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DURABILITY, LUBE OIL CONTAMINATION AND A FERROGRAPHY STUDY ON A DIESEL ENGINE FUELLED WITH DISTILLED TYRE OIL

Summary

This research work focuses on durability tests on diesel engines powered by 30 vol% distilled tyre oil with diesel (DTPO30). The duration of the study was for 1500 running hours and includes an analysis of engine performance, emission formation, viscosity, wear, and additives in lubrication oil with a ferrographic examination. The respective wear and additives in the oil were measured every 450 hours. In the engine running on DTPO30, brake thermal efficiency (BTE) declined by up to 0.5% and brake specific fuel consumption (BSFC) also diminished by up to 1.5% after 1500 hours when compared with the initial stage operation. In addition, all the harmful emission parameters such as NOx, CO, and HC grew by between 0.7 % and 1.1%. The viscosity of lube oil was observed to fall by up to 13% with diesel and 36% with DTPO30 compared with the initial condition. The amount of additives was also lower in the lubrication oil in DTPO30 compared with in pure diesel. A higher carbon deposition was also found in many places, such as in the piston top, around the injector nozzle, and in the valve seat with DTPO30. The wear of each part was identified by estimating the metal contamination in the lube oil by means of a ferrography tester. Further, the metal contaminations in the lube oil were found to amount to as high as 79% in DTPO30. In addition, the size of the particles was identified to be larger than in the case of diesel.

Key words: *diesel engine, distilled tyre oil, lubrication oil, metal contamination, ferrography*

1. Introduction

In view of the expanding demand for fossil fuel and its rapid depletion, many researchers have been keenly engaged in finding an effective alternative. As a result, different alternative fuels have been derived from either organic or inorganic sources and tested on internal combustion engines. The performance, combustion and emissions from engines mainly rely on the thermal properties and chemical structures of those particular fuels. Mostly, the viscosity of various virgin alternative fuels has been found to be higher, which leads to poor atomization and poor mixture formation. The fuels from palm, soybean and waste tyre oil have a viscosity of about 4.2, 4.03, and 16 mm^2/s respectively, whereas diesel has a viscosity of 2.7 mm^2/s. Consequently, ignition delay, incomplete combustion and higher emissions have been encountered. Most of the alternative fuel research has been concluded with a few time tests, but not with a durability test. It is important to note that abnormal combustion induces unwanted friction and wear in various engine-moving components. From this perspective, researchers have attempted a durability analysis of diesel engines using alternative fuels. This kind of analysis mostly includes wear and deposition measurements.

From the ideology of an alternative fuel approach, distilled waste tyre oil has been selected for use in diesel engines to reduce solid tyre waste which has an adverse impact on the environment. A recent survey indicates that 1.6 billion tyres are sold annually while the same quantities of tyres are discarded [1]. Only 15-20% of discarded tyres are considered for recycling. The remaining 75% to 80% are deposited directly in the environment, thus creating more pollution. However, the high calorific value of waste tyres makes them a good feedstock for fuel production [2]. Here, the waste tyres are processed in a pyrolysis process in a controlled environment for extracting oil. Then, the tyre oil is distilled using a fractional distillation column which in turn achieves controlled CO_2 emissions. Tyre waste is a viable potential source for conversion into oil because it is a petroleum product. From the derived content of previous investigations, waste tyre oil has the potential to enable diesel engines to run smoothly with better performance. Yet the emissions have been observed to be higher than those of diesel operations [1-3].

The pyrolysis technique is employed to extract oil from tyre waste, which is then subjected to a distillation process to separate it into different products. The first stage of distilled oil possesses better properties than diesel compared to other tyre oils such as raw tyre and second-stage distilled oils. Engine testing has been carried out with different blends of mixed waste tyre oil and plastic pyrolysis oil in various blending ratios, and it has been found that a 30 vol% of mixed tyre and plastic oil produces better performance and reduced emissions compared to other blends. The blend proportion of both tyre and plastic oil was 15 vol% each in diesel (15 vol% of tyre oil + 15 vol% plastic pyrolysis oil + 70 vol% of diesel), and it was prepared by magnetic stir action. At maximum loading conditions, the brake thermal efficiency of D1WPO30 (30 vol% of stage 1 waste plastic oil + 70 vol% diesel) has been found to be about 9.5% higher while specific fuel consumption was 13.5% lower than the WPO30 (30 vol% raw waste plastic oil + 70 vol% diesel) sample. The emission of NOx, CO, and HC was observed to be 8%, 12%, and 11% lower with D1WPO30 than raw WPO30. However, compared with diesel operations, they were found to be 12%, 15%, and 13% higher [2].

Several studies have been conducted to test these samples on a diesel engine. The rate of heat release and cylinder pressure was observed to be higher with the tyre oil blend (W10 – 10 vol% of tyre oil with diesel) compared with diesel. In addition, ignition delay increased with an increase in tyre oil volume; brake thermal efficiency with the tyre oil blend (W10) fell by up to 2.2% compared to diesel, and CO declined by 13.7% with W10 compared to diesel at full load, while NOx increased by 7.62%. Soot decreased by about 10.94% with W10 compared with diesel at full load [3]. An addition of 4 vol% of diethyl ether (DEE) to tyre oil blends (40 vol%) caused a reduction in the ignition delay, brake specific fuel consumption, and NOx by up to 6%, 10%, and 25% compared with the normal tyre oil blend [4].

A durability test was carried out on a diesel engine for a study period of 700 hours with diesel and palm biodiesel (B100) separately. A greasy kind of deposition was found when diesel was used, whereas a dry deposition was captured in palm biodiesel. These deposits were mostly located on the piston top, injector nozzle, and valve seat. But no unusual wear was recognized on the pistons and rings [5]. A 10 vol% of Karanja biodiesel (K10) was tested for 512 hours in a diesel engine; a darker and dry carbon deposition was noticed on the piston top and injector nozzle with the K10 samples compared to the diesel, and corrosion marks were found on the piston top [6]. Another diesel engine was engaged in testing for 500 hours using a diesel and biodiesel blend. This analysis was carried out under maximum load and transient load conditions. The maximum carbon deposition was observed to be about 1.188g with biodiesel at maximum load while it came to 0.645g with diesel at maximum load [7]. A diesel engine was used for up to 3500 hours using biogas and diesel in a dual fuel mode of operation; carbon and sulphur were found on the combustion chamber wall at a maximum level of hard and thick deposits. This indicates that a small amount of fuel was combusted near the wall and left its residues as a deposition [8]. A single-cylinder (model: YanmarTF140E) engine was tested for up to 200 hours using four different additives with diesel. The additives included 20 vol% blends of 4-Diisoamylethe, 4-Methylacetophenone, 4-Methylguaiacol, and 4-Propylguaiacol. The deposition with the first two additives was found to be similar, but the others produced more deposition in the squish region with a grainy and glaring effect [9]. The amount of different wear debris was analysed in the lubrication oil from the diesel engine combination of diesel and biodiesel (B100) for 200 hours. The total quantity of wear metal in the lube oil was about 17ppm with diesel and 39 ppm with B100 [10]. Similarly, a diesel engine was tested at two different periods under biogas and diesel in a dual-fuel mode of operation. The measured total debris was 147 ppm with the 900-hour operation and 212 ppm with the 2000 hours of operation [8]. From the perspective of a durability test on a diesel engine, no study was found on tyre pyrolysis oil as an operating fuel. Generally, raw tyre pyrolysis oil has more carbon and sulphur content which causes high CO_2 emissions. However, these were reduced drastically when raw tyre pyrolysis oil underwent a distillation process with a temperature range between 100°C to 300°C [11].

