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Design and Performance Optimization of Off-highway Diesel Engine with Mechanical Fuel Injection Equipment for TIER-IV Emission Norms

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ABSTRACT:

The two cylinder diesel engines are most demanding product in Indian market for power genset and tractor applications. But major task faced by engine manufacturers all over the world is to upgrade running engine designs with minimum and cost-effective modifications to meet the next level of emission norms. This saves the precious lead time and investments. In addition uncomplicated design has to be sustained as far as possible while improving emissions. Further the basic desires of the end user in off-road market are good response, transient performance, better low end torque, best fuel efficiency and smooth operation of the engine besides best in class reliability. Additional requirements needed to sustain the market with higher power to weight ratio and increased life of the engine. Henceforth turbocharging applications for off-road diesel engines are promising solution for enhancing rated power, low speed torque, transient performance, optimized fuel efficiency and engine downsizing. A trade-off is required to match some incompatible design issues like overall dimensions, cost, emissions control and performance in order to sustain the existing design. Future diesel engine emission standards will restrict vehicle emissions, particularly nitrogen oxides. In the present work, performance improvement for 1.7L, 2 cylinder in-line naturally aspirated diesel engine with mechanical fuel injection pump for off-road application is developed to contain all needs of the market. Design up-gradation of this engine for Tier IV is made with minimal design changes by optimal combinations of fuel injection equipment. This includes proper optimization of performance with improvements in nozzle geometry, change in injector end pressure. But due to the increased fuel flow rates for improving the engine performance as well as emission reduction, there is also a requirement for increased air flow. Henceforth in this study air flow rate is simulated and discussed for selection of turbocharger and intercooler. Further elaborate design and analysis study is also done on cooled exhaust gas recirculation system for exhaust gas cooling efficiency, Diesel Oxidation catalyst, Selective Catalytic Reduction /Lean NOx Trap substrate selection for reduced pressure drop and maximum retention time for exhaust gas to achieve Tier IV norms in turbocharged intercooled two cylinder engine.

KEYWORDS:

Off-road Diesel engine; Injector; Turbocharger; Intercooler; Exhaust gas recirculation, Selective catalytic reduction

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1. Introduction

Regulations are set worldwide to impose more restrictions on the emission levels for certification of diesel engines in various applications. The main challenge is to accomplish the new requirements, which involve the concurrent reduction of particulate matter and oxides of nitrogen - NOx [1]. A reduction in NOx is usually achieved at the disbursement of increase in smoke, which makes the development work yet more thought-provoking [2]. It is mostly acknowledged that the injection nozzle flow exit characteristics strongly affect the performance and exhaust emissions of direct injection diesel engines by controlling the atomization process of the injected fuel and the consequent spray formation. Amid others, the shape and manufacturing of tapered nozzles with smaller hole sizes to be developed to fulfil future emissions legislation [1]. Working with parameters such as combustion space and nozzles are also listed as one of the means to optimize large engines for lower engine-out NOx. Amongst several methods applied for particulate matter reduction over the years, one among them is the optimization of the combustion and fuel injection [3, 4].

Sarvi and Zevenhoven [5] state that the number of nozzle holes has an effect on emissions and specific fuel ingesting in a large medium-speed engine. In recent years, the orifice diameters of injection nozzles have decreased gradually. The target is to reduce the fuel droplet size. However, effects are not only been unambiguous since in some cases larger droplets are associated with less rather than more soot: greater momentum ensures a more deeply penetrating spray and improved air consumption [6]. Nevertheless, a reduced orifice diameter with an improved spray quality facilitates high power densities with very low emissions when simultaneously combined with significantly increased pressures according to Tang et al [7]. Therefore turbocharging is an imperative step to increase power density and meet future emission norms in a small single and two cylinder loads as well as passenger carrying vehicles in developing countries, which are typically naturally aspirated and usually incapable of achieving emissions norms. For a small engine delivering a specific power of less than 50kW/L, a waste gate turbocharger may be used [8].

