Effect of Exhaust Gas Recirculation (EGR) on performance, emissions, deposits and durability of a constant speed compression ignition engine

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Effect of Exhaust Gas Recirculation (EGR) on performance, emissions, deposits and durability of a constant speed compression ignition engine

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ABSTRACT

To meet stringent vehicular exhaust emission norms worldwide, several exhaust pre-treatment and post-treatment techniques have been employed in modern engines. Exhaust Gas Recirculation (EGR) is a pre-treatment technique, which is being used widely to reduce and control the oxides of nitrogen (NO_x) emission from diesel engines. EGR controls the NO_x because it lowers oxygen concentration and flame temperature of the working fluid in the combustion chamber. However, the use of EGR leads to a trade-off in terms of soot emissions. Higher soot generated by EGR leads to long-term usage problems inside the engines such as higher carbon deposits, lubricating oil degradation and enhanced engine wear. Present experimental study has been carried out to investigate the effect of EGR on soot deposits, and wear of vital engine parts, especially piston rings, apart from performance and emissions in a two cylinder, air cooled, constant speed direct injection diesel engine, which is typically used in agricultural farm machinery and decentralized captive power generation. Such engines are normally not operated with EGR. The experiments were carried out to experimentally evaluate the performance and emissions for different EGR rates of the engine. Emissions of hydrocarbons (HC), NO_x, carbon monoxide (CO), exhaust gas temperature, and smoke opacity of the exhaust gas etc. were measured. Performance parameters such as thermal efficiency, brake specific fuel consumption (BSFC) were calculated. Reduction in NO_x and exhaust gas temperature were observed but emissions of particulate matter (PM), HC, and CO were found to have increased with usage of EGR. The engine was operated for 96 h in normal running conditions and the deposits on vital engine parts were assessed. The engine was again operated for 96 h with EGR and similar observations were recorded. Higher carbon deposits were observed on the engine parts operating with EGR. Higher wear of piston rings was also observed for engine operated with EGR.

1. Introduction

Better fuel economy and higher power with lower maintenance cost has increased the popularity of diesel engine vehicles. Diesel engines are used for bulk movement of goods, powering stationary/mobile equipment, and to generate electricity more economically than any other device in this size range. In most of the global car markets, record diesel car sales have been observed in recent years [1]. The exhorting anticipation of additional improvements in diesel fuel and diesel vehicle sales in future have forced diesel engine manufacturers to upgrade the technology in terms of power, fuel economy and emissions. Diesel emissions are categorized as carcinogenic [2]. The stringent emission legislations are compelling engine manufacturers to develop technologies to combat exhaust emissions. To meet these emission regulations with competitive fuel economy, exhaust gas after-treatment and optimized combustion are necessary. However, it is still unresolved which concept will succeed considering production and economic feasibility [3].

Diesel engines are very popular power plants for decentralized power production in rural areas all over the world as well as for powering the farm equipment due to their fuel economy, ease of maintenance and robustness. Diesel engines are assumed as a good alternative to gasoline engines because they produce lower amount of emissions [4]. On the other hand, higher emissions of oxides of nitrogen (NO_x) and particulate matter (PM) have been noticed as major problems. Although, major constituents of diesel exhaust include carbon dioxide (CO_2), water vapor (H_2O), nitrogen (N_2), and oxygen (O_2); carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x), and particulate matter (PM) are present in smaller but environmentally significant quantities. In

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modern diesel engines, first four species normally consist of more than 99% exhaust, while last four (the harmful pollutants) account for less than 1% exhaust [5]. NO_x comprise of nitric oxide (NO) and nitrogen dioxide (NO_2) and both are considered to be deleterious to humans as well as environmental health. NO_2 is considered to be more toxic than NO. It affects human health directly and is precursor to ozone formation, which is mainly responsible for smog formation. The ratio of NO_2 and NO in diesel engine exhaust is quite small, but NO gets quickly oxidized in the environment, forming NO_2 [6]. Since diesel engine mainly emits NO hence attention has been given to reduce the NO formation [7].