The objective of this article is to study the quantity of deposition and wear metal contamination by means of a ferrographic analysis of lube oil in a diesel engine operated with a distilled waste tyre oil blend. Among other methods for analysing the wear metal debris, ferrography is better as it can show the shape and size of the debris in detail, whereas FTIR, ferrous density and elemental methods are not able to indicate the shape and size. Carbon and other depositions were analysed visually. Different metal contaminations due to friction and wear during the engine run using DTPO30 (30 vol% of distilled tyre pyrolysis oil + 70 vol% of diesel) were analysed and compared with diesel fuel. Ferrography was also used to analyse the structure of wear metals in various samples of lube oil.

2. Materials and methods

Tyre pyrolysis oil was derived from waste tyres using a thermal degradation process and was then processed with a fractional distillation column. The distillation was carried out between 110ºC and 300ºC; here, most of the carbon and other impurities were separated. The properties of different tyre oil samples are provided in Table 1. The calorific value and the cetane number of crude tyre oil obtained by pyrolysis were found to be lower than those of diesel; these lower values induced higher fuel consumption and delayed combustion [12]. However, the sulphur content and acid value were higher than in diesel and these values produced higher emissions. Due to these undesired properties, raw tyre pyrolysis oil (TPO) was subjected to a distillation process. The properties of distilled tyre pyrolysis oil (DTPO) and its blends were found almost similar to those of diesel.

Two new diesel engines were selected with the same specification for a durability analysis. Both engines were coupled with dynamometers as shown in Figure 1 in the same operating conditions. One engine was operated with diesel and the other was operated with DTPO30. The optimal blend ratio DTPO30 that enhances performance and reduces the level of emissions was found in a previous investigation [2]. The specification of each engine is given in Table 2. The engines were operated for up to 1500 hours and then dismantled for visual inspection. The entire lubrication oil was replaced after every 450 hours, which was then analysed with ferrography for metal contamination. After 150 hours at each step, a sample of 250 ml was collected from the engine to test its viscosity. At this time, only the 250 ml was replaced with fresh oil.

Table 1 Properties of various sample fuels

	Density kg/m3	**Kinematic viscosity CST**	**Gross calorific value in kJ/kg**	**Flash Point °C**	**Fire Point °C**	**Acid Value**	**Sulphur Content in %**	**Cetane number**	**Evaporation temperature in °C**
Test Methods	IS 1448 P 32	IS 1448 P 25	Bomb colorimeter	IS 1448 P 69	IS 1448 P 69	IS 1448 P2	IS 1448 P 33	IS 15607: 2005	Fractional distillation column
Diesel	832	3.05	46500	50	56	0.5	0.045	55	145°C to 360°C
TPO	965	3.6	41229	41	45	2.21	1.02	50	110°C to 350°C
DTPO	895	0.18	43773	35	41	2.1	0.55	52	138°C to 300°C
DTPO30	856	0.76	45500	42	46	1.05	0.1	53	140°C to 360°C

Table 2 Engine Specification

Details	**Kirloskar, single cylinder, 4 stroke, air cooled and CI engine with 661 cc**
Cylinder bore in mm	87.5
Stroke length in mm	110
Rated power output in kW	5.2 with 1500 rpm
Compression ratio	17.5:1
Injection pressure in bar	200
Injection timing ° CA	23
Injection duration (ms) and targeted mass per injection (mg)	1.75 ms and 30 mg per injection
Injection type	Direct injection
Fuel	H.S. diesel
Dynamometer arm length in mm	185 mm arm length, eddy current, water cooled.
Lube oil sump capacity	3.7 l

Table 3 Measuring equipment

Instruments	**Unit**	**Operation**	**Manufacturer and Model**
Pressure transducer (Cylinder pressure)	Bar	Piezoelectric principle	M/S Kistler, Model:603CBA00350.0 IEPE
Crank angle encoder	Degree	The optical disc is used to give trigger pulse signal information for every rotation.	M/S Apex Innovations, Model: Type 2614D21
Thermocouple	°C	-200 to 1260°C	M/S Apex Innovations, Model: K Type
Fuel flow sensor	ml/min	Differential Pressure transmitter	M/S Unitech Differential Pressure Transmitter, Model Number: UT-1402
Air flow sensor	kg/s	Differential Pressure transmitter	M/S Baumer CTX, Model: AWM720P1
AVL digas analyser	NOx(ppm), CO (vol%), HC (ppm),	Selective absorption of infrared energy at particular wave length	AVL di gas 444 analyser
AVL smoke meter - smoke opacity	Percentage	Measuring the intensity of smoke with respect to opacity as a parameter	AVL 437 C smoke meter

The various pieces of equipment used for testing is shown in Figure 1 and are listed in corresponding details in Table 3. The specification of lube oil was referred to from the manufacturer data given in Table 4.

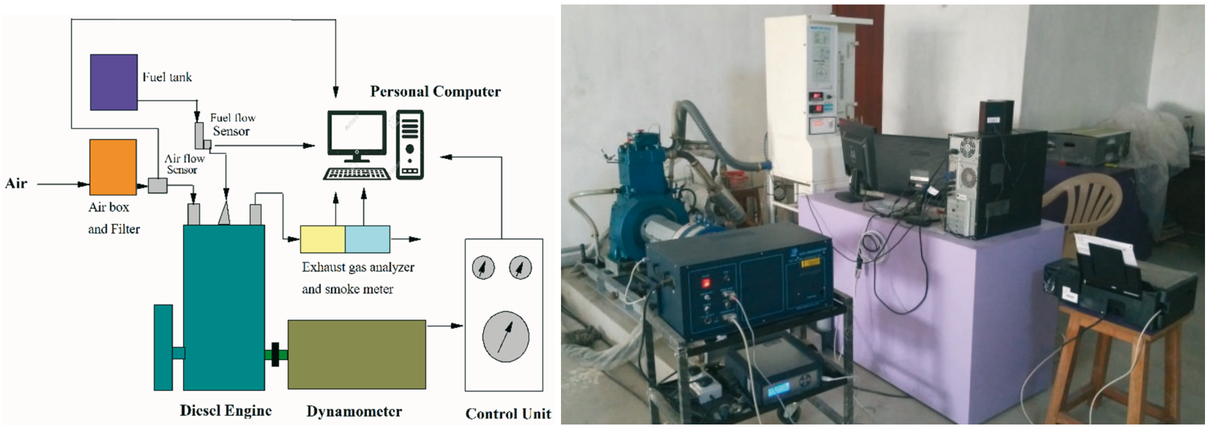

Fig. 1 Diesel engine test setup

Table 4 Lubrication oil specification engaged

SAE GRADE	15W-40
Kinematic Viscosity, cSt @40°C	121
Kinematic Viscosity, cSt @100°C	15.5
Viscosity Index, Min.	135
TBN, mg KOH/g	10.8
Flash Point, (COC)°C, Min.	200
Pour Point °C, Max.	(-) 24

