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Effect of Exhaust Back Pressure on Performance and Emission Characteristics of Diesel Engine Equipped with Diesel Oxidation Catalyst and Exhaust Gas Recirculation

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ABSTRACT:

Currently the emission norms are becoming more stringent, continuous modifications are taking place in existing I.C engines as well as in after treatment devices (ATDs). Exhaust Gas Recirculation (EGR) and Diesel Oxidation Catalyst (DOC) are the mandatory ATDs controlled electronically to optimize engine brake power, fuel consumption and emissions. The conversion efficiency of ATDs mainly depends on exhaust pressure, temperature, flow rate and fluid characteristics of exhaust gas. However, the installation of ATDs increases the exhaust back pressure in the exhaust system. The back pressure of engine also depends on the parameters like engine operating conditions, design of exhaust valves, valve lift time, exhaust gas dynamics and exhaust manifold design etc. In this paper the attempt is made to study the effect of back pressure on performance and emission of diesel engines equipped with EGR and DOC. Here we have not modified the intake and exhaust valves instead, we varied the back pressure of exhaust system using back pressure control valve (BPCV). BPCV is operated manually at three positions, they are 100%, 87.5% and 75% BPCV lifts. The readings are taken in different combinations of BPCV lifts and brake torque at 20, 40, 60, and 80 N-m. The results obtained shows variation of BPCV lift and brake torque effected on performance of engine, DOC and EGR operations as well as fuel consumption. The NO_x is reduced by 15%; HC and CO are reduced significantly. However, there is an increase in brake specific fuel consumption (BSFC) and exhaust smoke.

KEYWORDS:

Back pressure; Valve lift; Brake torque; Internal EGR; Back pressure control valve; NO_x

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ABBREVIATIONS:

DOC	Diesel Oxidation Catalyst
ATDs	After Treatment Devices
EGR	Exhaust Gas Recirculation
BSFC	Brake Specific Fuel Consumption
BP	Back Pressure
BPCV	Back Pressure Control Valve
SCR	Selective Catalytic Reduction
VGT	Variable Geometry Turbocharger
BMEP	Brake Mean Effective Pressure
PM	Particulate Matters
CR	Compression Ratio
HC	Hydro Carbon Emission
NO_x	Oxides of Nitrogen

1. Introduction

Emissions are inevitable. The stringent emission norms have become driving force for the development of new engine technologies and ATDs, which have certainly reduced emission level in I.C engines. The ATDs like DPF, EGR, SCR and DOC fitted to the engine exhaust system to reduce the emission levels [1], these ATDs functions effectively only under certain conditions. EGR is one such ATD where the part of the exhaust gas is recirculated back into combustion chamber via EGR valve, due to which the overall combustion temperature of the engine reduces. The lower combustion temperature reduces NO_x emission. In small diesel engines of off-road vehicles and two/three wheelers, EGR is mounted internally by modifying intake, exhaust valve lift profile and BPCV. Back pressure of the engine exhaust is the gas pressure that is produced by exhaust gases to overcome the fluid resistance to discharge gases to the atmosphere [2]. The variation of back pressure depends on exhaust flow rate, exhaust restrictions created due to mufflers, ATDs and bends in exhaust pipe where the flow is sufficiently turbulent. The pressure drop in exhaust system is proportional to the square of the velocity ($\Delta BP \sim v^2$). For elements such as particulate filters where the flow is laminar, the pressure drop is proportional to the product of dynamic viscosity and velocity ($\Delta BP \sim \mu v$) [3].

During exhaust stroke, in four stroke diesel engine the combusted gas is expelled out of the combustion chamber where, exhaust gas will flow from the region of higher pressure gradient to lower pressure grandniece. The gases coming out are with high pressure, velocity and are harmful. These harmful gases need to be treated before pumping to the environment. Adding ATDs like

DPF, EGR, SCR and DOC certainly decrease the velocity of the exhaust gas therefore it increases the back pressure of the exhaust system [1, 2]. Change in exhaust back-pressure will lead to increase in pumping losses, reduction in intake manifold pressure, effects on scavenging, variation in combustion pressure and leads to turbocharging problems [2]. Therefore, optimum design of exhaust manifold should be taken care to optimize back pressure of the engine to increase performance engine and ATDs [1-5]. All engines have a maximum allowable exhaust back pressure specified by the engine manufacturer. Generally, muffler and DPF create back pressure in the range of 6 kPa. The engine manufacturers like Cummins, Caterpillar and John Deer having engine capacity ranging in the size of 15-1000kW have back pressure limit of 6.7-10.2kPa [2]. Therefore, here an attempt is made to study the effect of back pressure on performance and emission of I.C engine.

