated speed conditions. The only drawback of this strategy is performance drop, as the engine does not need EGR at rated speed due to the requirement of fresh air availability. Being a small single-cylinder engine second option was adopted as the engine is working most of the time at 75% load condition [3]. A detailed study is carried out with different EGR rates.

With the supply of EGR, there is a drop in volumetric efficiency as exhaust gases mix with fresh air and reduce fresh air availability. The temperature of the incoming air also increases and this further reduces the volumetric efficiency of the engine. As the fresh intake flow of air is decreased the engine performance gets deteriorated. Hence selection of EGR rate is done based on minimum deterioration in engine performance with maximum benefits in terms of emissions. Figure 12 shows the adaptation of the EGR in the engine, while Figure 13 shows the effect of various EGR hole sizes on the bsfc of the engine. There is always a general trend of increase of BSFC with increase in EGR supply rate; this is due to a decrease in the fresh air availability. Engine performance gets affected by higher EGR rate and more fuel needs to be injected to get more power; however due to limited fresh air availability this leads to higher emission compared to performance enhacement. With optimise swirl, retarded injection timing and lower ID high pressure pipes; combustion quality can be improved, which leads to improvements in BSFC trends. Same is visible for 6 mm and 10 mm EGR rate, where BSFC is lower compared to 5 mm and 7 mm EGR rate. EGR with a hole size 10 mm gives around 25% EGR rate while EGR with a hole size of 3 mm gives around 3% EGR rate.

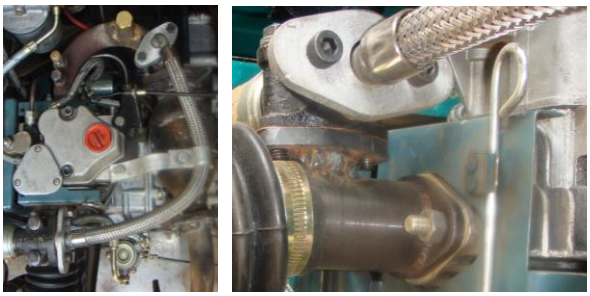

Figure 12. Adaptation of EGR on the modified engine

Trends for engine NOx emission under different loads for different EGR rate is shown in Figure 14. EGR rate affects fuel-air interaction due to the lower availability of fresh air. An increase in EGR rate delays the combustion and helps in the reduction of combustion temperature. This lower temperature is an unfavorable conditions for NOx emission formation and thus helps in the reduction of NOx emission. With an increase in engine torque, NOx emission increases; however, a higher EGR supply rate reduces peak torque values. Different EGR rates along with lower swirl, SIT and hpp have different effects on NOx emissions, as it is reduced by 60-180 ppm at various speed ranges. This reduction is higher for intermediate and higher speeds. With a higher EGR rate, engine peak torque is also reduced by 6%. These results trends are in line with the results of Kaleemuddin and Rao [3].

Effect of temperature on NOx emission for different EGR rates is shown in Figure 15. Due to lower swirl, retarded timings and lower ID high pressure pipes along with EGR has shown reduction of NOx emission and temperature for EGR hole size of 10 mm; however this has penalty in engine Torque (Figure 14). For hole size of 6 mm, the NOx emission is maximum along with high temperature lower BSFC (Figure 16), this is due to baseline cylinder head, advanced timings and lower ID high pressure pipes. This give more timing for mixing and better combustion; however penalty in NOx emissions.

Effect of Hydrocarbon emission also increased compared to the baseline engine for all the EGR rate; higher unburnt hydrocarbon due to improper combustion is the reason for this higher emission. While analyzing the CO and HC emission comparison for various EGR rates, it was observed that with an increase in the EGR rate, the HC emission initially increases then decreases till a certain EGR rate and further increases. This follows a complex trend and this is due to fuel-air mixture formation and air quantity availability at various EGR rates as shown in Figure 17 [18, 24]. The effect of CO emission with various EGR rates is shown in Figure 18. It increases initially with a lower EGR supply rate, however, it reduces for 10 mm orifice EGR supply rate. CO emission further can be reduced with the use of diesel oxidation catalysts (DOC) on the vehicle level, which is a very cost-effective solution for the reduction of CO emission.