The used lube oil samples were collected for ferrographic analysis of wear elements and contamination. The sample collection followed certain procedures to ensure cleanliness in the collection and storing of bottles.

Two engines were used for this analysis and operated under 75% loading conditions. The engine normally ran 8 to 10 hours daily. Fuel consumption was observed after every 150 hrs. The used lubrication oil samples were analysed to check for the presence of wear metal, contamination and additives using Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) ICP- OES (Make: Agilent Technologies 5110 model) and Ferrogram Maker and Wear Particle Analyzer (Make: T2FM 500 Spectro).

3. Results and discussion

After running the Kirlosker AV1 diesel engine for 1500 hours using diesel and DTPO30 individually, the engine was dismantled to check for depositions and unusual wear in various parts. In addition, the lubricating oil was collected and analysed for wear metal, contamination, additives, and ferrography was carried out at the Centre for Mechanical Engineering Research Institute (CMERI), Government of India, Durgapur, India. The fuel consumption and all the emission parameters were measured every 150 hours and compared with each other.

3.1 Performance evaluation

The fuel consumption for the diesel engines with diesel and DTPO30 is shown in Figure 2. The diesel consumption varied between 0.251 kg/kW-hr and 0.255 kg/kW-hr, whereas DTPO30 consumption in the diesel engine varied between 0.275 kg/kW-hr and 0.279 kg/kW-hr from the starting day until 1500 hours of running time had elapsed. The higher consumption of DTPO30 than diesel was due to the lower cetane number and non-homogeneity of the mixtures [13].

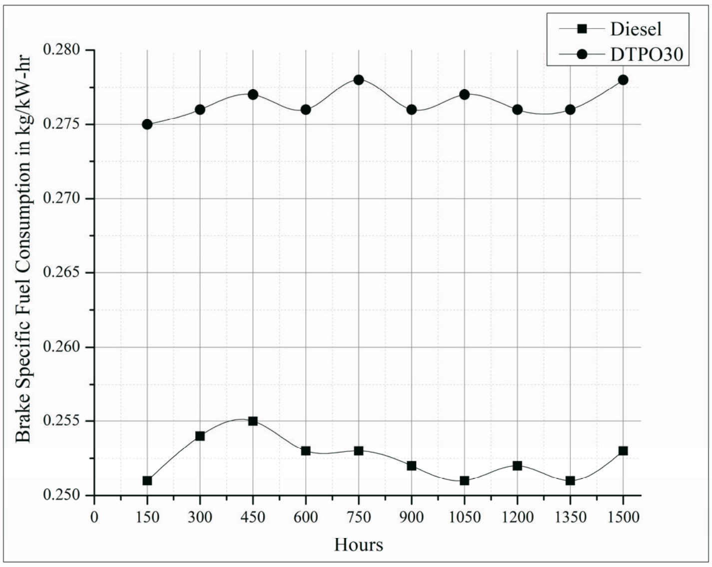

Fig. 2 Brake-specific fuel consumption for 1500 hours of running time

Brake thermal efficiency is a calibre of the engine to convert into the shaft work from the chemical energy of fuel. It varied from 32.95% to 33.15% with diesel for 1500 hours of running time. It varied between 30.35% and 29.9% with DTPO30 as shown in Figure 3. The fuel consumption of DTPO30 increased when the engine was operated for a long duration. The reasons for this increase were depositions on the combustion chamber walls and increased friction with the cylinder wall [5].

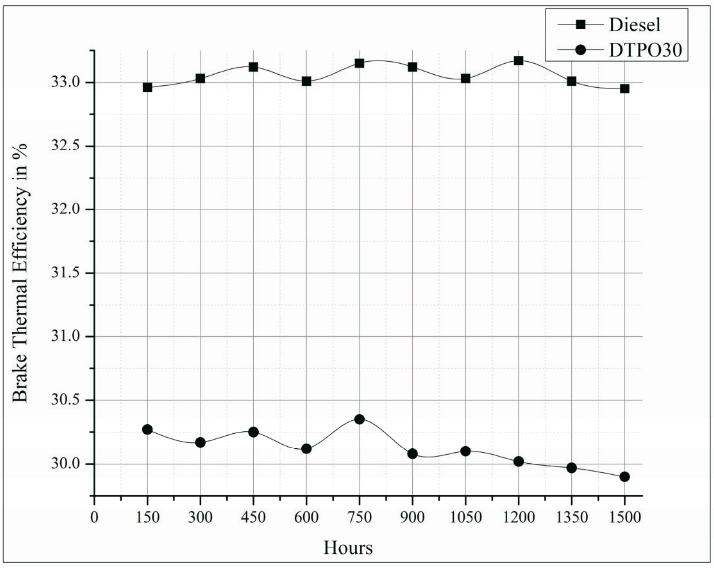

Fig. 3 Brake thermal efficiency for 1500 hours of running time

Here, brake thermal efficiency is a product of mechanical and indicated thermal efficiency. Concerning mechanical efficiency, due to the friction between the moving parts and auxiliaries, performance was affected when the engine operated with DTPO30 which in turn saw diminishing thermal efficiency while performing long-term operation [14]. Brake thermal efficiency is a product of the indicated thermal efficiency and mechanical efficiency. Since the compression ratio is constant for the entire operation, a reduction in indicated thermal efficiency directly affects brake thermal efficiency.