1.1. NO_x formation mechanism

NO is formed inside the combustion chamber in post-flame combustion process in the high temperature region. The NO formation and decomposition inside the combustion chamber can be described by extended *Zeldovich Mechanism* [8]. The principal reactions at near stoichiometric fuel–air mixture governing the formation of NO from molecular nitrogen are:

$$O + N_2 \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH \rightarrow NO + H$$

The initial rate controlled NO formation (i.e. when $[NO]/[NO_2]_e \ll 1$) can be described by the Eq. (1). In the expression, [NO] denotes the molar concentration of the species and $[O_2]_e$ and $[N_2]_e$ denotes the equilibrium concentration [7].

$$\frac{d[NO]}{dt} = \left(\frac{6 \times 10^{16}}{T^{0.5}}\right) \exp\left(\frac{-69,096}{T}\right) [O_2]_e^{0.5} [N_2]_e \text{ mol s/cm}^3 \qquad (1)$$

The sensitivity of NO formation rate to temperature and oxygen concentration is evident from this equation. Hence in order to reduce the NO_x formation inside the combustion chamber, the temperature and oxygen concentration in the combustion chamber need to be reduced. Even though, certain cetane improving additives are capable of reducing NO_x, the amount of reduction is reported to be inadequate. Moreover, most of these additives are expensive. Retarded injection is an effective method employed in diesel engines for NO_x control. However, this method leads to increased fuel consumption, reduced power, increased HC emissions and smoke. Water injection is another method for NO_x control however this method enhances corrosion of vital engine components. In addition, it adds to the weight of the engine system because of requirement of a water storage tank. It is also difficult to retain water at a desired temperature during cold climate [9].

1.2. Exhaust Gas Recirculation

Exhaust Gas Recirculation is an effective method for NO_x control. The exhaust gases mainly consist of carbon dioxide, nitrogen etc. and the mixture has higher specific heat compared to atmospheric air. Re-circulated exhaust gas displaces fresh air entering the combustion chamber with carbon dioxide and water vapor present in engine exhaust. As a consequence of this air displacement, lower amount of oxygen in the intake mixture is available for combustion. Reduced oxygen available for combustion lowers the effective air–fuel ratio. This effective reduction in air–fuel ratio affects exhaust emissions substantially. In addition, mixing of exhaust gases with intake air increases specific heat of intake mixture, which results in the reduction of flame temperature. Thus combination of lower oxygen quantity in the intake air and reduced flame temperature reduces rate of NO_x formation reactions [10,11]. The EGR (%) is defined as the mass percent of the re-circulated exhaust (M_{EGR}) in the total intake mixture (M_i).

$$EGR(\%) = \frac{M_{EGR}}{M_i} \times 100$$

Desantes et al. used NDIR-based CO_2 concentration measurement at the intake ($[CO_2]_{int}$) and exhaust manifold ($[CO_2]_{exh}$) for the determination of EGR rate [12].

$$EGR = \frac{[CO_2]_{int} - [CO_2]_{atm}}{[CO_2]_{exh} - [CO_2]_{atm}}$$

The engines using EGR emit lower quantity of exhaust gases compared to non-EGR engines because part of the exhaust gas is re-circulated [13]. Thus even if the concentration of toxic substances in the exhaust gas remains unchanged, the total quantity of emission of toxic substances reduce for the same volumetric concentration.

Diesel engines operating at low loads and generally tolerate a higher EGR ratio because re-circulating exhaust gases contain high concentration of oxygen and low concentration of carbon dioxide and water vapors. However at higher loads, the oxygen in exhaust gas becomes scarce and the inert constituents start dominating along with increased exhaust temperature. Thus, as load increases, diesel engines tend to generate more smoke because of reduced availability of oxygen [5].

Wagner et al. tried to achieve lower emission of NO_x and soot using highly diluted intake mixture. At very high EGR rate (around 44%), PM emission decreased sharply with a continuous drop in NO_x emission but this high EGR rate significantly affect the fuel economy [14]. Sasaki et al. conducted experiments using EGR on direct injection gasoline engine and reported that an appropriate volume of EGR improves fuel economy and HC emissions. This phenomenon was presumably due to the intake temperature increase by EGR, which improved the flame propagation in the relatively lean region of the air–fuel mixture, which is non-uniformly distributed [15]. Kusaka et al. also found that at low loads, EGR combined with intake heating can favorably reduce THC emission with improvement in thermal efficiency [16]. EGR was also used in a direct injection spark ignition engine as an effective way for improving fuel economy [17,18].