Simulations of IVECO cursor (7.79 L, VGT engine) at full load shows that for rich mixture operation with increase in back pressure leads to significant degradation of combustion efficiency, increased in BSFC, increase in exhaust valve temperature and turbine valve temperature with serious engine damage [8]. A simulation of the ECE 40 driving cycle on small IDI diesel engine equipped with internal EGR studied for different valve lift profile, 1D CFD model shows reduction in NO_x by 13% and notable negative effect on fuel consumption, PM/soot emissions [9]. In 12 litres, 315kW, cooled EGR, turbocharged heavy duty engine; the back pressure varied by using variable geometry turbocharger (VGT) or using exhaust BPCV with additional venture mixer positioned near intake manifold such that it gives extra suction power to EGR gas, the results show that there is increase in PM emission however there is reduction fuel consumption [10]. Hino E13C heavy-duty diesel engine, a combination of internal, cooled EGR was employed to reduce NO_x emissions under all engine operating conditions without increasing heat dissipation to engine coolant under high load. With implementation of common rail fuel injection and VGT, PM can be reduced. The cycle efficiency is improved by increasing CR and expansion ratio. Changing piston material to Aluminium alloy reduced heat loss and that showed simultaneous reduction in emissions and fuel consumption [6]. Another study shows that for diesel engine fuelled with methanol with 80 kPa applied back pressure, there was decrease in thermal efficiency and BMEP, this because of pumping loss and reduction in specific heat valve of fuel [11].

There are more literature data on the effect of back pressure on fuel consumption. For the turbocharged engines the increase of fuel consumption per 10kPa back pressure increased from 1.5% to 2.5% and from 3 to 4.5% for naturally aspirated engines and also found that 1.8% increase in BSFC per 10kPa back pressure [1]. In early 1970s it was found that fuel consumption of naturally aspirated engines was more sensitive and their fuel consumption increased by 3% for a 10kPa increase in back pressure however for turbocharged engine increased by 1.5% for every 10kPa increase in back pressure [12]. The variation in back pressure (2.2kPa-10kPa) at rated power in both two stroke and four stroke engines found that there was 1.5% increase in fuel consumption [13]. 2.5% increase in fuel consumption for 10kPa back pressure when vehicle tested on chassis dynamometer. For 10kPa increase in back pressure under same conditions, the fuel consumption increases ranging from 1% for newer engines to 4.5% for older engines [14]. Tests on a Volvo D12D Euro III engine shows that the increase in fuel consumption for a 10kPa increase in back pressure at rated power varied strongly with engine torque and BMEP, the fuel consumption was more at higher load than at lower load condition [15]. Some study also shows that engine output and fuel consumption depend on exhaust flow conditions therefore change in back pressure vary with engine operating conditions. Some have even claimed that fuel consumption is same regardless of speed and load [13].

The exhaust gases like HC, CO, NO_x and PM should be within the standard limit. By changing back pressure of the exhaust system will certainly affect emissions. It is observed that with slight modification in existing ATDs; there will be change in back pressure of the engine. Deutz on a BF6M 1012 Euro I engine [1], the soot increased about 89% per 10kPa back pressure increase, when back pressure exceeded the back-pressure limit for this engine (which was 7.5kPa). It should be noted that the increased emissions may affect operation of ATDs. A 1988 Cummins LTA10 engine equipped with a DPF showed a 23% increase in engine output per 10kPa back pressure. Also increase in PM emissions at rated speed, at 25% load, the back pressure increased from 1.5kPa to 11.3kPa this is due to increase in filter loading over a 10-hour period [16]. From these studies, it is found that increase in back pressure resulted in more emission of PM/ soot, CO and HC [2]. Based on previous study with increase in backpressure there is decrease in NO_x, however there is increase in BSFC, CO, soot [1-8, 13]. The NO_x can be decreased with diesel water emulsion [17]. Based on the previous studies for various engine configurations and test cycles; it is observed that attempt was made to study the variation of back pressure to improve the combustion efficiency, reduce fuel consumption and emissions. An interesting option for small diesel engines is “internal EGR”, which is obtained by modifying the intake or exhaust valve lift profile or exhaust BPCV to increase the fraction of exhaust residuals at the start of the intake stroke.

