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Experimental investigations of heavy metal addition in lubricating oil and soot deposition in an EGR operated engine

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Abstract

Exhaust gas recirculation (EGR) is a technique, which is being used widely to reduce and control the NO_x emissions from diesel engines. However, the use of EGR leads to rise in soot emission because of soot–NO_x trade-off. This EGR generated soot leads to several other problems inside the engine like degradation of lubricating oil, enhanced engine wear etc. In the present study, an experimental investigation has been carried out to evaluate the effect of EGR on characteristics of lubricating oil with time of its usage.

A two cylinder, air cooled, constant speed direct injection diesel engine of 9 kW rating was used for conducting the experiments. The experiments were conducted in two phases for a comparative study on the normally operated engine (i.e. without EGR) and the engine operated with EGR for 96 h in each phase. Lubricating oil samples were collected after every 24 h interval and were analysed for soot loading (total carbon content) and various metal addition due to wear of the engine. Higher metal contents were found in the lubricating oil drawn from the engine using EGR. Higher carbon deposits were also observed on vital parts of the engine operating with EGR.

Keywords: EGR; Heavy metals; Soot; Engine wear; Lubricating oil

1. Introduction

In recent years, popularity of diesel engines has increased due to its higher fuel economy and low maintenance cost. At the same time, regulatory emission norms around the world have been tightened in order to control the emissions from vehicles. For diesel engines, these norms particularly focus on emission of oxides of nitrogen (NO_x) and particulates. NO_x is primary as well as secondary pollutant. These gases are toxic to human nervous system apart from being responsible for smog formation in the environment [1]. They react with the volatile hydrocarbons to form troposphere ozone, which is a major pollutant in smog. For controlling the emission of NO_x from diesel engines, various techniques have been tried e.g. retarded injection timing, injection of diluents in combustion chamber, selective catalytic reduction, NO_x adsorbers, exhaust gas recirculation (EGR) etc. Most of these techniques have limitations in practical implementation on the engines. EGR has proved to be an effective method of reducing NO_x emissions and is practically implemented in most diesel engines worldwide. In EGR system, part of exhaust gas is recirculated and mixed with air in the intake manifold, replacing an equal amount of fresh air. This reduces the availability of oxygen and increases the heat absorbing capacity of the exhaust gas and air mixture entering the combustion chamber, since specific heat of exhaust gas is significantly higher than air. The oxygen in air is partially displaced by CO_2 and water vapour of the exhaust

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gases, thus reducing oxygen to fuel ratio. The reduction in oxygen availability in the combustion zone leads to lower flame temperature. This effectively leads to reduced NO_x formation [2]. The rate of nitric oxide (NO) formation is highly dependent on temperature and decreases with lowering of the temperature and availability of oxygen [3]. Thus combination of increase in specific heat and reduced oxygen in intake air reduces the flame temperature which controls the rate, at which NO_x formation reactions proceed [4]. However, studies have shown that particulate matter (PM) emission increases consistently as the EGR rate increases [5,6].

The EGR rate is given by the following equation:

$$\mathrm{EGR}\% = \frac{V_{\mathrm{EGR}}}{[V_{\mathrm{Air}} + V_{\mathrm{EGR}}]} \times 100$$

where, V_{EGR} = volume of recirculating exhaust gas; V_{Air} = volume of fresh air entered in intake manifold.

As the load increases, diesel engines start generating more smoke because of reduction in oxygen availability in combustion zone. Zelenka et al. have shown that as high EGR can be used at lower engine loads whereas at high loading condition, low EGR must be used [7]. The use of 10–25% EGR results in significant reduction in NO_x with a smaller rise in PM emissions without affecting the performance of engine [8–10].

Though EGR effectively reduces NO_x emission, rise in PM emissions leads to increase wear of vital engine parts such as cylinder liner, piston rings, bearings, valve train etc. The wear debris generated by wear of various engine parts contaminates the lubricating oil. Therefore, engines operated with EGR are normally exhibit higher level of lubricating oil contaminations and faster degradation of lubricating oil [10].

The objective of current study is to compare the performance of a constant speed diesel engine using EGR with respect to normal operating engine. The effect of EGR on lubricating oil and wear was studied by engine test for 96 h under each condition.