Das et al. used EGR to reduce NO_x emissions in hydrogen – supplemented SI engine without any undesirable combustion phenomena [19]. Sato et al. performed experiments using methanol in direct injection compression ignition engine and found that combustion performance becomes inferior under light load conditions because temperature in combustion chamber fell due to very high latent heat of methanol, thus hampering formation of combustible air–fuel mixture [20]. Selim et al. operated the diesel engine in dual fuel mode with natural gas and found inferior performance and emissions at low loads because lean mixtures formed at low loads were hard to ignite and had slow burning characteristics. EGR was found to be a method of improving engine performance and emissions of such engines [21].

However, application of EGR also leads to penalties. In case of diesel engines, these penalties include higher specific fuel consumption and particulate matter emissions. Effectively, a trade-off between NO_x and soot is observed with the use of EGR [22–27]. The reduction in flame temperature reduces the rate of soot oxidation/re-burning. As a result, in EGR system, more soot is formed during combustion and it remains un-oxidized and eventually appears in the exhaust [10]. The rise in smoke (soot) level of engine exhaust due to EGR affects the engine performance in various ways. Increased soot level causes considerable increase in the carbon deposits and wear of the various vital engine parts such as cylinder liner, piston rings, valve train and bearings. Wear of the materials also increase due to chemical reactions taking place on the surface (adsorption, corrosion) or due to abrasion of material or rupture of anti-wear film by soot. The application of EGR also adversely affects the lubricating oil quality and engine durability [28–33].

Gautam et al. experimentally proved that soot interacts with oil additives reducing its anti-wear properties possibly by abrasive wear mechanism. Increased wear due to EGR is because of presence of soot in lubricating oil [29]. Studies on valve-train wear in presence of soot were performed by Nagai et al. As the EGR rate was varied from 0 to 17% to 25%, the wear of cam noses and rocker arm tips was found to increase significantly [30].

If the exhaust gas is re-circulated directly to the intake, it results in increased intake charge temperature i.e. hot EGR. An increase in inlet charge temperature always results in shorter ignition delay and may improve thermal efficiency [34]. If the exhaust gas is cooled before recirculation to combustion chamber, then it is called cooled EGR. Cooling of EGR increases the charge density therefore improves volumetric efficiency of the engine. Also, it provides additional benefits by lowering NO_x emissions to a greater extent. However, condensation of moisture present in the exhaust increases corrosion in combustion chamber. Plee et al. reported that major influence on NO_x emission is due to change in temperature rather than oxygen availability [35].

In the present study, EGR was implemented to see the effect of EGR on wear of piston rings. The piston rings are most vital parts between piston and cylinder. The engine was operated for 96 h in normal running conditions and the wear of the piston rings and deposits on vital engine parts were assessed. The engine was again operated for 96 h with EGR and similar observations were made for piston ring wear and deposits. Since, EGR results in more soot formation, which in-turn affects the lubricating oil by thickening the oil and increases the wear debris in lubricating oil. Increased soot level and wear debris in lubricating oil may adversely affect the piston rings because piston rings are used to scrap off the excess lubricating oil from the cylinder liner and return it to oil sump. Engine performance and carbon deposits on injector tip, cylinder head and piston crown were also investigated.

Table 1
Test engine specifications.

Model	Indec PH2 diesel engine
Engine type	Two cylinder, direct injection, air cooled, vertical engine
Bore/stroke	87.3/110 mm
Rated power	9 kW
Rated speed	1500 rpm
Compression ratio	16.5:1
Total displacement volume	1.318 l
Fuel injection release pressure	210 bar
Inlet valve opens/inlet valve closes	4.5° BTDC/35.5° ATDC
Exhaust valve opens/exhaust valve closes	35.5° BBDC/4.5° ATDC

2. Experimental setup and methodology

A two-cylinder constant speed diesel engine generator set was chosen to study the effect of EGR on the performance and emissions, carbon deposits, and wear of diesel engine components. The specifications of engine are given in Table 1. The engine is coupled with an AC generator and the current generated is used by a resistive load bank, thus in-turn loading the engine. The generator is calibrated and all losses in the generator such as copper losses, armature current losses and friction and windage losses (unaccounted losses) are accounted for and taken into consideration while analyzing the data.

