Experimental Investigation of the Effect of Exhaust Gas Recirculation on Lubricating Oil Degradation and Wear of a Compression Ignition Engine

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This experimental investigation was aimed to investigate the effect of exhaust gas recirculation (EGR) on wear of in-cylinder engine parts. EGR setup was prepared for a two-cylinder, air-cooled, constant-speed direct-injection compression-ignition engine. Test setup was run for 96 hr *under predetermined loading cycles in two phases; normally, operating condition (i.e., without EGR) and with a fixed EGR rate of 25%. Addition of metallic wear debris in the lubricating oil samples drawn after regular interval from both engine operating phases was investigated. Relatively higher concentrations of all wear metals were found in the lubricating oil of the EGR-operated engine, which indicates higher wear of various engine parts. Weight loss of piston rings used in both phases was compared to quantify the amount of wear of piston rings. To quantify the amount of cylinder wear surface roughness parameters of cylinder liners were measured at three positions (top dead center, mid-stroke, and bottom dead center) on thrust and anti-thrust side. A qualitative analysis was also carried out by taking surface profiles and Scanning Electron Micrographs at same locations.* [DOI: 10.1115/1.2136368]

Introduction

High compression ratio and lean fuel-air mixture give high thermal efficiency to compression-ignition (CI) engines. High fuel economy with high power makes these CI engines popular worldwide. In last decade, diesel engine technology has advanced significantly in terms of speed, power, and efficiency, due to which these engines are gaining popularity even in the passenger car segment [1]. Stringent emission norms for limiting emission of oxides of nitrogen (NO_x) and particulate matter (PM) from diesel engines have been adopted worldwide. In order to meet these norms, different pre and post combustion techniques have been adopted. Exhaust gas recirculation (EGR) is one of the techniques, which is being effectively used to control the NO_x emissions from light-duty diesel engines. Use of EGR in medium and heavy duty diesel engines has been limited so far because of increase in soot, engine wear and oil degradation [2,3]. With the use of EGR, approximately 40–50% reduction in NO_x emission can be achieved [4]. But there is trade-off between NO_x and soot emission. It is believed that as the EGR rate increases, the level of NO_x goes down, but soot increases [5]. The soot generated in the engine can either come out to the atmosphere with the exhaust or may stick to various in-cylinder engine parts or can get adsorbed to the lubricating oil film present on the cylinder walls and finally reach oil sump. The soot can also reach oil sump with blow-by gases. Soot in the lubricating oil accelerates its degradation [6]. Soot present in the lubricating oil consists of up to 90% carbon with traces of metallic elements [7].

In the EGR system, the majority of soot comes to the lubricating oil when it is scrapped down due to motion of rings or blow-by gases [8]. Cadman and Johnson [9] found ten times higher particulate concentration in the lubricating oil drawn from engines using 15% EGR compared to baseline.

Higher soot/carbon generated by the EGR system is the main cause of higher engine wear [10]. Soot particles act as abrasives and are adsorbed by the oil film present on the cylinder liner surface. When these soot particles are deposited at the interface between the piston rings and cylinder liner, a three-body wear mechanism occurs. The three-body wear mechanism involves two surfaces and entrapped particles, and wear occurs at the particle-surface interface. The diameter of soot particles generally ranges from 0.03–0.10 μm, whereas the thickness of boundary layer lubricating oil film is typically <0.025 μm [11,12]. Ishiki et al. [13] confirmed higher wear in piston rings of EGR-operated engines due to accelerated abrasive wear, experimentally.

Another possible reason for higher wear of various parts in the engine operated with EGR is corrosion, which occurs due to the formation of sulfuric acid by reaction of SO_x (formed during combustion) with the condensed water on cylinder surfaces [14]. When the sulfuric acid reaches oil sump, it reduces the total base number (TBN) of lubricating oil thereby affecting properties of the lubricating oil. The carbon (soot) in the lubricating oil reduces the effectiveness of antiwear film. Soot could hinder the additives from reaching the contact area by adsorbing them, thus, reducing the functionality of these additives [15,16].