Waste gate turbochargers provide a cost effective solution to increase the peak power, torque output and reduce the smoke and particulate matter emissions [9]. But matching the turbine and compressor diameter with the air flow requirements of the engine is crucial. Larger compressor housings give more air flow at higher speeds but have an adverse effect at low speed part load points. Larger turbine housing diameters improve air flow and specific fuel consumption at higher speeds because of lower pumping losses [10]. However, the application of too small turbine inlet area can cause a series of unusual phenomena, such as increased exhaust back pressure, which-especially at higher engine speeds-lead to increased fuel consumption. On the contrary, wide waste-valve will result premature opening of the waste-gate valve before and during higher engine operational conditions. This usually will affect the unfavourably the vehicle operational performance and durability as well as the fuel injection system influences the engine performance. The integration of a fuel control device becomes necessary. In order to achieve the compromising solution of the performance parameters of the turbocharger components and the engine, the engine optimization methods were considered.

This study concentrated on investigating the effects of the injection nozzle parameters on the performance and exhaust emissions of off-road diesel engine and requirement of a turbocharger and intercooler injection system. The main aim is to optimize the injection pressure, hole size of the injector and spray cone angle to keep the engine-out emissions and fuel consumption low. But the optimization of the engine itself is not sufficient when aiming at the very low emissions for upcoming off-road engine Tier IV emissions legislation with an output of more than 25kW. Further the strategies for meeting the emissions reduction after-treatment techniques are computationally design optimized. One alternative will exploit cooled Exhaust Gas Recirculation (EGR) and Diesel Oxidation Catalyst (DOC). The other option relies on the use of a catalyst based on selective catalytic reduction(SCR) of NOx.

2. Experimental setup

Fig. 1 shows the naturally aspirated engine set up with radiator system for cooling. Tables 1 and 2 show the specifications of injection system and intercooler selected for this study. Fig. 2(a) shows the combustion chamber design and injector installation.

Fig. 1: Naturally aspirated engine setup

Table 1: Specifications of injector

Hole Size (mm)	Cone Angle (Degree)	No. of Spray holes	Pressure, bar
0.220	146p	5	220/240/250
0.262	146p	5	220/240/250

Table 2: Specifications of intercooler and engine

Specification	Value
Inter cooler design type	Cross flow heat exchanger – water spray cooled
No. of air tubes	9
Inner fin pitch	3.5mm triangular
Pressure drop	3.8 kPa
Outside fin pitch	4.5 mm
OFA	3.71 m^2
Engine stroke	127 mm
Engine bore dia.	91.44 mm
Engine compression ratio	18.5:1
Engine No. of valves	2
Inlet valve open	13 deg BTDC

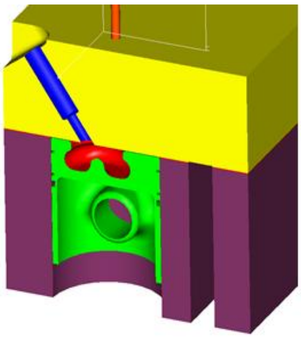

Fig. 2(a): Design of combustion chamber and injector installation

Fig. 2(b) shows the passage and flush mounting sensor installation arrangement. Based on natural frequency of passage (passage resonance), 3mm clearance between sensor and combustion gas is considered for this flush mounting installation to collect the cylinder pressure data. Fig. 2(c) shows the waste-gate turbocharger and intercooler installation on the engine. Fig. 3 shows EGR installation set up. With external engine control unit (ECU) support, signals are given to electronic vacuum modulator, this further actuate the EGR valve to open. The hot gases then pass through EGR cooler for hot exhaust gas cooling.