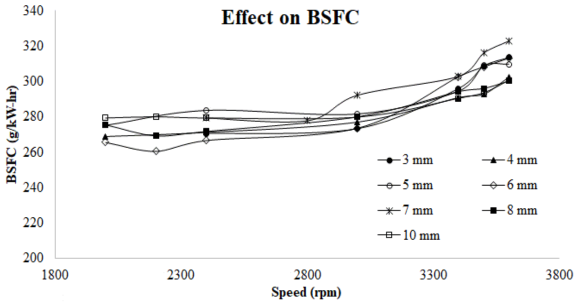

Figure 13. Effect of various EGR rate on BSFC at full-load

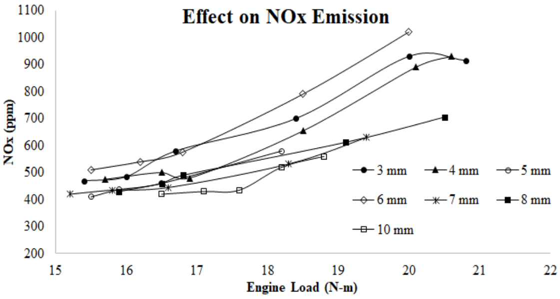

Figure 14. Load Vs NOx emission effect for various EGR rate on at full-load

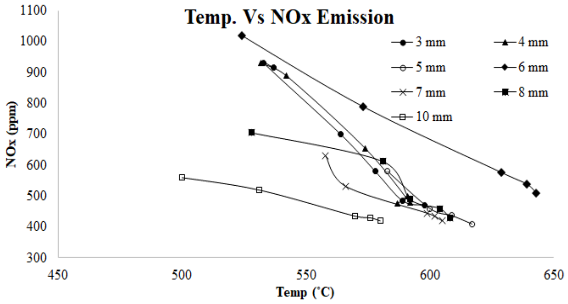

Figure 15. Temperature Vs NOx emission effect for various EGR rate on at full-load