The cylinder liner of a normally operating engine (operating without EGR) undergoes maximum wear at top dead center (TDC) and bottom dead center (BDC) because of boundary lubrication conditions prevailing at these locations. At these locations, the hydrodynamic lubricating oil film collapses due to near-zero relative velocity between the piston ring and liner [17]. The present experimental study is aimed at quantifying the wear of piston rings and cylinder liners because of the use of EGR in a typical constant-speed diesel engine and comparing it to the same

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Table 1 Technical specification of the test engines

Manufacturer/Model	Indian Ntl. Diesel Engine Co., (Under License from Hawker Siddley Ind. Ltd., UK) Petter Design/Indec PH2
Engine type	Two-cylinder, four-stroke, air-cooled, direct-injection CI engine
Bore/stroke (mm)	87.3/110
Rated power	9.32 kW @ 1500 rpm
Compression ratio	16.5:1
Displacement volume (cc)	1318
Fuel-injection pressure (MPa)	21

Table 2 Engine test cycle for endurance

Load (%)	Duration (minutes)
No load	20
100	30
50	120
No load	20
75	60
No load	20
100	30
75	60

engine operating with EGR under similar operating conditions. The other parameters, such as lubricating oil, fuel, etc., are kept identical for the entire experiments.

Experimental Setup and Methodology

The experiments were conducted on a constant-speed, two-cylinder, four-stroke diesel engine. This type of engine is typically used for captive power generation and for agricultural irrigation purposes. The technical specifications of the engine are given in Table 1. The exhaust gas recirculation setup was installed on the engine. Hot exhaust gases were recirculated and mixed with fresh air in intake manifold. The schematic diagram of the experimental setup is shown in Fig. 1.

The experiments were conducted in the following two phases:

1. baseline engine operation, i.e., engine operated without EGR under normal operating condition
2. engine operation with a fixed EGR rate of 25%

The engine test runs were conducted for 96 hr in each phase of the experiments. A typical load cycle of 6 hr (continuous) was selected for both phases. The engine test cycle for endurance is shown in Table 2.

A new set of cylinder liners, pistons, and piston rings were installed in the engine in the beginning of each phase of the experiments. SAE 20W/40 lubricating oil was filled in the engine at the start of test run, and no makeup oil was added. In both the phases of the engine experiments, no major breakdown was observed.

Wear of the engine is a slow and continuous process. In the engine, metallic wear debris is washed away by lubricating oil and they accumulate in the oil sump. Hence, wear-particle analysis is a powerful technique to examine the condition of vital engine parts.

Lubricating oil samples were drawn from the engine after every 24 hr of engine run for wear-metal analysis. Lubricating oil samples were analyzed on a flame atomic absorption spectroscopy unit (Make: Varian AAS spectra Model: AA 220FS) for evaluating the metallic composition of wear debris. After completion of both phases of the experiments, the piston rings were weighed in order to evaluate their wear. The liner surface profile was evaluated for various surface characteristics before and after the completion of each phase. A surface profilometer (Make: Mitutoyo, Japan, Model: SJ-301) was used for surface evaluation. Scanning electron microscopy (Make: FEI, Holland, Model: Quanta 200) was done for liner surfaces at TDC, BDC, and midstroke positions for both phases.

Experimatal Results and Discussions

Wear-Metal Analysis of Lubricating Oil Samples. Several sliding and rotating metallic components are involved in engine operation and wear debris originates from these parts. This debris