For recirculation of the exhaust gas, appropriate plumbing was done. No insulation on the pipe line was provided therefore allowing the re-circulated exhaust gases to partially cool down. The schematic diagram of the engine setup is shown in Fig. 1. The quantity of EGR can be regulated by a control valve installed in

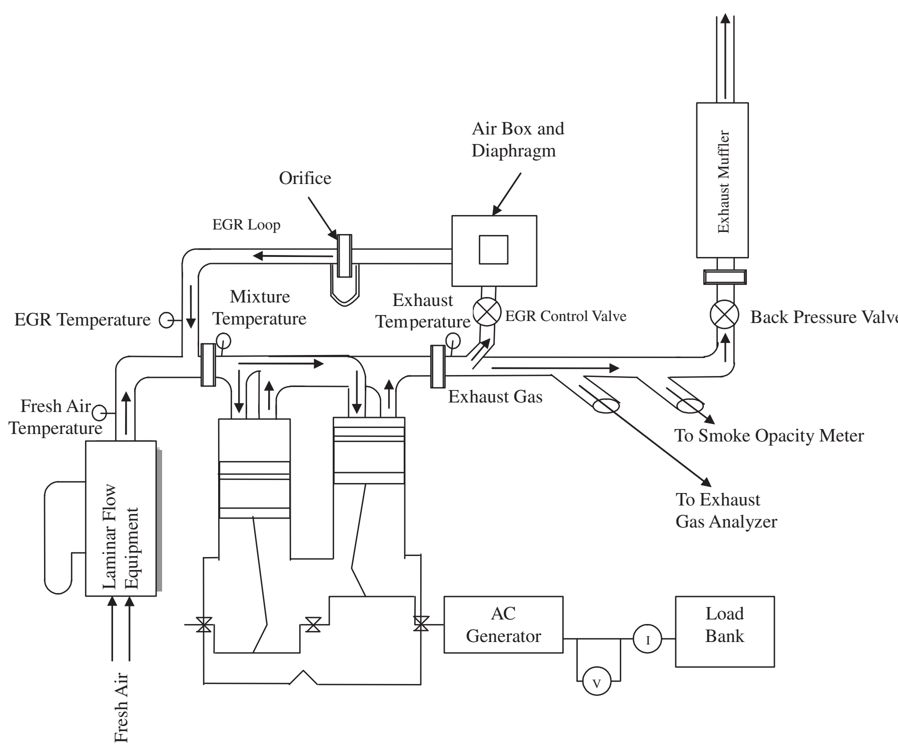

Fig. 1. Schematic diagram of engine setup using EGR.

the EGR loop. An air box was provided in EGR loop to dampen the fluctuations of the pulsating exhaust. An orifice was installed in the EGR loop to measure the flow rate of re-circulated exhaust gas. To measure the intake air flow rate, a laminar flow equipment (LFE) (Make: Cussons, UK Model: 7025) was installed.

Suitable instrumentation for measurement of temperatures at several locations was done. Fuel consumption measurement was done using a gravimetric fuel consumption meter (Make: AG Measurements, India). Exhaust gas emission measurements were done by raw exhaust gas emission analyzer (Make: Horiba, Japan, Model: EXSA-1500). Oxygen, CO and CO_2 were measured by a Non-Dispersive Infrared Analyzer (NDIR), THC by a Heated Flame Ionization Analyzer (hot FID) and NO_x by a Chemiluminescence Analyzer. The exhaust gas opacity was measured by a smoke opacity meter (Make: AVL, Austria, Model: 437).

To achieve the objectives of the study, engine was run under normal operating condition and at different EGR rates. The data for HC, NO_x, CO, smoke opacity, exhaust gas temperature, and fuel consumption were recorded. Then, engine performance and emission patterns were compared. Optimum EGR rate was found on the basis of performance and emissions of the engine. Then, the engine was run with and without EGR for total 96 h in each phase separately using a fixed test cycle shown in Table 2. A qualitative analysis of the soot deposits on various vital engine parts was done photographically. Photographs of cylinder head, piston crown, and injector tip were taken for both phases. The wear of piston rings was also studied. For this purpose, piston rings were weighed before and after 96 h of the engine test run for both set of experiments, to compare the piston ring wear (on the basis of loss in weights of the rings). Rings were cleaned properly before measurements and were weighed in a balance having least count of 0.1 mg.