3.2 Engine emission

NOx formation from the engine was found higher with DTPO30 than with diesel. This is because of the higher cylinder pressure, ignition delay and non-homogenous nature of the fuel mixture [15]. In the case of long operation, the variation lies between 2055 ppm and 2072 ppm with diesel, and 2212 ppm and 2234 ppm with DTPO30, as shown in Figure 4. The higher variation with DTPO30 is due to the increase in cylinder temperature caused by particle deposition around the walls. On the other hand, higher cylinder temperature reduces soot formation as a result of better combustion as shown in Figure 7. The possibility of reducing the unburnt mixtures left the combustion chamber with a consequent near-complete oxidation reaction [16]. In general, DTPO30 has higher aromatic content which increases the high heat release rate during the premixed stage of combustion to form more NOx. The variation of unburned hydrocarbon (UBHC) lies between 40 ppm and 42 ppm for diesel fuel, and 49 ppm and 57 ppm for DTPO30 as shown in Figure 5. Higher UBHC was found with DTPO30 than with diesel due to an increase in flame quenching and wall wetting at the cylinder lining and the runaway of fuel particles from the combustion chamber to the crevice region [17].

Figures 6 and 7 indicate the carbon monoxide (CO) and smoke opacity variations for 1500 hours of running time. The maximum elevation of CO was 0.003 vol% with diesel and 0.005 vol% with DTPO30. Later on, due to high deposits on the walls in DTPO30 operations, imbalance occurred in the chemical kinetics and also in the engine operated with rich mixtures for compensating the loads, thus increasing CO in the emissions. Similarly, the smoke opacity increased from 38.8% to 39.13% with diesel and 59.4% to 60.34% for DTPO30. Here, the soot particles were found to be lower with DTPO30 than diesel due to the higher heat rate. Most of the emission parameters increased by around 7.2% for NOx, 47% for CO, 41% for HC, and 53% for smoke; this is mainly because of the increasing deposits on the walls, friction, and the wear of the engine parts [18].