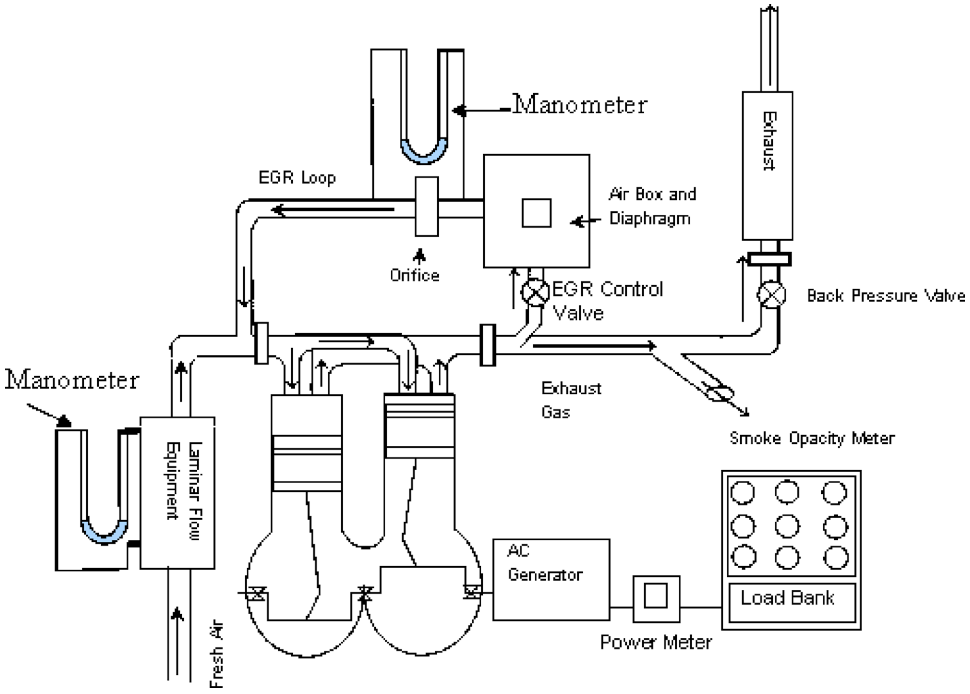

Fig. 1 Schematic diagram of experimental setup

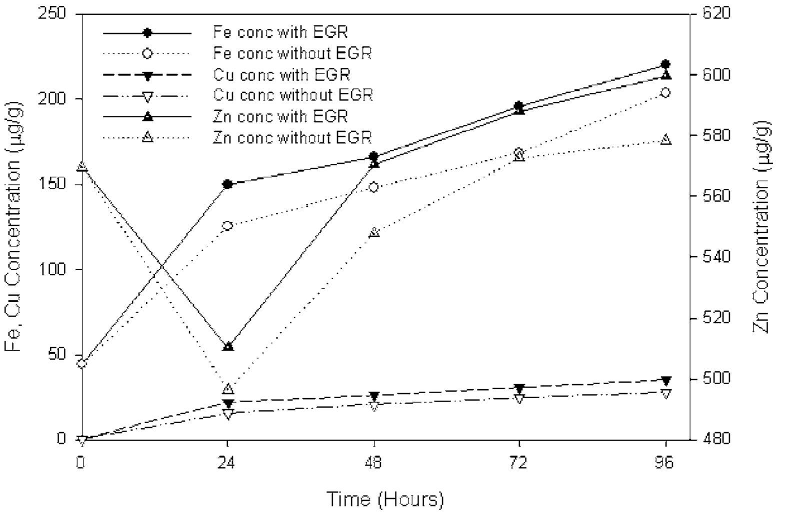

Fig. 2 Fe, Cu, and Cr concentration as a function of lubricating oil usage

finally accumulates in the lubricating oil sump. The oil samples drawn at regular intervals were analyzed for various metals present in the debris, such as Fe, Cu, Cr, Ni, Al, Mn, Pb, Mg, and Zn. For extracting the metals from lubricating oil samples, dry-ashing technique was used [18]. An approximately 5 gm lubricating oil sample was taken in a silica crucible and kept on hot plate at 120°C until it became free from moisture. Then the sample was kept in a muffle furnace at 450°C for 4 hr, thereafter at 650°C for 2 hr. The dried ash was then dissolved in 1.5 mL concentrated HCl, and the mixture was diluted to 100 mL using distilled water. Thus, all the nonorganic components present in lubricating oil gets transferred into the aqueous solution. The samples were then analyzed by atomic absorption spectroscope (AAS) for different metals. The concentration of various wear metal present in lubricating oil samples are shown in Figs. 2–4.

Figures 2–4 show an increasing trend of metallic concentration in the lubricating oil with usage for both experimental phases. The rate of rise in concentrations is initially higher, and then it slows down. The reason for this behavior may possibly be due to the use of new in-cylinder engine parts for each phase. Higher wear of these parts is observed possibly due to higher wear during initial running-in.