3. Results and discussion

The engine was run on different loads at 1500 rpm with different EGR rates (from 0% to 20%) to investigate the effect of EGR on engine performance and emissions. The performance and emission data was analyzed and presented graphically for thermal efficiency, BSFC, exhaust gas temperature, HC, CO, NO_x emission, and smoke opacity.

3.1. Engine performance analysis

The trends of thermal efficiency are shown in Fig. 2. Thermal efficiency is found to have slightly increased with EGR at lower engine loads. The possible reason may be re-burning of hydrocarbons that enter the combustion chamber with the re-circulated exhaust gas. At part loads, exhaust gas has less CO_2 and fairly high amount of O_2. Also, partly-cooled EGR acts like a pre-heater of the intake mixture. When this exhaust gas is re-circulated in the cylinder, the unburned HC in exhaust gas burns because of sufficient O_2 available in combustion chamber and reasonably high intake temperatures. At higher engine loads, the thermal efficiency remains unaffected by EGR. At higher loads, exhaust gas has higher amount of CO_2, which reduces maximum temperature in combustion chamber along with oxygen availability therefore re-burning of HC is not significant.

Fig. 3 represents comparison of BSFC for all datasets using EGR with baseline data. BSFC is lower at lower loads for engine operated with EGR compared to without EGR. However, at higher engine loads, BSFC with EGR is almost similar to that of without EGR. At higher loads, amount of fuel supplied to the cylinder is increased at higher rate and oxygen available for combustion gets reduced. Thus, air fuel ratio is changed and this increases the BSFC.

The exhaust gas temperatures are shown in Fig. 4. It has been observed that with increase in load, exhaust gas temperature also increases. When the engine is operated with partly-cooled EGR, the temperature of exhaust gas is generally lower than temperature of exhaust gas at normal operating condition. Exhaust gas temperature decreases with increase in EGR rate. The reasons for temperature reduction are relatively lower availability of oxygen for

Table 2
Engine test cycle for endurance test.

Load	Duration (min)
No load	20
100% load	30
50% load	120
No load	20
75% load	60
No load	20
100% load	30
75% load	60
Total	360 (6 h)

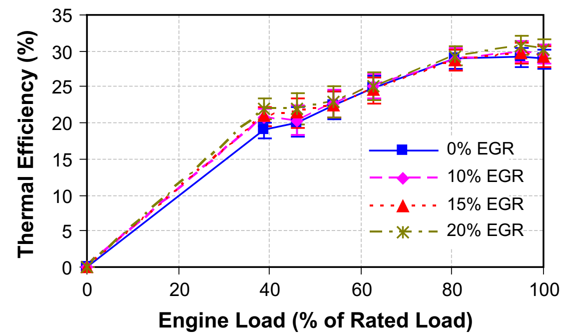

Fig. 2. Thermal efficiency for different EGR rates.

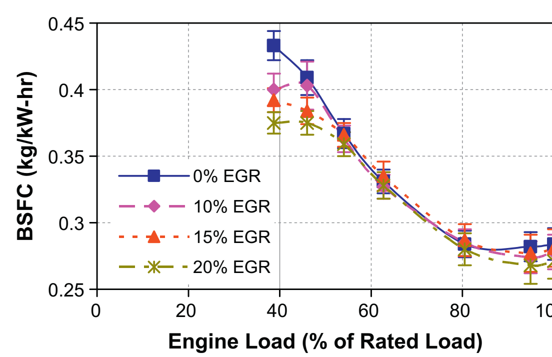

Fig. 3. Brake specific fuel consumption for different EGR rates.