In EGR operated engines, vital engine parts wear faster due to chemical reactions and abrasive action on the surface by increased number of soot particles, and squeezing out of anti-wear film. As a result, lubricating oil is exposed to higher levels of contaminants, which affects the performance and life of lubricating oil and damage the surfaces of various engine parts to a greater extent [11]. Rounds proposed that wear occurs when the decomposition products of the anti-wear additives get preferentially adsorbed onto soot allowing metal-to-metal contact [12]. The diesel soot particles are agglomerates of small, spherical particles of diameter of approximate 0.02 μm and size ranging from 0.5 μm and bigger [13]. Thickness of boundary layer lubricating oil film is characterized as $\geqslant 0.025$ μm, which is significantly less than diameter of soot particles [14]. Low speed and high load engine operations, typically during start up and shutdown, may face insufficient lubrication at boundary layer lubrication zones (i.e. at TDC and BDC positions) of the cylinder liner. Soot particles at times have diameters larger than lubricating oil film thickness. These soot particles start acting as abrasives particles, leading to higher wear of surface materials. From a common oil sump, these abrasive particles circulate throughout the engine and continue the chain reaction of wear [15].

2. Experimental setup and methodology

The engine experiments were conducted in two phases. In the first phase, engine was run under normal operating conditions without EGR (baseline) and in the second phase, the engine was run with a 25% EGR rate. The soot deposition in both phases of experiment was qualitatively compared by taking pictures of in-cylinder engine parts. For comparing the engine wear of both the phases of engine experiments, samples of lubricating oil were collected after every 24 h of engine run and were analyzed for heavy metals and soot content using atomic absorption spectrophotometer (Varian AAS spectra AA 220FS) and total organic carbon (TOC) analyzer (Shimadzu, TOC-V CPN), respectively.

A constant speed, two cylinder, four stroke, air cooled, direct injection, diesel engine (Indec PH2) of 9.7 kW rating coupled with an AC alternator was chosen for this experimental study. The specifications of this engine are given in Table 1.

New set of cylinder liners, piston rings and pistons were installed for each phase of engine experiment. Fresh lubricating oil was filled in oil sump before each set of experiment. There was no further addition of make-up lubricating oil during each phase. After completing each phase, engine was dismantled and cleaned thoroughly by draining out the lubricating oil from the sump.

Experimental EGR setup was fabricated (Fig. 1). The short route EGR systems are more effective than long route system in reduction of NO_x and fuel economy, hence the exhaust gases were recirculated through shortest possible path [16].

An air box is provided to dampen the fluctuations of the recirculating exhaust gas. To measure the volumetric flow rate of recirculating exhaust gas, an orifice plate with a U-tube manometer was installed. To measure vol-

Table 1
Technical specification of the test engines

Manufacturer, Model	Indec PH2, CI Engine
Bore diameter	87.3 mm
Stroke length	110 mm
Power per cylinder	4.85 kW@1500 rpm
Compression ratio	16.5:1
Displacement	1318 cc
Fuel injection pressure	210 kg/cm^2

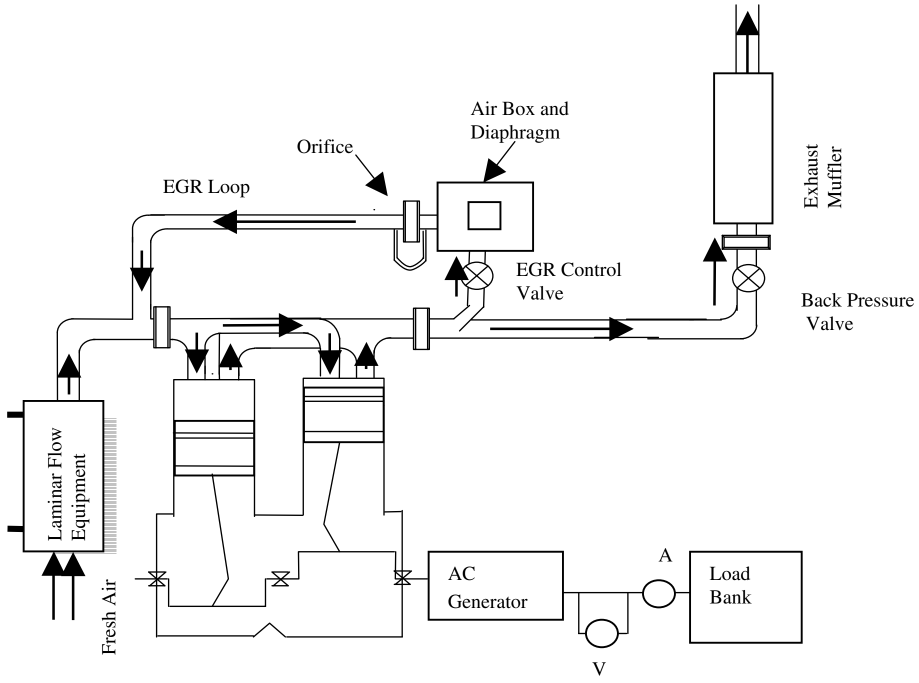

Fig. 1. Schematic diagram of experimental setup.