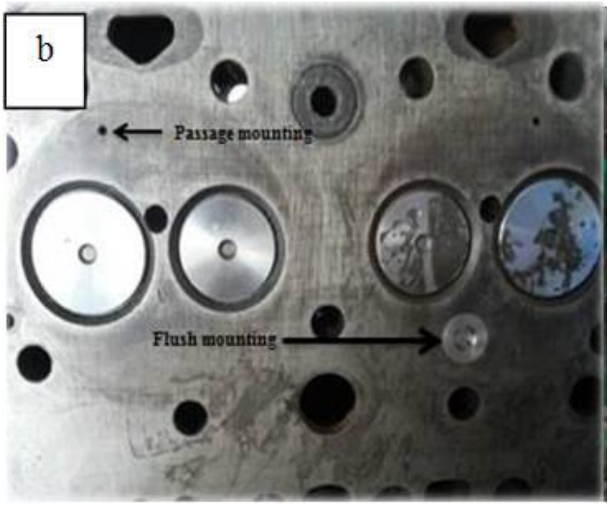

Fig. 2(b): Combustion sensor installation

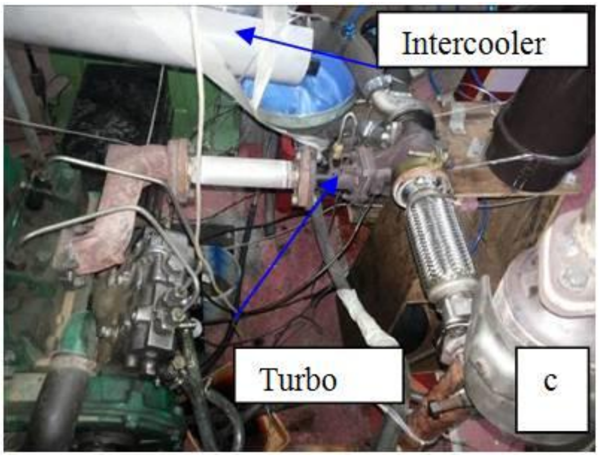

Fig. 2(c): Waste-gate turbocharger and intercooler installation

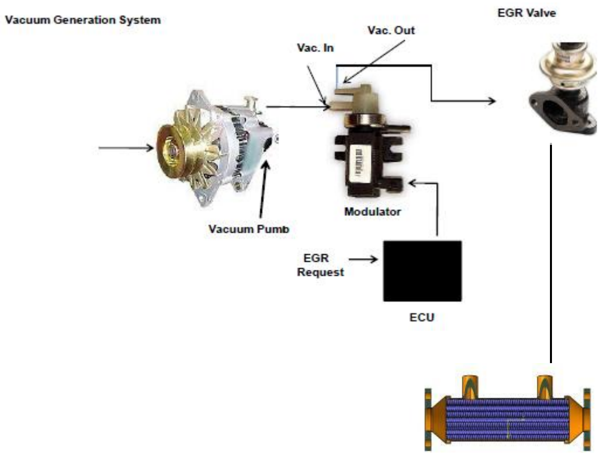

Fig. 3: External ECU control for pneumatic cooled EGR system

3. Results and discussions

Fig. 4 shows the engine power produced by varying the injector pressure and nozzle hole size. The base nozzle is 220 bar pressure with 0.22 mm hole diameter. The modified nozzle with 0.26 mm hole size with 250 bar pressure provides 20% improvement in power when compared with base engine at 100% throttle. These injection nozzle flow exit characteristics strongly affect the power performance of direct injection engines by controlling the atomization process of the injected fuel and the subsequent spray formations. Same trend is observed at part throttle. Fig. 5 shows the engine torque produced by varying the injector pressure and nozzle hole size. The modified nozzle with 0.26 mm hole size with 250 bar pressure provides 19% improvement in torque when compared with base engine at 100% throttle. Same trend is observed at part throttle.