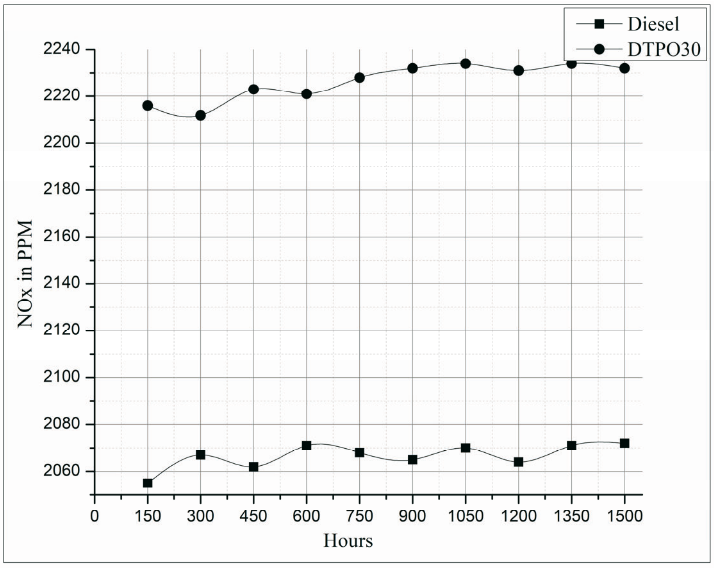

Fig. 4 NOx formation for 1500 hours of running time

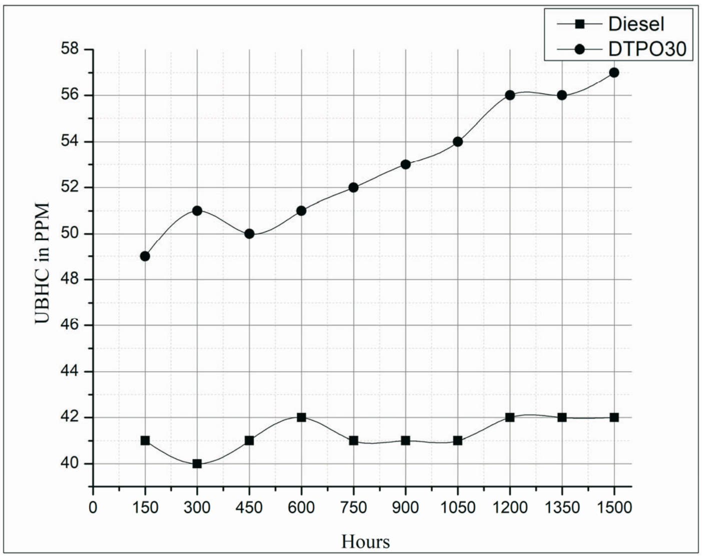

Fig. 5 UBHC formation for 1500 hours of running time

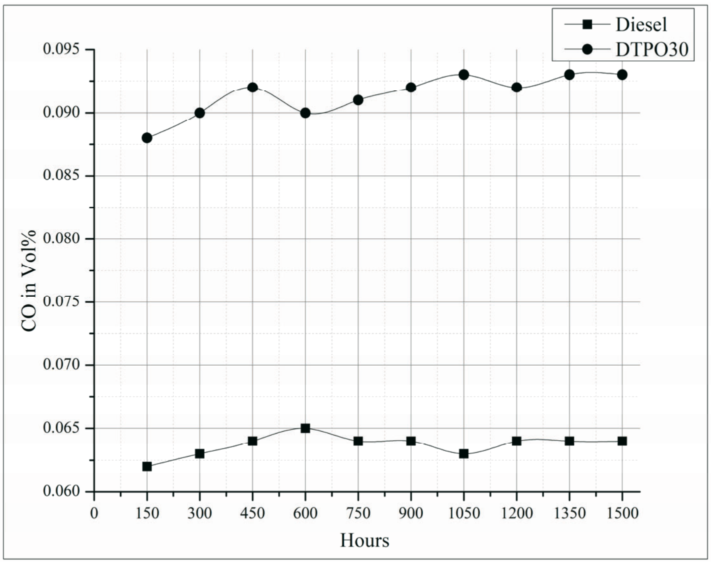

Fig. 6 CO formation for 1500 hours of running time

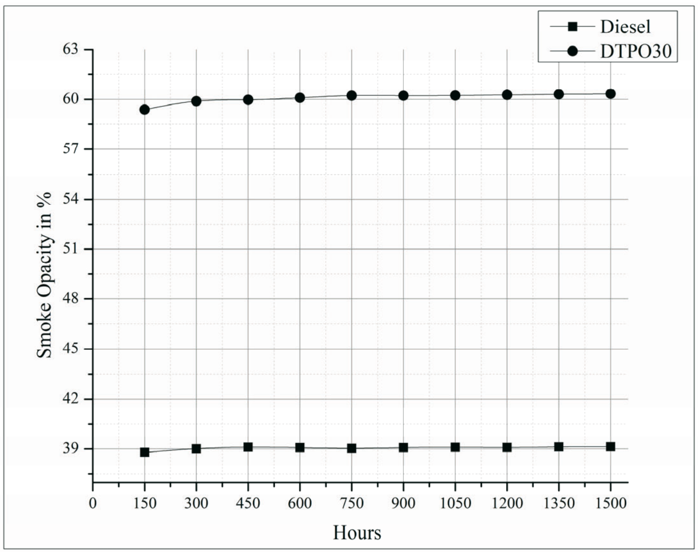

Fig. 7 Smoke opacity for 1500 hours of running time

3.3 Oil conditions: Kinematic viscosity and total base number

The variation of kinematic viscosity and the total base number (TBN) is given in Table 5. For up to 450 hours of operation, the viscosity of oil fell by 4.7 cSt with diesel and 5.6 cSt with DTPO30 at 40ºC, while it declined by 0.9 cSt with diesel and 4.1 cSt with DTPO30 at 100ºC. The 250 ml sample oil collected from the oil sump every 150 hours was subjected to tests that included viscosity and TBN. Then, it was replaced with 250 ml of fresh oil. Dilution and deterioration in oil films were the main reasons for the lower viscosity [19]. The major deterioration found with DTPO30 was due to more thermal cracking, depletion of additives and oil contamination. Each lubrication oil was required to maintain the minimum viscosity to reduce metal contact (adhesive wear) under various loads and temperatures. The viscosity of the oil declined when the temperature increased. Mostly, adhesive wear was found on various engine parts such as piston rings and piston cylinder liners, pistons, connecting rods, crankshafts, bearings, cam-tappets, and rocker arm-valve streams. Due to the absence of oil during the cold start, there was greater friction and wear. Then the probability of oil dilution was through fuel leakage through worn liners or pistons when the engine was operated for more than 1500 hours. On the other hand, there was an accumulation of unburned fuel in the combustion chamber due to blow-by conditions when the engines operated in idle conditions or close to idle conditions [20].

Table 5 Oil conditions: viscosity and TBN

Hours	Fuel	Kinematic Viscosity, cSt @40°C	Kinematic Viscosity, cSt @100°C	TBN, mg KOH/g
1	Diesel	119.8	14.5	10.8
	DTPO30	119.9	14.6	10.8
150	Diesel	118.7	14.2	10.9
	DTPO30	118.1	13.2	11
300	Diesel	118.3	14.2	10.9
	DTPO30	116.4	12.1	11.2
450	Diesel	115.3	14.1	11.1
	DTPO30	116.1	11.3	11.5
600	Diesel	118.2	14.1	11.2
	DTPO30	117.6	13.2	11.9
750	Diesel	117.9	14.1	11.2
	DTPO30	115.9	11.9	12.1
900	Diesel	115.1	13.8	11.1
	DTPO30	115.1	10.7	11.8
1050	Diesel	118.1	14.1	11.3
	DTPO30	117.5	13.1	12.1
1200	Diesel	117.5	13.9	11.2
	DTPO30	114.9	11.7	12.2
1350	Diesel	115.1	13.6	11.1
	DTPO30	114.2	10.4	11.8
1500	Diesel	118.7	14.1	10.9
	DTPO30	118.1	13.0	11.2

The TBN in lube oil is a measure of the ability to neutralize acid products from combustion and oil deterioration. These acids mostly reduce the service hours of lubrication oil [21]. The TBN increased up to 8.33% and 15.7% with diesel and DTPO30 operations compared with fresh oil. The higher value with DTPO30 was due to the chance of fuel leaking into the lube oil, where tyre oils normally have a higher acid number (see Table 1).

3.4 Wear elements analysis

Generally, all engines operate under different operating environments, i.e. service cycle, load variants, fuel types, lube oil grade, maintenance cycle, etc. Each engine from a different environment shows a different extent of wear metals. To avoid malfunctions in engine parts, it is better to use the manufacturer's recommended genuine parts. Any particles of any size entering into engine parts by means of oil can cause severe damage. In this study, the lubrication oil was changed after every 450 hours of running following the manufacturer's recommendations. During that time, the oil samples were subjected to wear element and ferrography analysis.

Table 6 indicates the wear metal, contamination and additives in the lube oil. The recommended limits for wear metal and contamination are included. The maximum quantity of iron metal in the lube oil was found to be about 166.2 ppm in DTPO30, whereas it was 31.2 ppm with diesel. The maximum limit recommended by the manufacturer was 80 ppm. Mostly, iron debris is from the piston, piston rings and liner, etc. Next to iron, aluminium was found higher than the permissible limits with DTPO. The measured maximum aluminium was 41.22 ppm, whereas diesel produced about 11.2 ppm. Besides aluminium and iron, other debris was measured and found to be under the limits. Most of the wear debris was found higher with DTPO30 than with diesel; this was mainly because of the lower viscosity, higher heat release rate, and occasional knocking effects during combustion. Due to the addition of DTPO with diesel, the viscosity declined which resulted in less lubrication affecting the stroke volume. During combustion, the heat release rate was found to be maximum, where the thermal expansion increased and caused more friction and wear. Along with the high heat release rate, the engine peak pressure and its fluctuations induced more wear debris than the diesel operations did [2]. The new engine was used in both cases; here, metal burrs in new engine parts increased the elemental concentration in lube oil in the 450-hour samples. Oil replacement after 450 hours perhaps enabled the engine to run normally, which caused low wear in the engine parts compared with the 450 hours sample. Between 900 hours and 1350 hours, there were slightly more wear metals than in the 900 hours samples. This was due to the long period of operation and the instability that occurred due to the depositions.

Table 6 Wear, contamination and additives

Analysis	Classification	LIMITS	450 Hours		900 Hours		1350 Hours		Engine Parts	Testing Method
			DTPO30	Diesel	DTPO30	Diesel	DTPO30	Diesel		
Wear Metals	IRON, Fe	0-80 PPM	166. 2	29.69	141.2	23.3	147.3	31.2	Piston, rings, liner	ASTM D 5185-18
	CHROMIUM, Cr	0-10 PPM	3.36	>1	2.99	1.4	3.78	1.8	Rings, liner	
	TIN, Sn	0-15 PPM	4.81	0.66	4.87	0.54	5.01	0.89	Piston	
	SILVER, Ag	-- PPM	>1	1	1.4	>1	>1	>1	Bearings	
	ALUMINIUM, Al	0-15 PPM	36.82	9.91	31.23	7.45	41.22	11.2	Piston	
	NICKEL, Ni	-- PPM	7.08	>1	3.54	>1	5.67	>1	Valve train	
	COPPER, Cu	0-25 PPM	17.01	2.63	19.45	6.37	17.01	21.98	Rings	
	LEAD, Pb	0-25 PPM	28.21	3.93	24.56	7.45	33.4	6.56	Piston	
	TITANIUM, Ti	-- PPM	>1	>1	>1	>1	>1	>1	Valves	
	CADMIUM, Cd	-- PPM	>1	>1	>1	>1	>1	>1	Crank shafts	
	MANGANESE, Mn	-- PPM	3.81	>1	1.21	>1	2.1	>1	Connecting road	
	VANADIUM, V	-- PPM	1.55	2.06	1.4	1.1	1.2	1.3	Crank shafts	
Contamination	SILICO, Si	0-15	64.72	9.62	61.23	5.67	71.2	10.4	Piston	
	SODIUM, Na	0-15	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	Salt water, thickener	
		New oil							Reason for additions	
Additives	CALCIUM, Ca	35 PPM	14.89	35.95	13.91	33.15	15.42	28.93	Detergents	
	MAGNESIUM, Mg	836 PPM	469.96	749.23	487.56	767.6	543.22	771.34	Detergents	
	BORON, B	100 PPM	84.41	92.33	88.98	101.33	88.34	99.45	Solid lubricant	
	ZINC, Zn	1275 PPM	886.18	916.86	945.23	901.27	876.34	897.38	Anti-friction	
	PHOSPHOROUS, P	1500 PPM	967.17	1043.49	945.34	1023.45	997.56	1068.98	Anti-friction	
	MOLYBDENUM, Mo	150 PPM	144.87	146.98	137.56	144.44	134.56	143.45	Solid lubricant	
	BARIUM, Ba	0 PPM	6.76	1.99	4.1	1.67	3.87	1.13	Detergents	