Table 2
Engine test cycle for endurance test

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

umetric flow rate of fresh air entering to intake manifold, a laminar flow equipment (Cussons, UK) was installed.

Engine run of 96 h in each phase was completed in 16 test cycles of 6 h each. The test cycle designed for the test run is given in Table 2. Engine was run for 16% of the total time at full load, 34% of time at 75% load 34% of time at 50% load and 16% of time at no load condition in each 6 h test cycle.

The lubricating oil samples were collected from the engine after each 24 h interval for conducting various oil analyses.

3. Experimental results

3.1. Carbon deposits on vital engine parts

After completing each phase of 96 h, engine was disassembled and deposit formed on cylinder head, injector tip and piston were visually inspected. The photographs of deposits formed on all these parts are shown in Figs. 2–4.

Fig. 2 shows carbon deposits on the cylinder head of EGR system and baseline system respectively. It can be clearly seen that carbon deposits on the cylinder head of engine operated with EGR is significantly higher than that of engine operated without EGR.

Fig. 3 shows carbon deposits on injector tip of EGR operated engine and baseline engine after 96 h. It is evident that the amount of carbon deposits on the injector tip of engine employing EGR are more as compared to injector tip of normally operated engine.

Fig. 4 shows carbon deposits on piston of engine operated with EGR and baseline (without EGR) engine respectively. The pictures show that in the EGR operated engine, carbon deposits are significantly higher than engine operated without EGR.

The carbon deposits on the in-cylinder engine parts are higher in engine operating with EGR than normally operating engine (without EGR) and the possible reason for this is higher amount of soot formation in EGR operated engine. In combustion process when soot particles are formed, major part of this carbonaceous material comes out with exhaust gases while a small fraction gets deposited on the in-cylinder parts and cylinder walls. Soot particles interact with the lubricating oil film present on cylinder walls and a fraction of deposited soot goes into the oil sump with lubricating oil returned by oil rings and blow-by gases. Thus with the engine run, lubricating oil gets loaded with soot particles, which affect the lubricating oil properties and performance.

Fig. 2. Carbon deposits on the cylinder head after 96 h of engine operation.

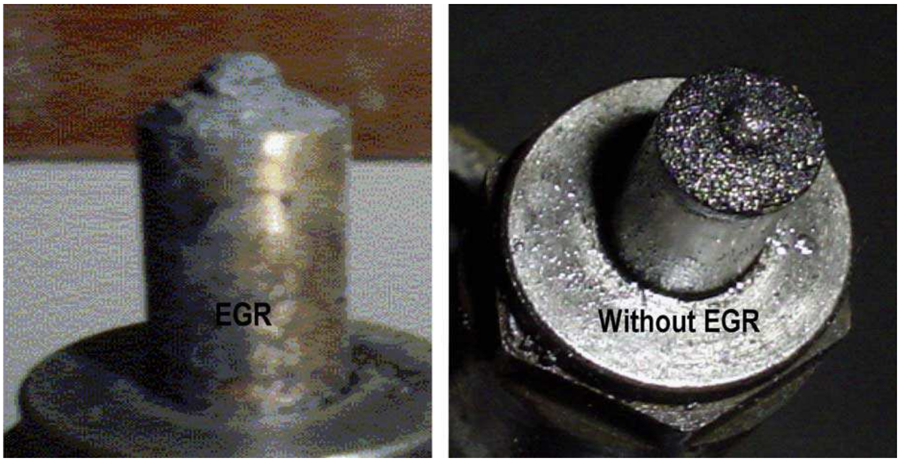

Fig. 3. Carbon deposits on the injector tip after 96 h of engine operation.

Fig. 4. Carbon deposits on the piston crown after 96 h of engine operation.