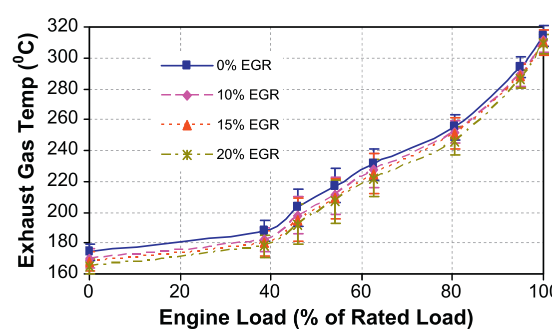

Fig. 4. Exhaust gas temperature for different EGR rates.

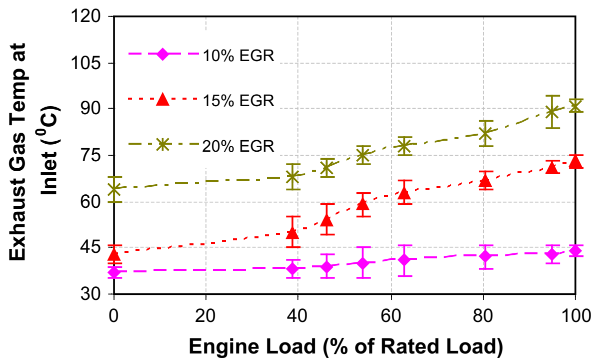

Fig. 5. Exhaust gas temperature at the entry to the inlet manifold for different EGR rates.

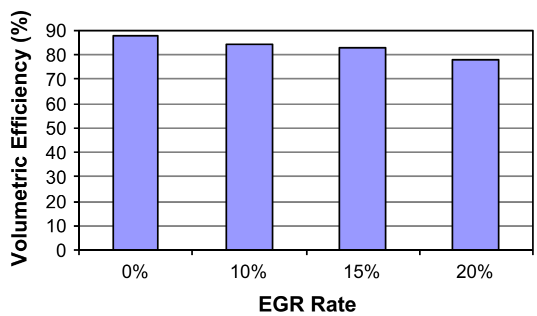

Fig. 6. Volumetric efficiency for different EGR rates.

combustion and higher specific heat of intake air mixture as explained earlier.

Fig. 5 represents the variation of exhaust gas temperature at the entry to the inlet manifold for different EGR flow rates. These graphs show that exhaust gas temperature at entry to inlet manifold is not very high because exhaust gases are partly cooled before mixing with fresh air at atmospheric temperature. At part loads, this temperature at various EGR rates is close to atmospheric temperature. However, when load and EGR rates are increased, the exhaust temperature at the entry to the inlet manifold becomes higher than atmospheric temperature and therefore EGR acts as a pre-heater to fresh intake air.

Fig. 6 represents volumetric efficiency for different EGR rates. It can be seen that as the EGR rate is increased, volumetric efficiency decreases. The intake air mass flow reduces because of EGR implementation and this means the volumetric efficiency drops. Ghazikhanietal et al. also found that volumetric efficiency drops when EGR rate is increased [36].

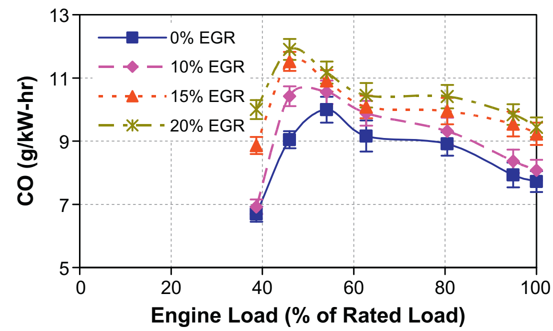

Fig. 8. Carbon monoxide for different EGR rates.

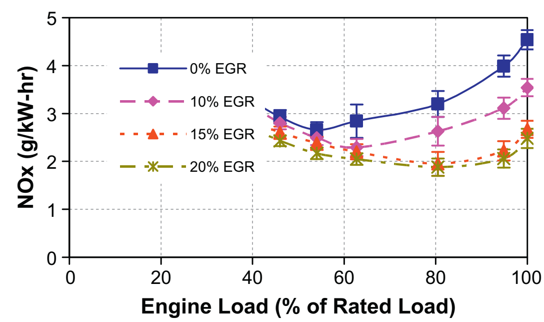

Fig. 9. NO_x for different EGR Rates.