Contamination like fuel, water, glycol, and air in the lubricating oil can lead to a reduction in viscosity; hence, it is imperative to reduce the contamination and mechanical wear. Adhesive wear mostly occurs due to poor lubrication and high loads. Contaminated sodium and silicon were found in the used lube oil; silicon in particular was contaminated at higher levels than the limits under DTPO30. This silicon contamination was due to mechanical wear in the piston material. The sodium contamination was either from salted cooling water or grease thickeners; it may also have been due to hydrolysis, oxidation, aeration, and dielectric effects [22].

The presence of various additive elements in the lube oil is indicated in Table 6. Normally, additives are substances formulated to improve the chemical and physical properties to enhance lubrication. The selection of different additives and their quantities is based purely on the lubricant type (application) and environmental factors. Several additives were found in the lube oil such as anti-friction, detergents, and solid lubricants for enhancing the properties.

Here, zinc and phosphorus were used for improving the anti-friction capacity. These additives were lower especially with DTPO30 when the engine operated over a long duration. Molybdenum and Boron were added as a solid lubricant for providing lubrication at high temperatures. These solid lubricants declined slightly by being broken to nano-size under high loads for a long duration. Calcium, barium, and manganese were used as detergents for neutralizing the acids which were generated from oxidation. DTPO30 produced more acid during combustion and it also had the chance to mix with lube oil when the engine liner was worn. Calcium and magnesium were found to be much lower with DTPO30 than with diesel.

3.5 Ferrography analysis

A ferrograph is a qualitative analysis which classifies particles based on size and shape from any lubrication oil to check life and wear rates of the parts. The samples were analysed every 450 hours by means of ferrography, but significant variations were noticed from sample to sample. Only the major variations in both fuels are shown in Figure 8. The size of the wear particles was bigger from the engine using DTPO30 than from the engine using diesel. The shape was also found to be uniform with diesel which denotes steady-state wear, but unusual shapes were found with DTPO30 fuel, and this denotes non-uniform wear, while sometimes pealing occurred during the operation of the engine. Figure 8 shows more wear particle accumulation for DTPO30 than for diesel after 450 hours of running. Moreover, longer and thinner wear particles were noted with DTPO30 fuel, whereas slightly reduced length particles were reported from diesel. This higher wear with DTPO30 is due to more knocking with greater vibration during the running of the engine [2].

The size and shape of the wear metals at different times are shown in Table 7.

Table 7 Size and shape of burr

Hours of Operations	Diesel		DTPO30	
	Width	Shape	Width	Shape
450	50 µm to 100 µm	Discrete burrs	100 µm to 120 µm	Discrete burrs
900	50 µm to 70 µm	Long burrs	50 µm to 80 µm	Long burrs
1350	70 µm to 110 µm	Long burrs and discrete burrs	100 µm to 150 µm	Long burrs and discrete burrs
1500	70 µm to 110 µm	Long burrs	80 µm to 110 µm	Long burrs

3.6 Visual inspection

For visual inspection, the whole engine was dismantled after running for 1500 hours. Figure 9 shows the intensity of deposition on different engine parts from diesel and DTPO30. On the piston top, a lesser and dry deposition was noted with diesel, but more greasy-like deposits were identified with DTPO30. During combustion, the unburned fuels at the walls formed as a darker deposition due to their non-homogeneous nature [23]. In the case of the injector and valve seat, again more deposits surrounded the injector nozzle with DTPO30 than with the diesel injected nozzle. Deposits were found with the least corrosive elements in the engine running on DTPO30. Most of the deposits from DTPO30 were found loose and wet when compared with diesel. Around the piston rings, more carbon deposits were identified with DTPO30 fuel due to fuel escaping from the combustion chamber to the oil tank.