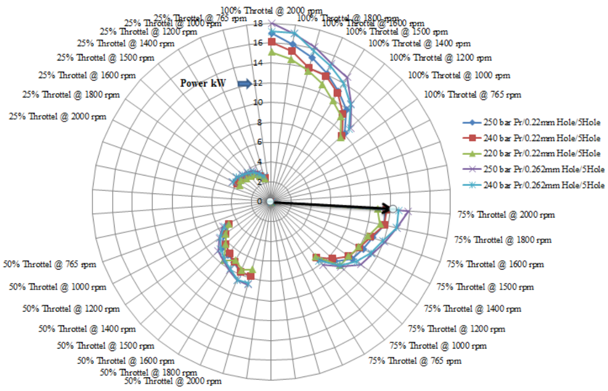

Fig. 4: Engine power comparison in full load and part load

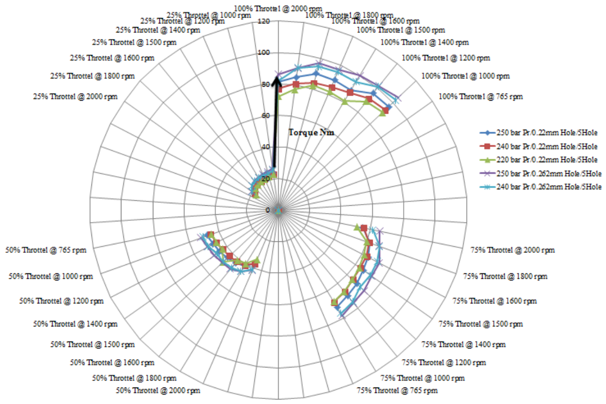

Fig. 5: Engine torque comparison in full load and part load

Fig. 6 shows the engine combustion pressure produced by varying the injector pressure and nozzle hole size. The modified nozzle with 0.26 mm hole size with 250 bar pressure provides 10% improvement in combustion pressure when compared with base engine at 100% throttle. Same trend is observed at part throttle.

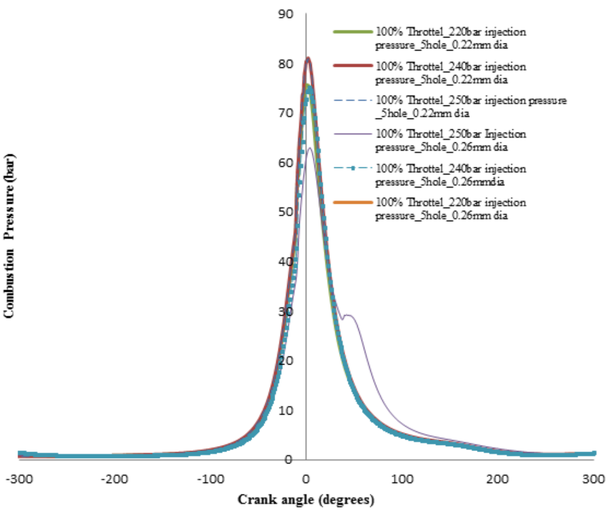

Fig. 6: Combustion pressure comparison at full load with only injector parameters changes

Fig. 7 shows the engine exhaust temperature produced by varying the injector pressure and nozzle hole size. The modified nozzle with 0.26 mm hole size with 250 bar pressure provides 12% improvement in exhaust temperature when compared with base engine at 100% throttle. Same trend is observed at part throttle. Fig. 8 shows the engine out NOx produced by varying the injector pressure and nozzle hole size. The base nozzle is 220 bar pressure with 0.22 mm hole diameter. The modified nozzle with 0.22 mm hole size with 250 and 240 bar & 0.26 mm hole size with 250, 240, 220 bar pressure are investigated. In which base nozzle is only giving less NOx emission when compared to other nozzle parameters. Next lowest is 250 bar with 0.22 mm hole nozzle at full throttle condition. Fig. 9(a) and (b) show the engine out smoke produced by varying the injector pressure and nozzle hole size. Similar trend as in NOx emission is observed for the engine out smoke.