Each of these metals can be traced back to several engine parts. Typical sources of these metals present in the lubricating oil are the piston rings, piston, cylinder liner, bearings, connecting rod, crank shaft, valves, lubricating oil additives, etc. Table 3 represents the origin of each metal to different engine parts.

After the initial experimental phase, the rate of metal concentration increase in lubricating oil decreases. The results obtained prove the statement given by Sachs [21] that an engine component has three phases during its life span. The highest possibility of wear of a component is in its initial stage. After few hours of engine operation, the failure possibility reduces and the wear rate decreases. The wear rate again rises when the life of the engine component comes to an end in the last phase, enhancing the possibility of wear leading to failure.

The metallic concentration in the lubricating oil of an engine operated with EGR is always higher than an engine operated without EGR. This indicates higher wear of engines operated without EGR in comparison to engines operates without EGR. Figure 4 shows the variation in Zn concentration as a function of lubricating oil usage. It has been found that the concentration of Zn initially decreases and then increases for both phases. The possible reason for the initial decrease in Zn concentration may be the thermal stressing of the Zn containing additives followed by their evaporation. In the later part of the engine experiments, wear of

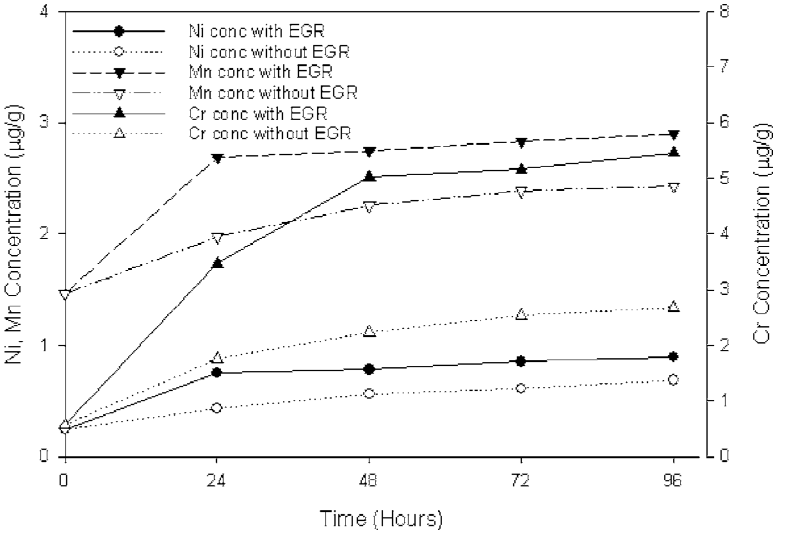

Fig. 3 Ni, Al, and Mn concentration as a function of lubricating oil usage

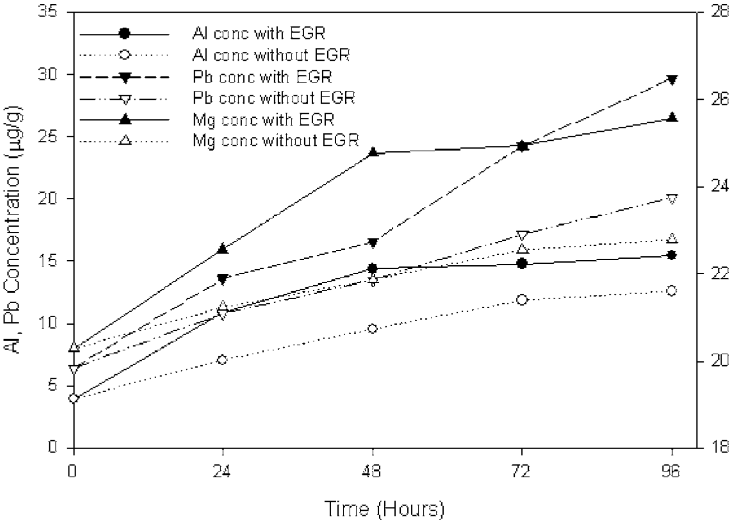

Fig. 4 Pb, Mg, and Zn concentration as a function of lubricating oil usage

various engine parts, such as bearings and galvanized piping, etc., increases Zn concentration in the lubricating oil. Thus, wear metal analysis gives an indication toward higher wear in EGR-operated engines compared to normally operated engines.