In this experimental study, D.I diesel engine equipped with internal EGR and DOC. The study aimed to reduce NO_x using internal EGR systems and also to reduce HC, CO using DOC. We know that back pressure of engine exhaust effect on performance of EGR and DOC. With the help of BPCV we have introduced back pressure in engine exhaust manually at three positions (i.e. 100%, 87.5%, and 75% valve opening) under 20, 40, 60 & 80 N-m brake torques and studied its effect on performance, fuel consumption and exhaust emissions.

2. Experimental procedure

The experiments are conducted on a twin cylinder, naturally aspirated, water-cooled, direct injection diesel engine with internal EGR and DOC. The exhaust BPCV is fitted after the DOC and exhaust valve lift and it is controlled manually as shown in Fig. 1. The specifications of the working engine are listed in Table 1 and the actual experimental set-up is shown in Fig. 2. The engine is directly coupled to an eddy current dynamometer using flexible flange coupling and a stub shaft assembly. The output of the eddy current dynamometer is fixed to a strain gauge load cell for measuring load applied to the engine. Exhaust gas analysis is performed using NO_x analyser Series 89 Techno vision, DOC KARTAR and smoke is measured using a smoke meter analyser AVL 437. Fuel flow rate is measured by means of mass flow meter. A hot wire mass airflow sensor determines the mass flow rate of air flowing into the engine's air intake system.

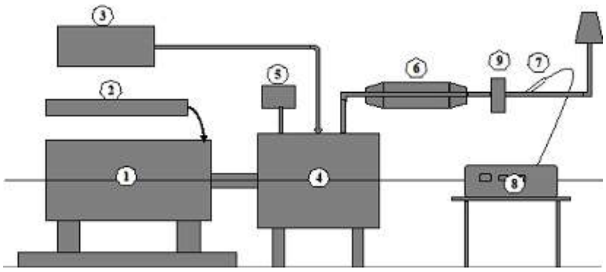

Fig. 1: Layout of engine set up with following details: 1). Magnetic dynamometer, 2). Dynamometer controller, 3). Fuel tank, 4). Engine, 5). Air filter, 6). DOC, 7). Gas analyser probe, 8). Gas analyser, and 9). Backpressure control valve

Fig. 2: Layout of actual engine setup

Table 1: Engine specifications

Engine specification	Value
No. of cylinders	Two
Bore x stroke	102 x 116 mm
Cubic capacity	1.896 lit
Compression ratio	17.5: 1
Rated power	kW @1500 rpm

The engine is started and warmed-up at low idle conditions, long enough to establish the recommended oil pressure and also checked for any fuel, oil and water leakages. After completion of the warm-up procedure, the engine is run on no-load condition and the engine speed is adjusted to rated rpm (1500 ± 10rpm) by adjusting the fuel injection pump. The engine runs to gain uniform speed after which it is gradually loaded. The experiments are conducted for three BPCV lifts viz, 100%, 87.5% and 75% at four brake torque levels viz, 20, 40, 60 and 80 N-m. For each condition the engine is run for minimum period of 6 minutes and data collected during the last 2-3 minutes of operation. Simultaneously, engine exhaust emission (NO_x, CO, HC and smoke) readings are noted using devices listed in Table 2. The experiment trails are repeated thrice and the average value is taken. The experimental results are analysed and discussed.

Table 2: List of emission measuring devices

Name of the device	Model	Specifications
Smoke meter analyser	AVL 437 C	Opacity: 0- 99.99%
NO_x analyser	Series 89 Techno vision	Range: 0- 2000 ppm
DOC	KARTAR	Catalyst: Rhodium, Loading: 5 gms, Mesh type: honeycomb

3. Results and discussions

The engine experiment is carried out to analyse the effect of percentage of BPCV lift on fuel consumption (BSFC) and exhaust emissions like smoke, NO_x, CO, and HC at various load conditions.