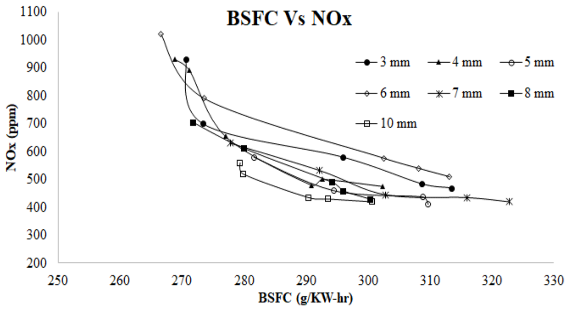

Figure 16. BSFC Vs NOx emission effect for various EGR rate on at full-load

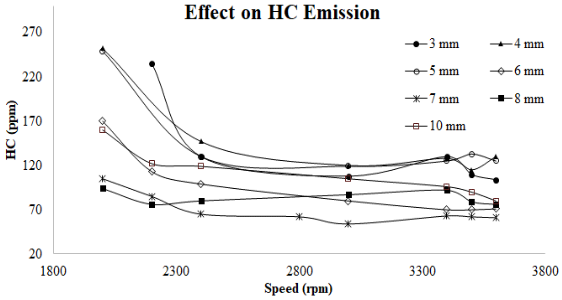

Figure 17. HC Vs BSFC emission effect for various EGR rate on at full-load

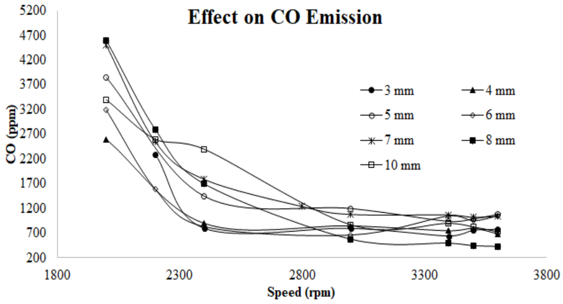

Figure 18. CO emission effect for various EGR rate on at full-load

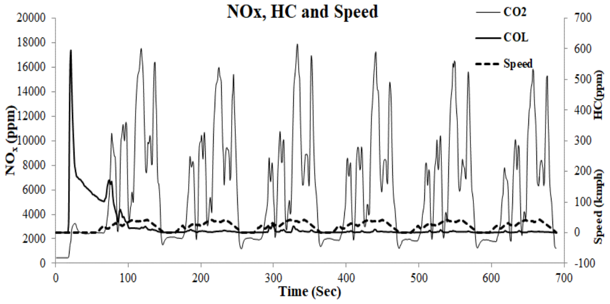

Figure 19. Vehicle NOx and HC emissions with modified engine

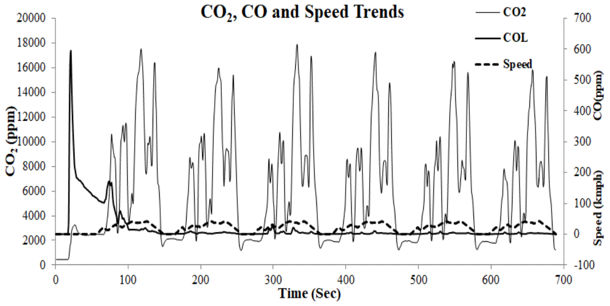

Figure 20. Vehicle CO_2 and CO emissions with modified engine

Table 2. Emission results of Baseline and Modified Engine

	CO	HC+NOx	PM
Limits BSIII (g/Km)	0.5	0.5	0.05
Baseline Results (g/Km)	0.159	0.61	0.04
Limits BSIV (g/Km)	0.345	0.38	0.0354
Limits BSVI (g/Km)	0.2	0.2	0.0208
With Modified Engine (g/Km)	0.141	0.32	0.032

Performance tests on modified engine on the chassis dynamometer

The upgraded engine was mounted on the vehicle and emission is measured. Due to the advanced injection timing of the baseline engine, HC and CO emissions are lower. With retarded timing for the modified engine, it is observed that even though there is an initial increase of 200 ppm in CO emission and 70 ppm in HC emission for the first 2 cycles (after Cold soak), the overall emissions are much lower for the remaining cycles as shown in Figure 20. NOx emission has lower values throughout the cycle due to the EGR strategy as shown in Figure 19. It is reduced by 48% compared to the baseline engine. These trends are in line with the results of Kaleemuddin and Rao [3].

Vehicle HC, NOx emission is reduced, with increases in CO emission. PM emission also reduced slightly. As there is a significant reduction in NOx emission levels, hence it can be concluded that EGR with a 10 mm orifice size has worked well. Engine torque is reduced by approximately 6%, which can be further improved with combustion optimization and fuelling.

The performance and emission traces of the modified engine shows an improvement of emission with a slight reduction in performance compared to the baseline engine as mentioned in Table 2. With retarded injection timings and higher EGR levels with 10 mm orifice size, the CO emission is increased, which is easier to control with the use of after-treatment and cost-effective solutions. With the modified engine, it is observed that with higher EGR levels as well, there is a marginal reduction of PM levels.

Thus, modified engines have achieved a 48% reduction in HC + NOx, 20% improvement in PM, and 11% improvement in CO emission. As baseline CO values are already under the limit for BSIV emissions norms, values for the modified engine are also well within the limit for BS-VI emission norms. Engine HC + NOx emission needs further reduction by another 37% to meet BS-VI emissions norms along with PM emissions. Hence with this modification strategy, we have achieved BSIV norms without modifying the combustion chamber and the injection system. Further modifications on these parameters will be taken up to reduce the engine-out emissions to the lowest possible limit.