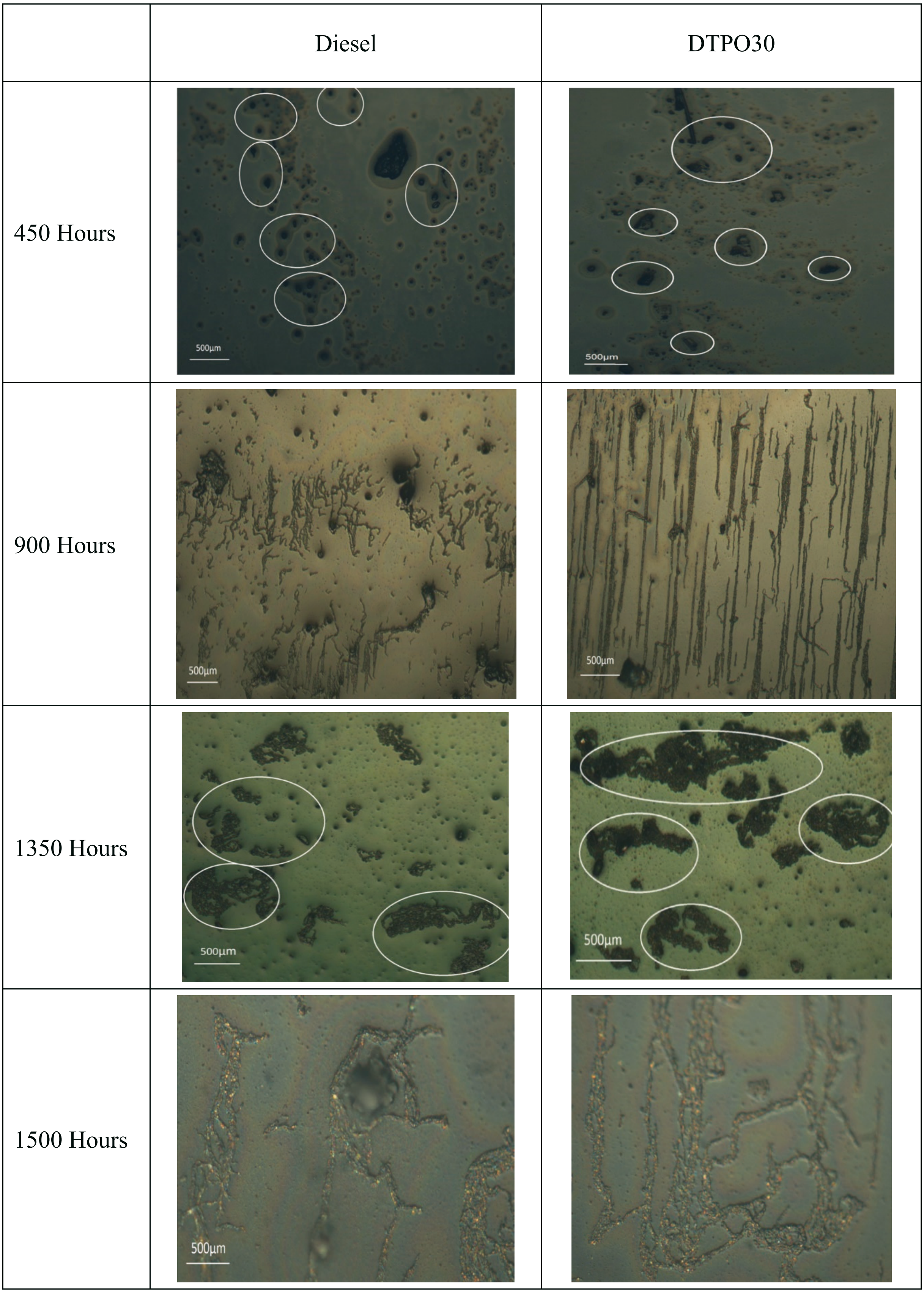

Fig. 8 Ferrography of oil samples from diesel and DTPO30

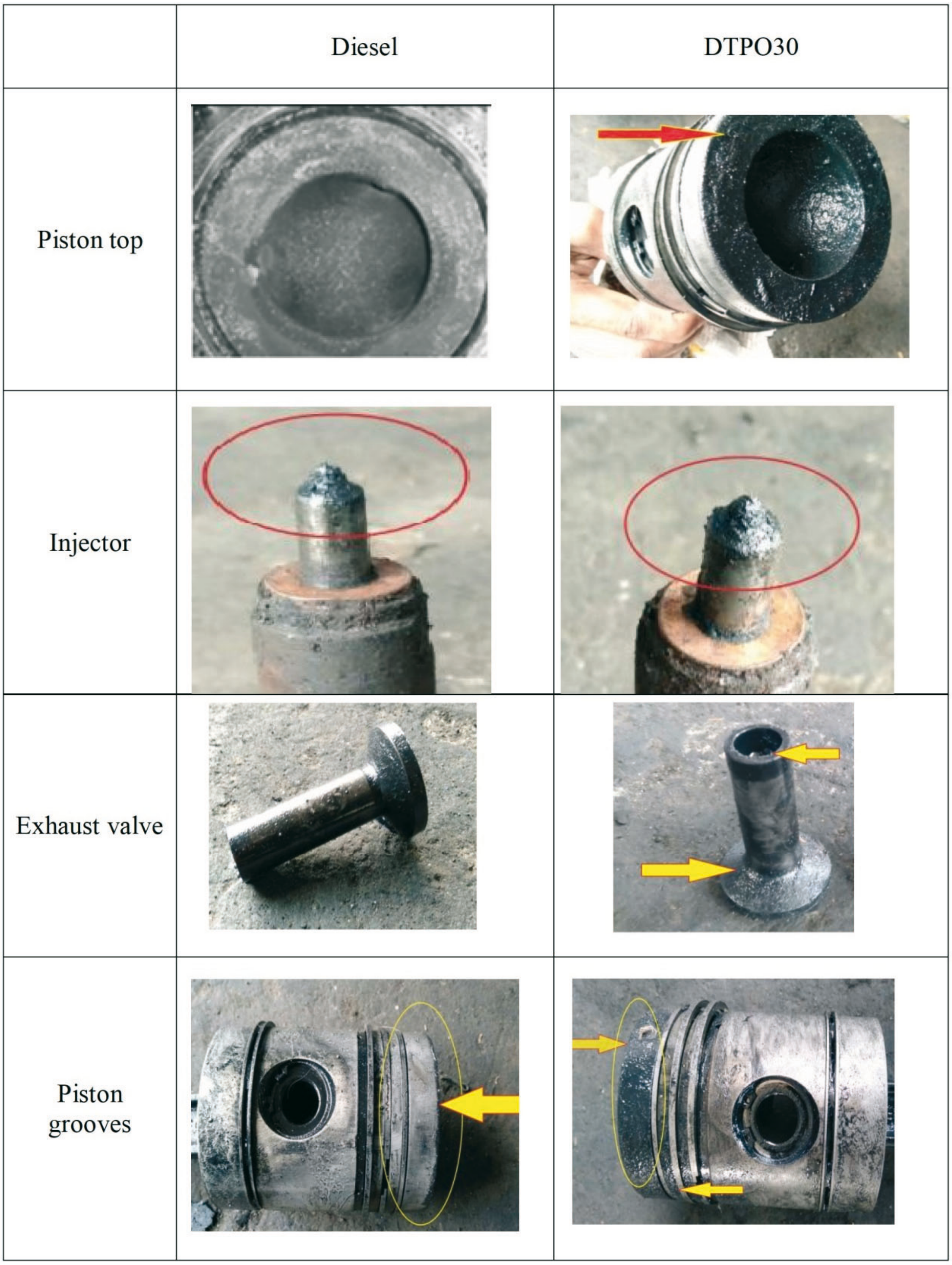

Fig. 9 Various engine parts after running for 1500 hours

3.7 Microstructure inspection

The Scanning Electron Microscopic (SEM) images were captured on the surfaces of the valve, piston rings, and piston top as shown in Figure 10. In the valve seat, a small cavity was found with DTPO30 fuel, whereas the engine using diesel did not have any significant changes on the valve surfaces. In the piston rings, more line surface cracks were identified with DTPO30 than in the rings where diesel was used. This was due to the higher temperature during cycles in DTPO30 combustions. The size (width) of the cavity on the valve seat was about 4.5 µm and the maximum width of the crack on the piston liner was 1.2 µm. More carbon deposition was noted on the piston top with DTPO30 fuel than when diesel was used. Due to the higher carbon content in tyre oil and the non-homogenous combustion with DTPO30, more carbon was deposited on the piston top.