4. Soot loading of lubricating oil

Engine soot, present in used lubricating oil in its aggregated form typically contains about 90% carbon, 4% oxygen, 3% hydrogen, and remaining nitrogen, sulfur and traces of metals [17]. Major part of the soot present in the lubricating oil is in the form of organic carbon. The lubricating oils from the engines contain negligible amount of inorganic carbon. Base stock of lubricating oils is organic compounds and additives of

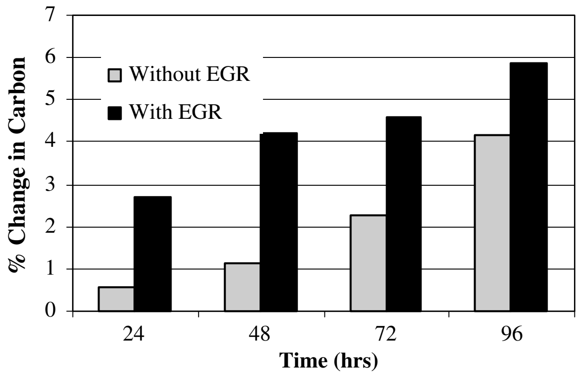

Fig. 5. Percent change in carbon content as function of lubricating oil usage.

complex organo-metallic compounds. There are very little chances of reaction of lubricating oil in order to form inorganic carbon while engine is running. Keeping these points in mind, the lubricating oil samples were analyzed for total carbon (TC) to quantify the addition of soot in the lubricating oil. The change in the amount of carbon present in the used oil compared to fresh oil is assumed to be a reasonable approximation of soot loading of lubricating oil. The lubricating oil was analyzed separately for inorganic carbon also.

The change in carbon concentration in the lubricating oil with its usage is shown in Fig. 5. The initial carbon concentration in the lubricating oil was about 88%.

From Fig. 5, it is clear that carbon concentration increase at a faster rate in lubricating oil drawn from EGR operated engine than normally operated engine. This higher increase in levels of carbon (in other words, soot) in the lubricating oil drawn from EGR operated engine may reduce the lubricating efficiency of the oil, resulting in increased wear of vital engine parts.

The lubricating oil picks up the wear debris of various metals from different moving engine parts and locations. The quantitative evaluation of wear particles present in lubricating oil gives an idea about the condition of various engine parts. Also, the disposal of used engine oils containing metal debris is a big environmental challenge. Wear metal analysis of the lubricating oil gives a qualitative result on wear of engine parts.

5. Metal analysis in lubricating oil

The analysis of heavy metals originating from wear debris in the lubricating oil has always been difficult due to high viscosity of the lubricating oil and non-uniform particle size distribution. For analyzing the heavy metals content in the lubricating oil, its viscosity needs to be reduced. The extraction of metals from the complex organic compounds of the oil is also desirable. For maximum possible extraction of metals from the lubricating oil samples, they were homogenised by shaking them vigorously and then putting them in a water bath at a temperature of 50 °C for 1 h.

For extraction of heavy metals from the lubricating oil, dry ashing technique was used [18]. The procedure adopted for extraction of heavy metals was as follows:

(a) Approximately 5 g of homogenized lubricating oil samples were weighed in previously washed and dried silica crucibles. The crucibles were then kept on a hot plate at a temperature of 120 °C till the lubricating oil gets completely dried up.
(b) The crucibles were then kept in muffle furnace at a temperature of 450 °C for 4 h and then at 650 °C for 2 h.
(c) The ash remained in the crucibles was then dissolved in 1.5 mL concentrated HCl.
(d) The solutions were then diluted to 100 mL by deionized water and stored in plastic bottles and kept in a refrigerator at a temperature of 10–15 °C.

The diluted samples were then analyzed by flame AAS. In the present study, since many sliding components are involved, it was anticipated that the wear debris originating from different metallic parts appear in lubricating oil. The elements, which can be detected as wear debris from lubricating oil, drawn from engine operating with and without EGR at regular intervals include Fe, Cu, Cr, Al, Ni, Zn, Mg, Pb, Mn. The results are shown in Figs. 6–8.

Iron: Iron in lubricating oil may originate from wear of cylinder liners, pistons, gears, rings, cam shaft, oil pump, crank shaft, bearings, etc. The results of the concentration of iron as a function of oil usages in both experiments are shown in Fig. 6. It has been observed that during initial running of engine, the iron concentration rises at a faster rate and followed by slower rise, possibly because of initial running-in of the engine.