3.1. Effect on fuel consumption

The amount of fuel consumed per unit time and unit brake power (BSFC) is measure at three BPCV lift at different brake torques. Fig. 3 indicates variation of BSFC with different brake torque at different BPCV opening condition. As there is a decrease in valve opening, at all load conditions it is found that there is increase in BSFC. Comparing full valve opening at 20 N-m brake torque with 87.5% valve opening, a 2% increase in fuel consumption is observed. However, in comparison with 75% valve opening shows an increase of BSFC by 10%. Similarly, full valve opening results were compared with 87.5% valve opening at 60 N-m brake torque, a 3% increase in BSFC is observed. From the fig.3 it is concluded that with the decrease in valve opening there is increase in BSFC.

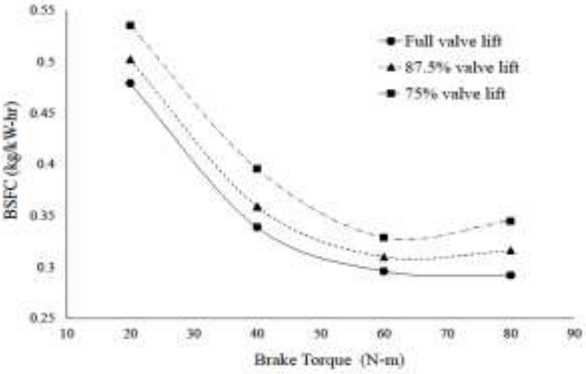

Fig. 3: Effect of percentage of BPCV opening on fuel consumption at various brake torques

3.2. Effect on exhaust emissions

The un-burnt hydrocarbon measured in ppm using AVL gas analyser. In Fig. 4, initially at low brake torque there is less variation of HC under the different BPCV opening conditions. However, as the brake torque increased further, the engine HC emissions found more in case of full valve opening. Comparing full BPCV opening with 75% BPCV opening at 80 N-m brake torque, found 42% reduction in HC is observed. In case of 87.5% BPCV opening and full BPCV opening there is 23% reduction in HC. The graphical trend shows that, initially at low brake torque there is significant difference between HC emissions. In all the three BPCV lifts, it is observed that with increase in brake torque there is an increase in HC emissions. Fig.5 shows the variation of CO with different brake torques at different BPCV opening conditions. At higher torque and full valve opening, CO emissions are higher, as the valve opening decreases the CO emission reduces due to oxidation of CO. As the load increased there is an increase in concentration of CO. There is not much variation in CO emission in the case of full valve and 87.5% valve opening; however, at 60N-m brake torque there is a decrease of 25.5% CO emission in comparison with full valve opening.

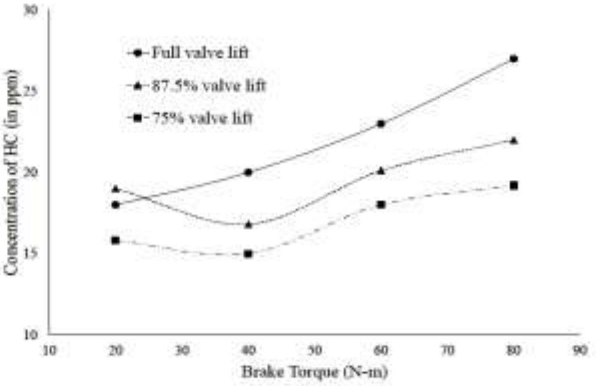

Fig. 4: Effect of percentage of BPCV opening on hydrocarbon emission at various brake torques

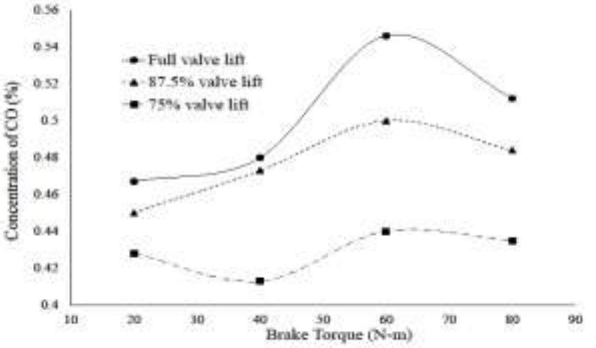

Fig. 5: Effect of percentage of BPCV opening on carbon monoxide emission at various brake torques