3.2. Engine emission analysis

Effect of EGR on unburned hydrocarbon (HC) and carbon monoxide (CO) are shown in Figs. 7 and 8, respectively. These graphs show that HC and CO emissions increase with increasing EGR. Lower excess oxygen concentration results in rich air–fuel mixtures at different locations inside the combustion chamber. This heterogeneous mixture does not combust completely and results in higher hydrocarbons, and carbon monoxide emissions. At part loads, lean mixtures are harder to ignite because of heterogeneous mixture and produce higher amount of HC and CO.

Fig. 9 shows the main benefit of EGR in reducing NO_x emissions from diesel engine. The degree of reduction in NO_x at higher loads is higher. The reasons for reduction in NO_x emissions using EGR in diesel engines are reduced oxygen concentration and decreased flame temperatures in the combustible mixture. At the part load, O_2 is available in sufficient quantity but at high loads, O_2 reduces drastically, therefore NO_x is reduced more at higher loads compared to part loads.

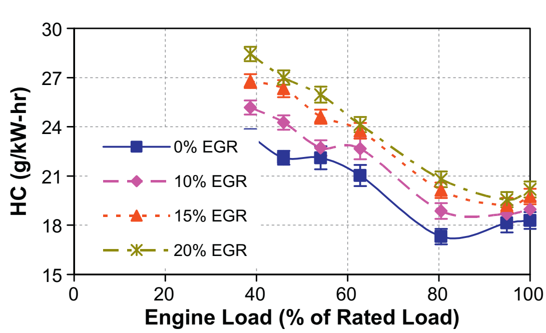

Fig. 7. Hydrocarbons for different EGR rates.

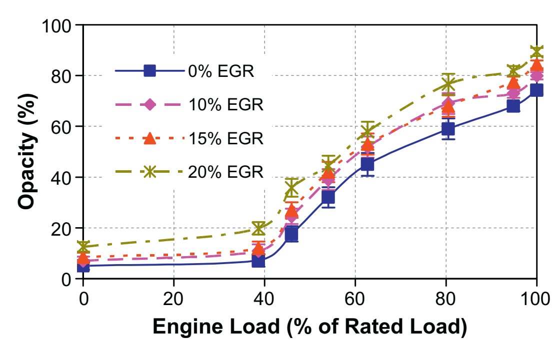

Fig. 10. Smoke opacity for different EGR rates.

Fig. 11. Carbon deposits on the cylinder head of the engine (a) using EGR (b) without EGR.

Fig. 12. Carbon deposits on the injector tip of the engine (a) using EGR (b) without EGR.

Fig. 13. Carbon deposits on the piston crown of the engine (a) using EGR (b) without EGR.

The smoke opacity of the exhaust gas is measured to quantify the particulate matter present in the exhaust gas. The smoke opacity is shown in Fig. 10. Higher smoke opacity of the exhaust is observed when the engine is operated with EGR compared to without EGR. The variation in the smoke opacity level at high loads was higher compared to that at lower loads. EGR reduces availability of oxygen for combustion of fuel, which results in relatively incomplete combustion and increased formation of particulate matter.

3.3. Engine deposits analysis

The physical conditions of various vital engine parts which are directly exposed to combustion in-cylinder liner are shown in Figs. 11–13. Figs. 11–13 show carbon deposits on the cylinder head, injector tip, and piston crown respectively of engine operated (a) with and (b) without EGR. It can be clearly seen that carbon deposits on the various parts of the engine operated with

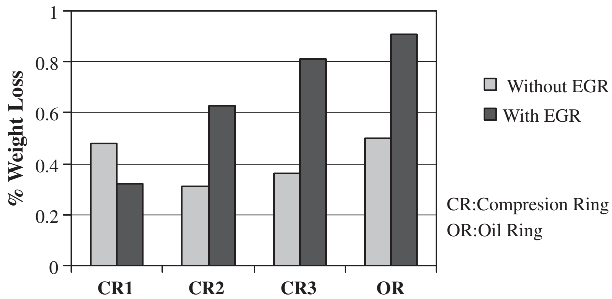

Fig. 14. Wear of piston rings of cylinder liner 1.