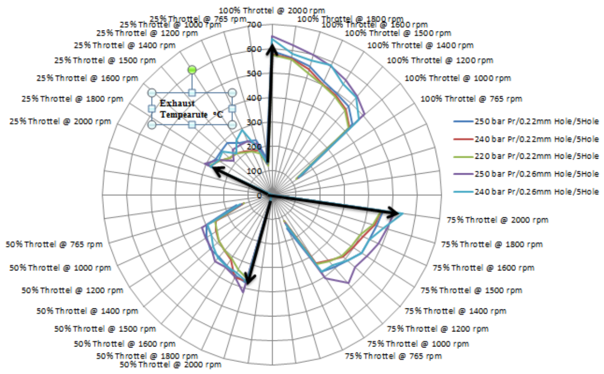

Fig. 7. Engine exhaust gas temperature comparison in full load and part load

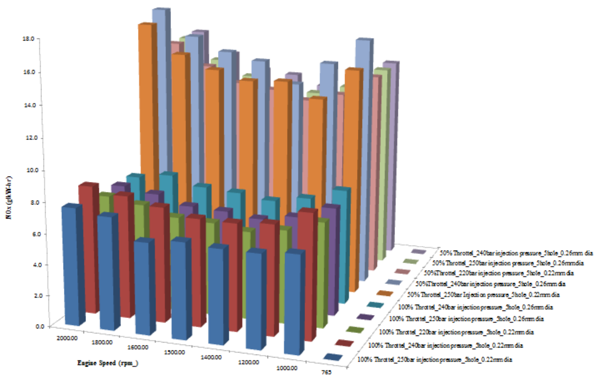

Fig. 8: NOx emission comparison in full load and part load

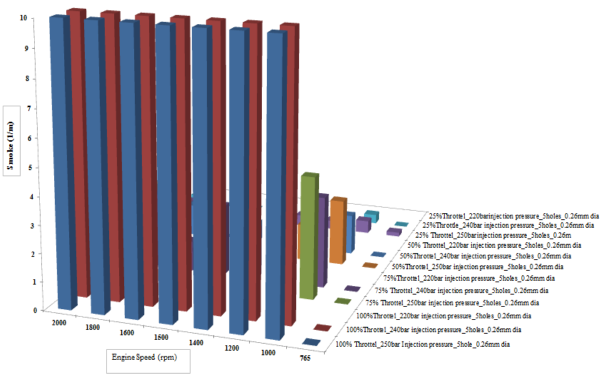

Fig. 9(a): Smoke comparison in full load and part load for 0.26mm dia. hole size

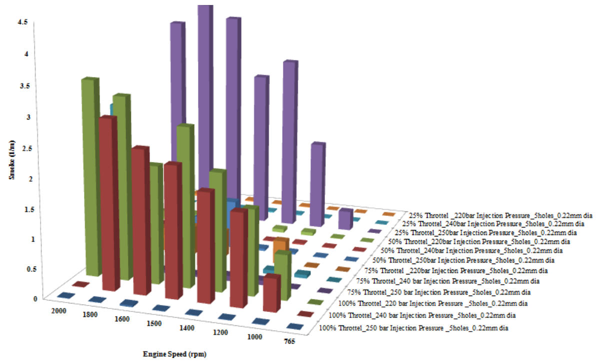

Fig. 9(b): Smoke comparison in full load and part load for 0.22mm dia. hole size

Based on simulation 20% air flow improvement is required from turbocharger (see Fig. 10) with turbine wheel diameter of 31 mm & compressor wheel diameter of 33 mm for improving the combustion due to increased fuel flow rate as well as for decreasing the emissions. Hence proper tuning of waste gate setting to be ensured further. Fig. 11 shows the simulation results of coolant flow and exhaust gas cooling efficiency of above 75% is targeted for these applications, based on this 900 L/hr (15LPM) coolant flow rate to be selected to avoid boiling risk. Fig. 12(a) to (d) show the coolant flow optimization based on hot spot formation inside EGR cooler. From the temperature distribution plots, 12LPM shows more hot spots at higher temperatures than other LPM's. For the 15LPM coolant flow lesser hot spots compared to 12LPM at certain locations on the cooler pipes. Coolant flow with 18 and 21 LPM is best. But comparing coolant flow rate condition 15LPM is optimum flow for this EGR cooler. Further ±10% variation can be expected compared to actual conditions.