Fig. 6 shows the variation of NO_x with different brake torques at different BPCV opening conditions. As the percentage of BPCV opening reduces, NO_x emission reduces at all brake torque conditions. Comparing full BPCV opening and 75% BPCV opening at 60 N-m brake torque, a 25% decrease in NO_x is observed. However, in comparison between full valve opening and 87.5% valve opening, there is decrease in NO_x by 9%. At different torque conditions on an average, there is a 15% reduction in NO_x. Fig 7 shows the variation of smoke emissions with different load at different BPCV opening condition. As the BPCV opening reduces, at all brake torque conditions it is found that there is an increase in smoke concentration. Comparing full BPCV opening with 75% BPCV opening at 20 N-m, an 85% increase in smoke concentration was observed. However, in comparison with full BPCV opening at the same brake torque with 87.5% BPCV opening, there was an increase of smoke by 168% recorded. Similarly compared to full valve opening at 60 N-m with 75% valve opening, a 30% increase in smoke is observed. However, in comparison with full valve opening and 87.5% valve opening at the same brake torque, there is an increase of smoke by 60%. As brake torque increases with increase in BPCV opening, there is increase in smoke concentration. However, the percentage of change in smoke concentration gradually decreases with increase in brake torque.

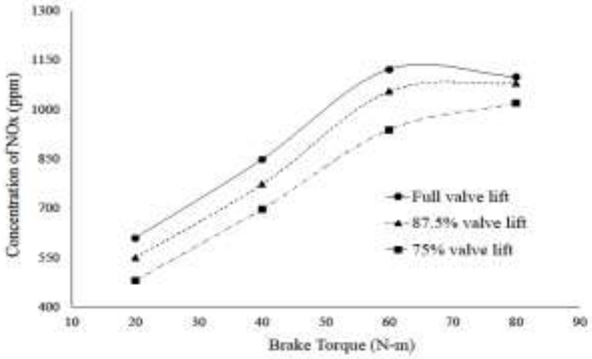

Fig. 6: Effect of percentage of BPCV opening on NOx at various brake torques

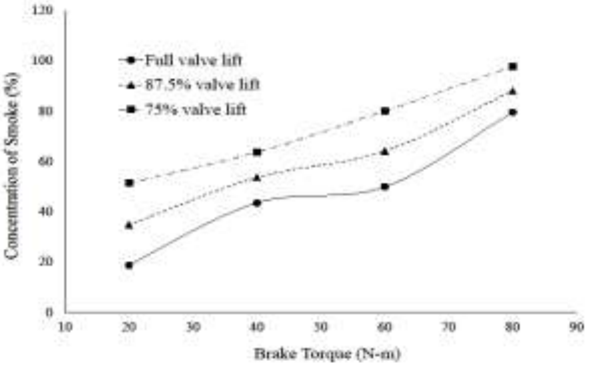

Fig. 7: Effect of percentage of BPCV opening on soot at various brake torques

4. Conclusion

From the presented experimental work various conclusions are drawn. Variation of Exhaust back pressure using BPCV lift and internal EGR had certainly affected combustion and emissions in conventional diesel engine. The increase in back pressure with brake torque leads to decrease in thermal efficiency and BMEP, this because of pumping loss and reduction in specific heat valve of fuel that leads to decrease in brake power because engine require additional fuel to overcome this pumping losses. Therefore, with increasing BPCV valve lift, fuel consumption (BSFC) increased. Using internal EGR, the amount of residual gas into intake system increased which leads to dilution of intake air, and decreased the concentration of O2, lowers heat release rate and cylinder peak temperature, therefore it is can inferred that throughout the operation there is an average decrease in NOx by 15%. Increasing back pressure in the exhaust system has increased the efficiency of DOC device by reducing HC and CO emission due to increased time of oxidation. Increasing back pressure, there was decrease in BMEP and thermal efficiency which leads to decrease overall temperature of combustion and decreased concentration of oxygen leads to more smoke formation. It can be concluded that increasing back pressure by varying BPCV lift under increasing load, helped to decrease in HC, CO and NOx emissions. However, there was significant increase in smoke and fuel consumption.

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