Soot Loading of Lubricating Oil. Major part of the soot present in the lubricating oil is in organic carbon form. The lubricating oils from the engine contain negligible amounts of inorganic carbon. The base stock of lubricating oils is organic. Additives are also complex organic metallic compounds. There is very little chance of a reaction of lubricating oil in order to form inorganic carbon while the 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 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 increases at a faster rate in lubricating oil samples drawn from an EGR-operated engine compared to a normally operated engine. This higher increase in levels of carbon (in other words, soot) in the lubricating oil drawn from an EGR-operated engine may reduce the lubricating efficiency of the oil, resulting in increased wear of vital engine parts and a reduced useful life of lubricating oil.

Wear of Piston Rings. In both phases of the experiments, new engine parts, including piston rings, were installed before starting the test. To quantify the amount of wear, piston rings were weighed before engine assembly and after 96 hr of engine run. The percentage weight loss of rings for both phases of experiments are shown in Fig. 6.

It has been observed that the top compression ring (CR1) of the engine operating without EGR has maximum weight loss among three compression rings (0.50% of its initial weight). The top compression ring faces the highest thrust of combustion gases and

Table 3 Typical sources of wear metals in lubricating oil [19,20]

Elements	Sources
Aluminum	Piston, bearing, dirt
Chromium	Compression rings, coolant, crank shaft, bearings, plating of cylinder liners
Copper	Bearing, piston rings
Iron	Wear from engine block, cylinder liner, rings, crankshaft, anti fiction bearings
Lead	Bearings
Magnesium	Bearings, cylinder liner
Nickel	Piston rings, valves
Zinc	Bearings, platting, brass components
Manganese	Steel shafts, valves