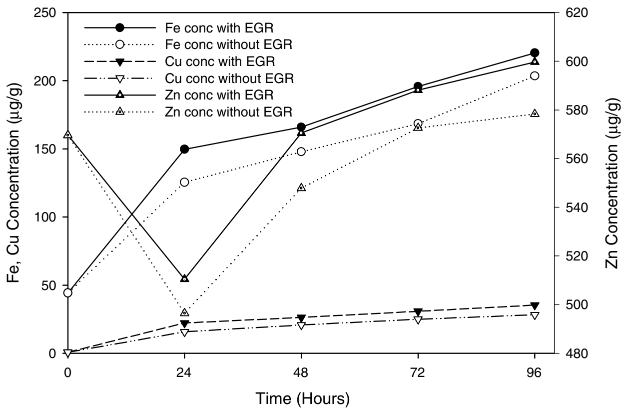

Fig. 6. Fe, Cu and Zn concentrations as a function of lubricating oil usage.

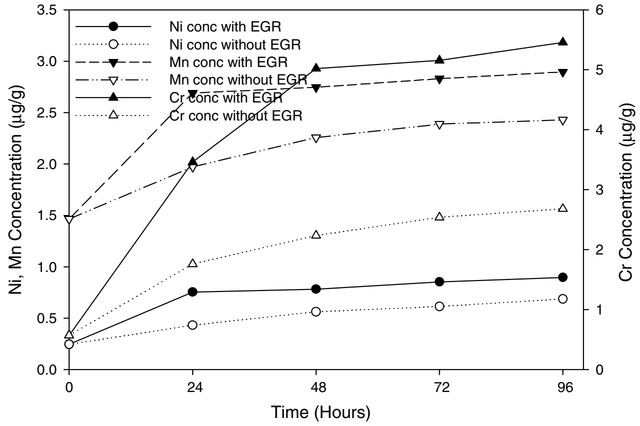

Fig. 7. Cr, Ni and Mn concentrations as a function of lubricating oil usage.

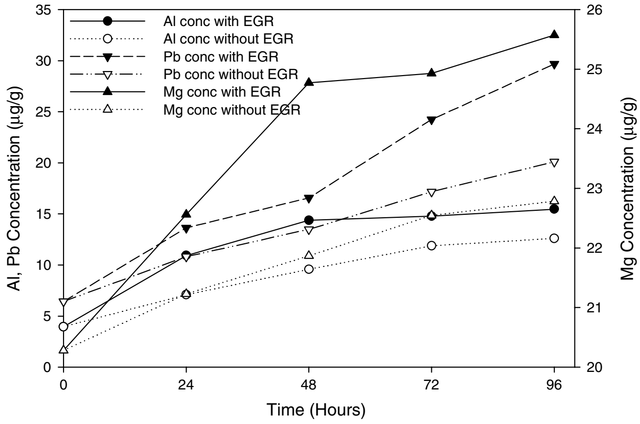

Fig. 8. Al, Pb and Mg concentrations as a function of lubricating oil usage.

During engine running, the piston rings rub against the liner surface. In the event of insufficient lubrication or lubricating film breakdown, metal to metal contact of rings and liner surfaces can take place, resulting in generation of wear debris due to wearing out of honed liner surface.

The figure indicates decreased rate of wear of engine parts in later phase of engine operation for both engines running with and without EGR. The most important observation from Fig. 6 is that the concentration of iron was found to be higher for EGR operated engine compared to the engine operating without EGR. The possible reason for higher Fe concentration in lubricating oil may be higher soot loading of lubricating oil, which reduces the lubricating efficiency of oil and at the same time, the soot particles take part in three-body wear acting as abrasive particles, leading to higher engine wear.

Copper: The copper in the wear debris originates from bushings, injector shields, valve guides, connecting rods, piston rings, bearings, bearing cages etc. It has been observed from Fig. 6, that for both experiments, copper concentration rises with almost a constant rate. The Cu concentration in lubricating oil drawn from EGR operated engine was approximately 5–7% higher.

Zinc: Zinc is added in the form of ZDTP to the lubricating oil as multi functional additive such as anti-oxidant, corrosion inhibitor, anti-wear additive, detergents, and extreme pressure additive. Hence, fresh lubricating oil contains a reasonable amount of zinc as organo-metallic complex. The initial amount of zinc in the lubricating oil was detected to be ≈570 μg/g. Wear of galvanized piping and addition of makeup oil are usually the main sources of increase in zinc concentration in used lubricating oil. Fig. 6 shows that concentration of zinc in the lubricating oil gets reduced during initial engine run, for both sets of experiments. After initial 24 h of engine run, the concentration of zinc in the lubricating oil was found to be rising. The reduction in the zinc concentration initially may be because of evaporation of zinc containing species from the lubricating oil (due to initial thermal stressing of the oil). After initial engine run, zinc concentration in the lubricating oil increases due to wear of various moving parts.