EGR system is significantly more than that of engine operated without EGR. The higher carbon deposits in the EGR system seem to be because of higher soot formation. These pictures support the results obtained by smoke opacity (Fig. 10).

3.4. Wear of piston rings

The piston rings are one of the most important components in the engine, which are essential for operation of the engine. Piston rings are subjected to high thrust imposed by combustion gases. Rings are used to reduce the friction between cylinder liner surface and the piston. They are made of very high strength material so that they can resist high temperature and high thrust of combustion process and at the same time have very low wear.

In both phases of experiments, new rings are installed before starting the test run. The rings are weighed before the installation in the engine and after 96 h of engine run. The percentage weight loss of rings in the cylinder liner 1 for both set of experiments has been shown in Fig. 14. A significant amount of weight loss of rings was observed after completion of test run. The weight loss of the rings takes place due to wear.

It has been observed that top compression ring of the engine operating without EGR has maximum weight loss among other compression rings. The loss in weight of top compression ring was approximately 0.50% of its initial weight. Top compression ring faces highest amount of thrust applied by combustion gases and is directly exposed to combustion process. Top ring always works in the highest temperature zone of cylinder liner. Hence, possibility of wear of top compression ring is maximum. The weight loss of oil ring was found comparable to top compression ring. The loss in weight of oil ring was also approximately 0.50%. The main function of oil ring is to scrap off excess oil from the cylinder liner surface and push it back to oil sump. This scrapped oil contains wear debris and it gets mixes with the lubricating oil in the oil sump. This oil is again re-circulated to the various engine parts where these wear debris present in lubricating oil act as abrasive particles there by increasing the wear rate.

In the engine using EGR, top compression ring faces lowest weight loss compared to other rings. The weight loss of top compression ring is about 0.30% of the initial weight of ring. The oil ring faces highest amount of weight loss in the engine using EGR. The amount of wear was approximately 0.90% of initial weight.

It has been observed that the extent of wear of top ring in the engine using EGR is lower than normal operating engine. The possible reason of this may be the lower temperature of the combustion chamber of the engine using EGR. However, the wear rate of second and third compression ring and oil ring is comparatively higher for engine using EGR. The possible reason for this may be presence of higher amount of soot and wear debris in the lubricating oil of the engine using EGR.

4. Conclusions

EGR is a very useful technique for reducing the NO_x emission. In the present research, experimental investigations were conducted to study the effect of EGR on performance and emissions, carbon deposits, and wear of various parts of a diesel engine. EGR displaces oxygen in the intake air by exhaust gas re-circulated to the combustion chamber. Exhaust gases lower the oxygen concentration in combustion chamber and increase the specific heat of the intake air mixture, which results in lower flame temperatures. Reduced oxygen and lower flame temperatures affect performance and emissions of diesel engine in different ways. Thermal efficiency is slightly increased and BSFC is decreased at lower loads with EGR compared to without EGR. But at higher loads, thermal efficiency and BSFC are almost similar with EGR than without EGR. Exhaust gas temperature is decreased with EGR. Hydrocarbons, carbon monoxide, and smoke opacity are increased with EGR, but NO_x emission decreases significantly. It can be observed that 15% EGR rate is found to be effective to reduce NO_x emission substantially without deteriorating engine performance in terms of thermal efficiency, BSFC, and emissions. At lower loads, EGR reduces NO_x without deteriorating performance and emissions. At higher loads, increased rate of EGR reduces NO_x to a great extent but deteriorates performance and emissions. Thus, it can be concluded that higher rate of EGR can be applied at lower loads. EGR can be applied to diesel engine without sacrificing its efficiency and fuel economy and NO_x reduction can thus be achieved. The increase in CO, HC, and PM emissions can be reduced by using exhaust after-treatment techniques, such as diesel oxidation catalysts (DOCs) and soot traps.

A qualitative analysis of soot formation was also done for in-cylinder engine parts. Higher soot deposits were observed on cylinder head, injector tip, and piston crown of EGR operated engine than without EGR operated engine. Wear of the piston rings was also estimated. The wear of top compression ring in the engine operated with EGR was found to be slightly lower than the engine operated without EGR. But the wear of the second, third compression rings and the oil ring in engine operated with EGR was far more than that of the engine operated without EGR.

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