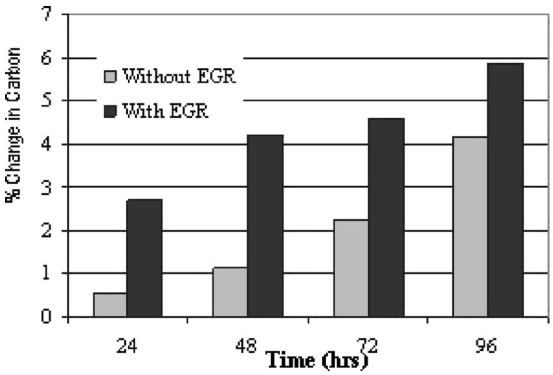

Fig. 5 Percent change in carbon content as function of lubricating oil usage

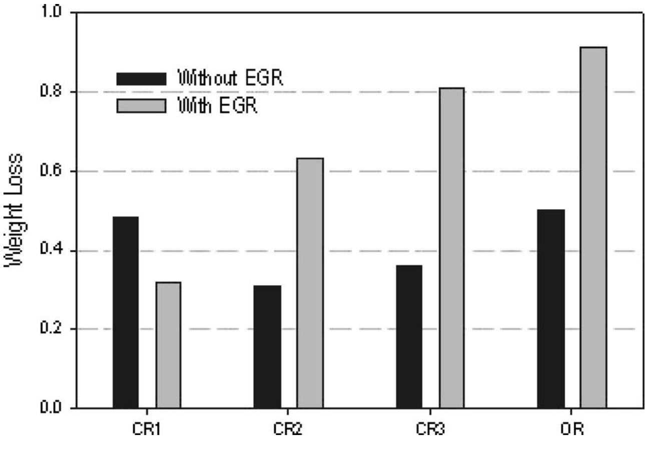

Fig. 6 Percent weight loss of piston rings after 96 hr of engine run

Table 4 Roughness parameters of engine operating with and without EGR

Parameter (μm)	Initial	After 96 hr of engine run: TDC	Midstroke	BDC
		Thrust side		
R_a	0.90 (1.18)[a]	0.75 (0.66)	0.50 (0.34)	0.60 (0.20)
R_q	1.15 (1.57)	1.03 (0.87)	0.78 (0.59)	0.64 (0.37)
R_t	7.18 (12.00)	6.49 (5.31)	6.98 (4.57)	7.37 (3.45)
R_p	2.78 (3.57)	0.98 (0.18)	1.81 (0.67)	1.24 (0.37)
R_v	3.01 (8.25)	5.51 (3.51)	5.17 (3.90)	6.13 (3.08)
		Anti-thrust side		
R_a	0.81 (1.72)	0.49 (0.47)	0.65 (0.60)	0.58 (0.16)
R_q	1.05 (2.59)	0.99 (0.65)	0.76 (0.85)	0.77 (0.34)
R_t	7.84 (21.98)	7.57 (5.27)	6.67 (5.43)	4.87 (3.53)
R_p	3.11 (10.76)	1.35 (2.20)	1.77 (1.23)	1.02 (0.36)
R_v	4.51 (11.22)	6.22 (3.07)	4.90 (4.20)	3.85 (3.17)

[a] The values in the parentheses are for EGR phase experiment.

works in the highest temperature zone; therefore, the top compression ring undergoes maximum wear. The weight loss of oil ring was found comparable to the top compression ring (approximately 0.50%). In the engine using EGR, the top compression ring faces the lowest weight loss compared to other rings (~0.30%), and the oil ring (OR) faces highest weight loss (~0.90% of initial weight). A possible reason for this may be a lower temperature of the combustion chamber of the engine using EGR, which exposes the top compression ring to lower gas thrust and temperature, causing lower wear. However, the wear of the second and third compression rings and the oil ring were comparatively higher for engines using EGR. The possible reason for this may be the presence of a higher amount of soot and wear debris at the ring-liner interface in the engine using EGR. The oil film present in the ring-liner interface region of second and third rings is significantly thicker compared to that of top ring-liner interface region.

Wear of Cylinder Liner Surfaces. In both sets of experiments, new cylinder liners were installed in the engine before starting the experiments. To check the wear of cylinder liner material during the engine run with EGR and without EGR, surface profiles were taken before and after 96 hr of the engine test run, at identical locations. The surface profiles were evaluated at three locations namely top dead center (TDC), midstroke, and bottom dead center (BDC) on thrust and anti-thrust side. TDC and BDC are the most important locations of the cylinder liner with possibility of high wear. The surface profilometer evaluates the surface textures and gives a number of surface roughness parameters, such as R_a, R_q, R_v, R_p, R_t, etc. The evaluation length was 12.5 mm. Profile magnification was 10× in the horizontal direction and 2000× in the vertical direction. The average roughness R_a is the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length. R_a does not give a clear picture about a surface. Surfaces may have the same value of R_a, but they may be quite different in the shape of the profile. Even if two profiles have similar shapes, they may have different spacing between features. Hence, it is needed to distinguish between surfaces that differ in shape or spacing. Other parameters for a surface that measures peaks, valleys, profile shapes and spacing, etc., need to be calculated. Root-mean-square roughness (R_q) of a surface is calculated from another integral of the roughness profile. The peak roughness R_p is the height of the highest peak in the roughness profile over the evaluation length. Similarly, R_v is the depth of the deepest valley in the roughness profile over the evaluation length. The total roughness R_t is the sum of these two, or the vertical distance from the deepest valley to the highest peak. In practice as R_a is a measure of the departure of the profile from the mean line and R_q is the rms roughness, they provide similar information about a surface. In practice, R_q is a more statistically significant parameter, whereas R_a has the advantage of being more a commonly used parameter.

The roughness parameters of cylinder liner for engines operated with and without EGR on thrust and anti-thrust sides are shown in Table 4, and surface profiles are shown in Figs. 7 and 8. It can be