CONCLUSION

Modifications are carried out on the engine with a conventional strategy to reduce the engine-out emission, dependency on after-treatment devices and to meet emission norms on existing engines. The performance and emission measurement trials are carried out on the engine dynamometer and chassis dynamometer. The following conclusions are arrived at based on the experimental studies with modifications on intake valve opening timings, higher fuel line pressure, lower Swirl, and EGR adaptation to achieve lower NOx CO and HC emissions at the vehicle level. The trends of various emissions presented in the above work have shown agreement with the previous research work and literature. The conclusions that emerged from the study are given below:

1. Cylinder head Swirl is an important parameter affecting the NOx emission. Lower Swirl with retarded injection timings delays the combustion, which increases in-cylinder pressure and temperature abruptly. This also helps in the reduction of NOx emissions.
2. Advanced IVO timings help in controlling the fresh air available in the combustion chamber by mixing exhaust gases with fresh air. This reduced the volumetric efficiency of the engine.
3. Lower internal diameter high-pressure pipes help in higher injection pressure and this helps in reduction in PM emission; with higher pressure and retarded injection timings have helped in better combustion and thus reduction of NOx and PM emissions.
4. The EGR technique is useful for the reduction of NOx emission; however, a higher EGR rate increases the CO and HC emission. With optimum EGE rate, injection timings, and Swirl, NOx and PM emission can be controlled. In the present case with a 10 mm orifice size 48% reduction in NOx emission is achieved.
5. A Higher EGR rate leads to limited availability of fresh air in the combustion chamber and this deteriorates the performance at rated engine speed.
6. The vehicle has successfully complied with BS-IV emission norms on the chassis dynamometer with the upgraded engine and shows improvements in emissions; however further reduction can be achieved by optimizing the combustion chamber, injection system, and after-treatment system.

ACKNOWLEDGMENT

The authors would like to thank HoD and the Department staff of the Powertrain Engineering Department (PTE) of the Automotive Research Association of India (ARAI), Pune, India for their support to carry out present research work.

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Persian Abstract

چکیده

موتورهای کوچک دیزل بدون اینکه مانعی در عملکرد و مصرف سوخت ایجاد کند چالشی بسیار دشوار برای مواجهه همزمان انتشار NOx و انتشار ذرات معلق می‌باشند. .تجدید نظر مکرر در قوانین انتشار گاز برای موتورهای کوچک دیزلی کار را دشوارتر می‌کند؛ زیرا آنها باید در طراحی و احتراق به‌روز شوند. این موتورهای کوچک با ظرفیت کم عمدتا در مناطق خاص/کشورها مورد استفاده قرار می‌گیرند که هزینه نقش اصلی را ایفا می‌نماید. از این رو، این موتورها فاقد استراتژی مشخص کاهش انتشار هستند. لازم است استراتژی کاهش انتشار با توجه به فناوری‌های موجود و پیامدهای هزینه آن تدوین شود. هدف از پژوهش فعلی توسعه یک استراتژی کاهش انتشار با صرفه‌جویی در موتور با استفاده از فناوری‌های متداول است. کار حاضر یک مطالعه تجربی از اثر چرخش سرسیلندر، زمان تزریق استاتیک (SIT)، باز شدن دریچه ورودی (IVO) و گردش مجدد گاز اگزوز (EGR) بر عملکرد و انتشار موتور دیزل تک سیلندر ۰/۴ لیتری است. میزان HC + NOx و انتشار ذرات معلق در وسیله نقلیه پایه (PM) به ترتیب ۰/۶۱ گرم در کیلوگرم و ۰/۰۴ گرم در کیلوگرم است که با توجه به هنجارهای انتشار فعلی و آتی، این میزان بالاتر می‌باشد. سرسیلندر چرخش پایین، زمان‌بندی پیشرفته IVO با زمان تزریق عقب مانده، کاهش ۱۸ درصدی در انتشار NOx با بهبود ۳ درصدی عملکرد در دینامومتر موتور را نشان می‌دهد. نرخ‌های مختلف چرخش گاز اگزوز نیز مورد مطالعه قرار گرفت و تأثیرات آن بر میزان انتشار و مصرف سوخت و میزان انتشار تجزیه و تحلیل گردید. میزان چرخش گاز اگزوز ۲۵٪ با IVO پیشرفته ۱۶ درجه با SIT 5 درجه و ۱/۹ چرخش سیلندر چرخشی ۴۸٪ بهبود در انتشار HC + NOx ، ۲۰٪ بهبود در انتشار PM و ۱۱٪ بهبود در انتشار CO از دینامومتر شاسی را نشان داد.