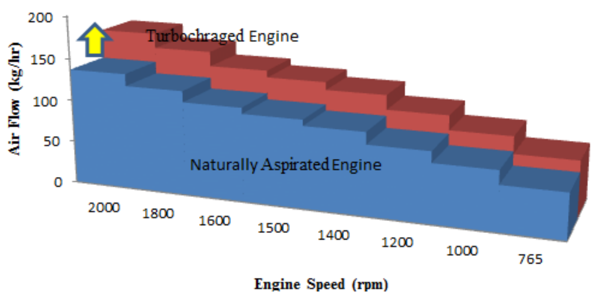

Fig. 10: Target air flow for turbocharged engine

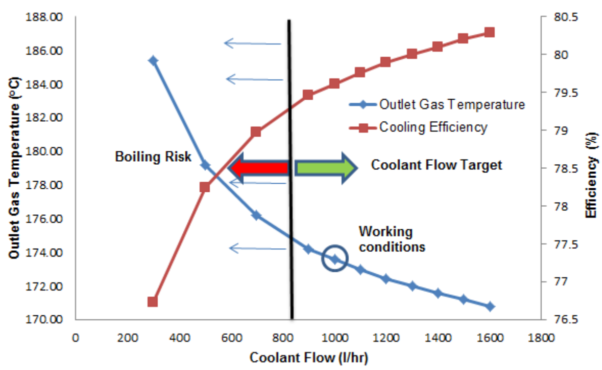

Fig. 11: Coolant flow vs. Efficiency for EGR cooler system

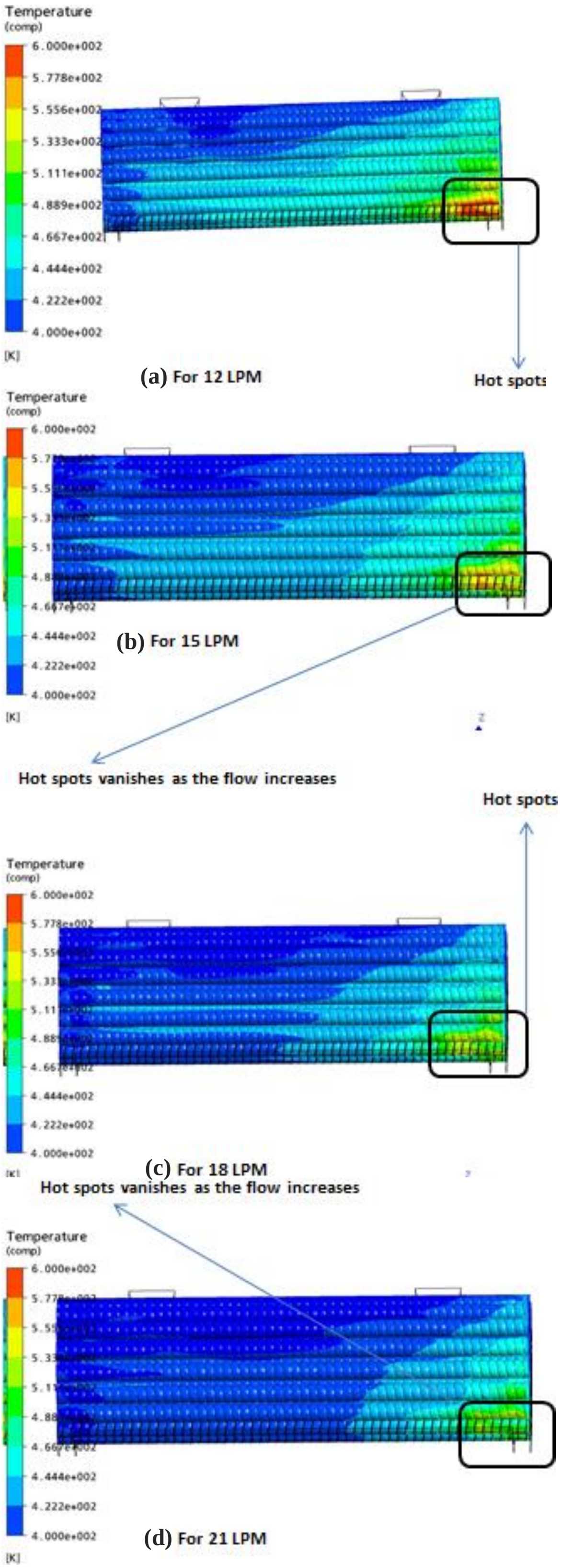

Fig. 12: Hot spot comparison vs. Coolant flow for EGR cooler

Fig. 13 shows the simulation results of substrate volume and pressure drop. Based on simulation target of lesser than 25 mbar and volume of 0.6 L is selected for diesel oxidation catalyst. For SCR/LNT applications, 2 to 2.4 L volume with pressure drop lesser than 15 mbar is selected. Substrate for these applications has 400 cells per square inch and 4.5 mm wall thickness. Fig. 14 shows the simulation results of catalyst volume at the maximum exhaust flow for the engine. This simulation helps to select best substrate volume on low temperature performance at high exhaust flow rate condition. The space velocity for DOC and SCR/LNT applications are above 1750000/hr and 45000/hr respectively.