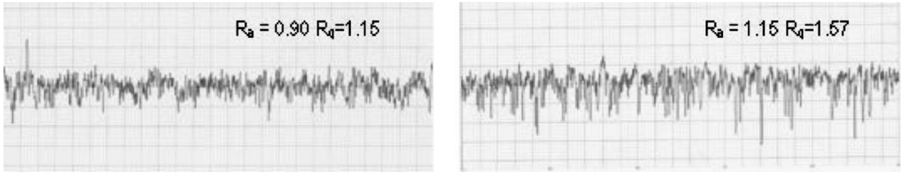

Fig. 7 Surface profile of fresh liner (*a*) without EGR (*b*) with EGR

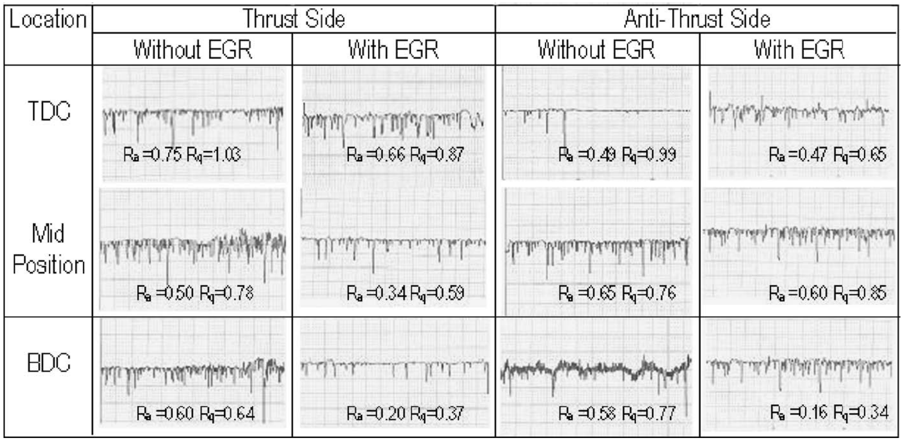

Fig. 8 Surface profiles of cylinder liner surfaces of engine operating with and without EGR after 96 hr

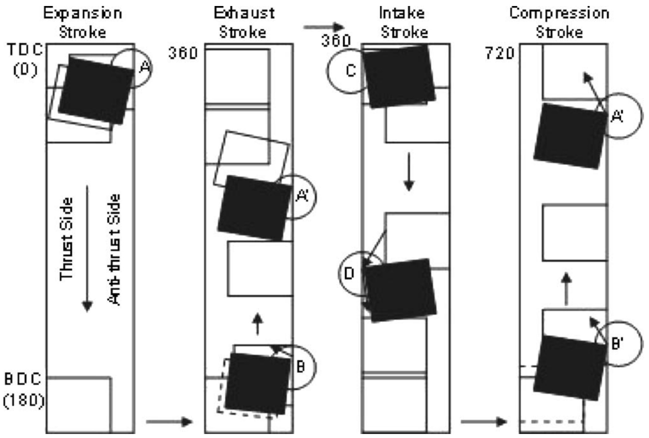

Fig. 9 Representation of piston motion [22]

observed that the wear of the liner at TDC is consistently more than at BDC and midstroke positions when engines operate without EGR. The lower values in Table 4 indicate a flatter and smoother surface, reflecting higher wear of the initial surface. The wear at TDC is more because this zone of cylinder liner faces the highest temperature due to hot, high-pressure combustion gases. TDC faces the highest load and relatively low piston speeds so boundary lubrication at TDC location breaks down, and, possibly metal-to-metal contact takes place, enhancing the wear.

It can also be observed that wear of the cylinder liner is higher on the anti-thrust side compared to the thrust side. This may happen because of the piston tilt during its strokes. In the four strokes of engine operation, the piston touches the thrust side of cylinder liner surface during intake stroke, when temperature and pressure of engine are low. For the remaining three strokes, the piston touches the anti-thrust side of cylinder liner surface, as shown in Fig. 9.

It can be observed from Fig. 8 that the BDC position of the cylinder liner faces higher wear compared to TDC and midstroke positions, when an engine runs with EGR. In the engine using EGR, the combustion temperatures are relatively lower compared to those without EGR conditions; hence, the engine powerpack gets exposed to less severe conditions causing relatively lower wear at TDC on the thrust side of the liner. While on anti-thrust side, since the piston touches the cylinder liner for three strokes (Fig. 9), inspite of low temperatures inside the combustion chamber, significantly higher wear takes place. At BDC position, boundary lubrication exists and the lubricating oil of an EGR system contains a higher amount of wear debris, which may also be responsible for excessive wear at BDC. The wear of thrust and anti-thrust sides were almost the same in all three locations.