Chromium: It comes in the lubricating oil from the wear of cylinder liner, compression rings, gears, crank shaft, bearings etc. Very small amount of chromium was found in the lubricating oils for both phases of experiments (Fig. 7) and the rate of rise in levels of chromium concentration were almost similar. The amount of chromium in the lubricating oil drawn from EGR operated engine was found to be more than that of engine operating without EGR, possibly due to higher wear of components containing Chromium.

Nickel: The organo-metallic additives having nickel are added in very small quantity to the lubricating oil as anti-wear additives. Hence nickel was found in fresh lubricating oil also. Nickel also originates from bearings, valves, gear plating etc. The nickel concentration rises at a faster rate for initial 24 h of running of both the systems (Fig. 7) and after 24 h, the rate of rise decreases. This may be possibly due to higher wear of components containing Nickel due to EGR.

Manganese: Manganese was found in very small quantities in the lubricating oil samples. Manganese comes to the lubricating oil because of wear of cylinder liner, valves, shafts etc. For initial 24 h of engine run the manganese concentration rises at a faster rate (Fig. 7). After 24 h of engine run, the rate of rise stabilizes. This may be possibly due to higher wear of valves and shafts due to EGR.

Aluminum: Aluminum originates from piston, bearings, push rods, oil pump, gears etc. It has been observed that the concentration of aluminum is higher in the lubricating oil drawn from engine using EGR system (Fig. 8). The rate of rise of aluminum concentration in the normal operated engine is almost constant throughout the experiment.

Lead: The organic complexes of lead are added in the lubricating oil as extreme pressure additive. The concentration of lead as a function of lubricating oil usage is shown in Fig. 8. It is detected in used lubricating oil because of additions due to wear of bearings and fuel blow-by.

Magnesium: Magnesium is added to the lubricating oil as detergent inhibitor additive. Wear of cylinder liner surface and gears causes magnesium loading to the lubricating oil. It was found that the magnesium loading was 18–20% higher in the lubricating oil from the engine using EGR system than one without EGR (Fig. 8).

The concentration of all heavy metals such as Fe, Cu, Cr, Al, Ni, Mn, Pb, Mg and Zn was found to be increasing in both phases of experiments. In the initial engine run, the concentration of these metals rises at a faster rate. Possibly initial engine running leads to insufficient lubrication because of freshly honed liner surface of new engine. After initial running in, wear rate decreases. Also the concentration of all these metals in lubricating oils drawn from EGR operated engine was higher. The above observations suggest that engine operating with EGR undergoes higher wear compared to an engine operating without EGR.

One of the possible ways to overcome this problem due to EGR is to remove the soot from the re-circulated stream of the exhaust by passing it through a filter. Diesel particulate filter can however not be used at this stage as they require very low sulphur (<50 ppm) fuel in order to be used. Hence a metal mesh/ disposable paper filter can be used to clean he re-circulated exhaust stream. This will however increase the maintenance issues/ cost of operations related to the engine.

6. Conclusions

In the present study, the performance of engine running with and without EGR in two separate phases of experiments was compared using tribological investigations on lubricating oil. The soot deposits on various in-cylinder engine parts give a qualitative estimation of amount of soot generation inside the engine and it was observed that the engine operated with EGR has higher soot deposits compared to normally operating engine. The soot generated inside the engine is also passed on the lubricating oil. The soot loading of the lubricating oil was also found higher in case of EGR operated engine compared to engine operating without EGR, which enhances wear of various vital engine parts in the engine. Higher heavy metals content in the lubricating oil drawn from EGR operated engine proves higher wear in engine operated with EGR.

Hence inspite of EGR being an effective technology for reduction of NO_x emission, higher soot generation limits the use of EGR in CI engines. Higher soot generation is the biggest penalty for this method of NO_x control which leads to poor engine performance in term of faster lubricating oil degradation and higher wear of vital engine parts. Hence usage of soot trap along with EGR is the key for simultaneous control of soot and NO_x emissions from the engine, without jeopardising the engine longevity.

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