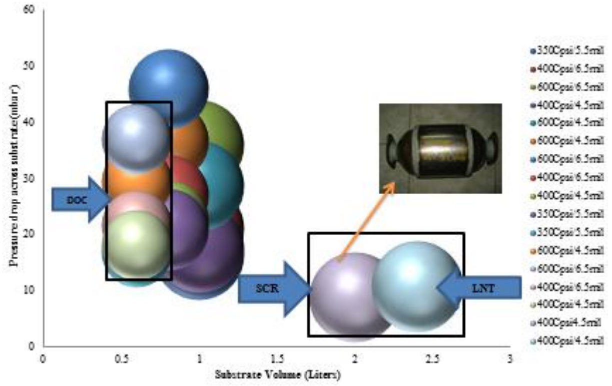

Fig. 13: DOC/SCR/LNT substrate volume vs. Pressure drop

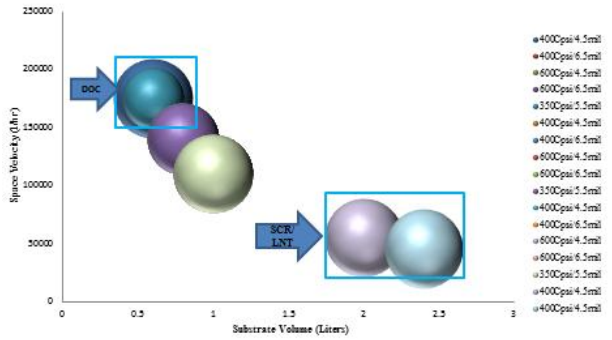

Fig. 14: DOC/SCR/LNT substrate volume vs. Space velocity

4. Summary

The effects of the injection nozzle parameters on the performance and exhaust emissions of off-road diesel engine with a turbocharger and intercooler injection system are investigated through experimental study. In terms of power 0.26 mm nozzle at 250 bar pressure provide 20% improvement in power and 19% improvement in torque when compared to base nozzle. This increase is due to 18% increase in hole diameter as a result fuel flow increased 23% at rated speed condition. Combustion pressure and exhaust gas temperature for 0.26mm nozzle at 250 bar pressure is improved by 10% and 12% respectively when compared to base nozzle. Smoke & NOx is less for 0.22 mm hole injector when compared to 0.26 mm hole. Hence more air supply is required with turbocharger for improving the combustion when using 0.26mm nozzle. EGR cooler with 75% cooling efficiency as well as with 0.6L DOC can be used for NOx emission during low NOx conversion. If more NOx conversion is required SCR/LNT will be used along with DOC based on simulated substrate volume for meeting Tier IV requirements.

REFERENCES:

[1] M. Gavaises. 2008. Flow in valve covered orifice nozzles with cylindrical and tapered holes and link to cavitation erosion and engine exhaust emissions, *Int. J. Engine Res.*, 9(6), 435-447. http://dx.doi.org/10.1243/14680874 JER01708.

[2] C.R. Ferguson and A.T. Kirkpatrick. 2001. *Internal Combustion Engines: Applied Thermoscience,* 2nd Edition, John Wiley & Sons Inc, USA.

[3] J. Pagni. 2008. Meeting and exceeding emissions regulations, *Twentyfour 7*, 4.08, 41-44.

[4] A. Mayer. 2008. *Particle Filter Retrofit for all Diesel Engines*, Expert Verlag, Germany.

[5] A. Sarvi and R. Zevenhoven. 2008. Large-scale Diesel Engines Emission Control Parameters. *Proc. ECOS*, Cracon-Gliwice, Poland.

[6] P. Eastwood. 2008. *Particulate Emissions from Vehicles*, John Wiley & Sons Ltd, UK.

[7] J. Tang, S. Pischinger, U. Grutering and J. Keck 2008. Effects on deposit formation in injection nozzles of direct-injection diesel engines, *MTZ*, 69(9), 754-761.

[8] K.C. Vora, S.S. Ramdasi, N.H. Marathe and A.V. Marathe. 2009. Development strategy for high specific power low emission diesel engines, *SAE Technical Paper 26-0020*.

[9] S.A. Niemi, J.M. Lauren and T.T. Murtonen. 2002. Effect of waste-gate turbocharging on the exhaust particulate matter of an off-road diesel engine, *SAE Technical paper 01-2159-(2002).*

[10] R. Padmavathi, K. Nandhakumar and P. Daithankar. 2010. Effect of turbocharging geometrical configurations on engine performance and emissions, *Proc. 10th Int. Symp.*, Stuttgart, Germany.