Scanning Electron Microscopy. In failure analysis, scanning electron microscopy (SEM) is a natural extension of optical microscopy. The combination of higher magnification, larger depth of focus, greater resolution, and ease of sample observation makes it one of the most heavily used instruments in research today.

The wear of cylinder liner surfaces was compared by scanning electron microscopy after 96 hr of engine operation. The magnification used is 400×. The SEM micrographs were taken at three locations (TDC, midstroke, and BDC) on both thrust and anti-thrust sides for both phases of the experiment. Figure 10 shows the micrographs of cylinder liner surfaces of both, normally operated engine and EGR-operated engine. It has been observed that in the normally operated engine, high wear was observed at TDC positions on both sides. Midstroke positions show significantly lower wear, and wear on anti-thrust side was higher than on the thrust side.

These observations (Fig. 10) substantiate the results of roughness parameters (Table 4) and surface profiles (Fig. 8). In an EGR-operated engine, the highest wear has taken place at BDC as obtained by surface profiles and also roughness parameters. The cross-hatched honing marks completely disappear at these locations, showing severe damage to the surface.

Conclusions

An experimental investigation was carried out to quantify the wear in an EGR-operated diesel engine vis-à-vis a normally operated diesel engine. Wear metals in lubricating oil, which originate from different moving parts, were analyzed. Higher wear metals were obtained in lubricating oil of an EGR-operated engine, suggesting increased engine wear because of EGR. This is attributed to increased soot contamination of the lubricating oil.

The wear pattern of piston rings and cylinder liner surfaces were also analyzed. It has been observed that piston rings of an EGR-operated engine face a very different trend than normally operated engine. The top compression ring of EGR-operated engine undergoes 0.1% lower wear than a normally operated engine, while the oil ring of an EGR-operated engine faces 0.4% higher wear than its counterpart. The wear pattern of surfaces of cylinder liner was evaluated for surface profile and various roughness parameters on the thrust and anti-thrust sides at three locations. In a

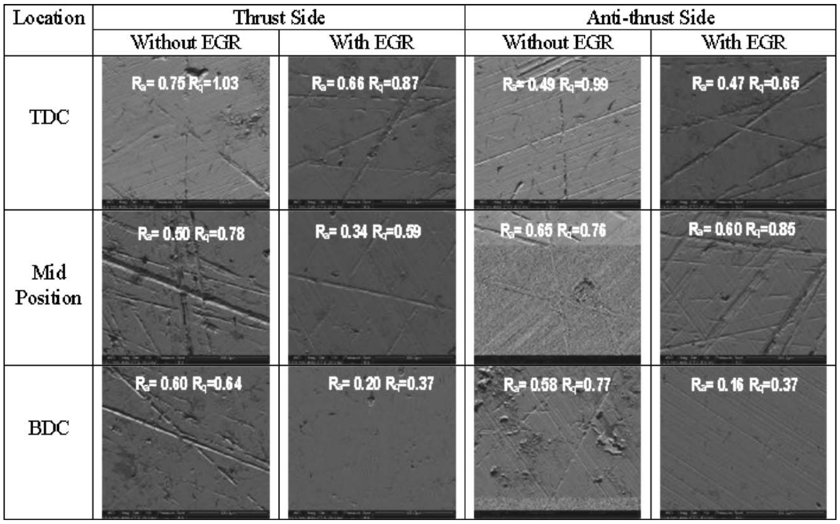

Fig. 10 SEM of cylinder liner surfaces of engine operating with/without EGR

normally operated engine, TDC location faced the highest wear on the anti-thrust side, whereas in an EGR-operated engine, highest wear took place at the BDC position and the wear was almost similar on the thrust and anti-thrust sides. The results obtained were also supported by scanning electron micrographs. The results of the experiments conducted on twin-cylinder contact-speed direct-injection diesel engines using SAE 20W40 lubricating oil and diesel #2 fuel suggest that using EGR to control NO_x enhanced wear of the engine.

Acknowledgment

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