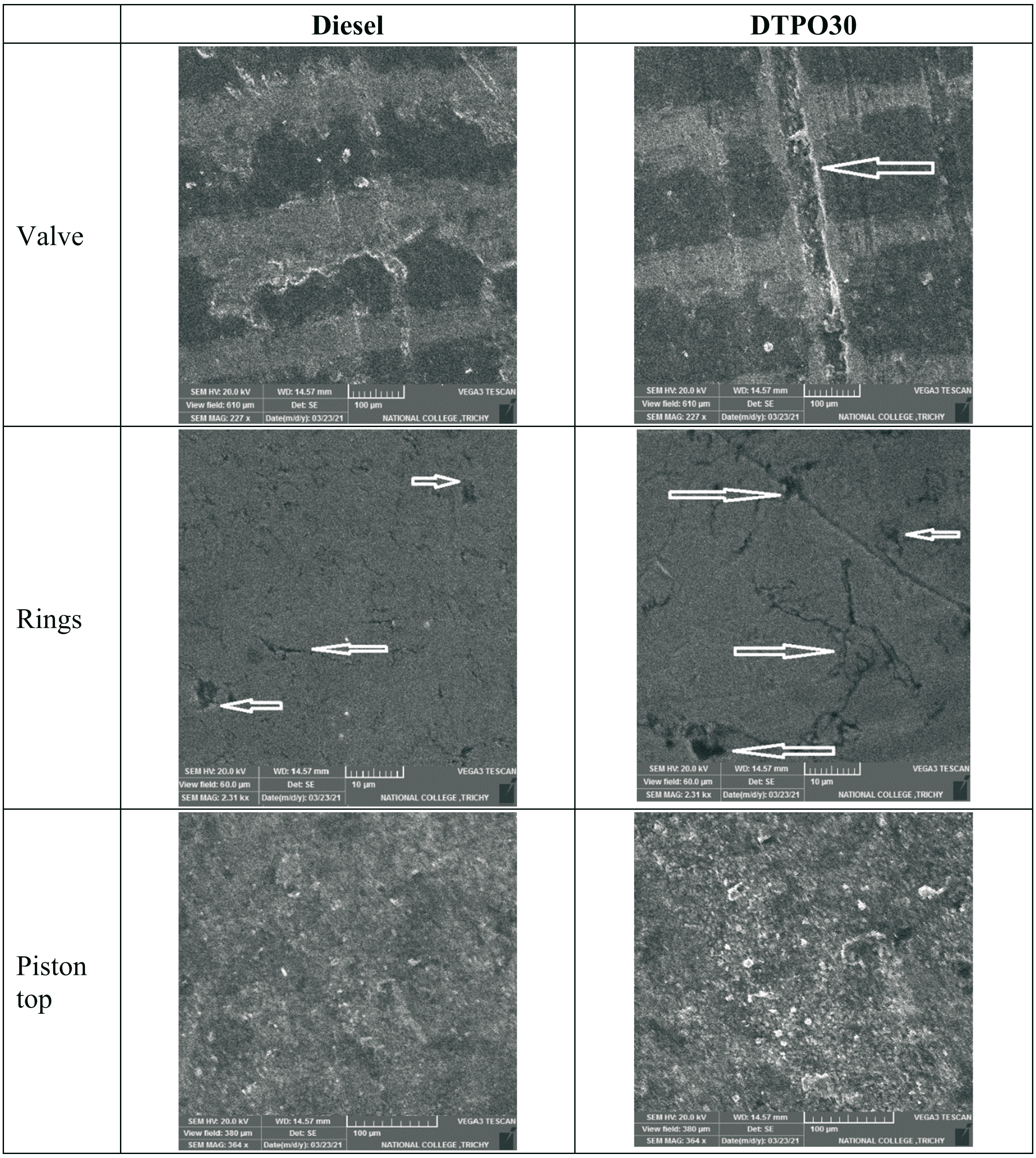

Fig. 10 SEM Images of engine parts after running for 1500 hours

4. Conclusion

The durability study was carried out on a diesel engine fuelled with DTPO30 and the results were compared with an engine operating on diesel. The test was conducted with new engines for 1500 hours as per the recommendation of the manufacturer. Due to some undesirable properties of raw tyre pyrolysis oil, it was subjected to distillation and then blends were prepared with 30 vol% named as DTPO30.

The fuel consumption was measured at periodical intervals of 150 hours and a 1.3% increment was noted from the start to 1500 hours of the operation of the engine. When compared with diesel, DTPO consumption was 2.1% higher. This hike was due to the non-homogeneity of fuel structures during blending. The 3.1 litres of SAE 15W-40 lubrication oil were used for lubrication in both cases; the oil deteriorated more with DTPO30; the kinematic viscosity at 100ºC fell by up to 36.3% compared to the initial condition with the use of DTPO30. When diesel was used, viscosity dropped to 11% compared with the initial condition. More deterioration was caused by oil dilution due to acids mixing from combustion and fuel leakages. In the case of the analysis of contamination, wear metal, and additives, a little higher wear metal content and contamination were noted with DTPO30 compared with diesel. Iron, aluminium, and silicon were found in excess with DTPO30; this indicated a greater wear rate in the piston, rings, and cylinder liner because of the high heat release and greater fluctuation in in-cylinder pressure during the combustion. Additives such as solid lubricants, detergents, and antifriction agents fell more in DTPO30 compared with diesel. Solid lubricants and anti-friction agents declined because of oxidation and aeration. There were fewer detergents as a result of the neutralization of the acids which were generated from the combustion. From the ferrography analysis, there were minimal significant changes between the samples after every 450 hours of operation: bigger sized metal wear was found along with short and thicker shapes when DTPO30 was used. This might be reduced by replacing the engine lube oil after 400 hours instead of 450 hours. The engines were dismantled after 1500 hours of running and a greasier and darker deposition was noted on the piston top, piston groove, injector, and valve seat from the engine using DTPO. For the engine using diesel, fewer dry and harder deposits were found in the piston top and injector. In sum, DTPO30 is suitable for diesel engines for a long duration of operation, but the time needed for lubrication oil changes should be shortened from 450 hours to 400 hours to reduce the wear rate and oil deterioration. Any fuel additives are also recommended to avoid wet carbon deposition during combustion.

Abbreviations

DTPO - Distilled Tyre Pyrolysis Oil

DTPO30 - 30 vol% Distilled Tyre Pyrolysis Oil + 70 vol% diesel

BTE - Brake Thermal Efficiency

BSFC- Brake Specific Fuel Consumption

NOx - Nitrogen Oxides

CO - Carbon Monoxide

UBHC - Unburned Hydro Carbon

D1WPO30 - 30 vol% stage 1 Waste Plastic Oil + 70 vol% diesel

WPO30 - 30 vol% raw Waste Plastic Oil + 70 vol% diesel

W10 - 10 vol% tire oil + 90 vol% diesel

DEE - Diethyl Ether

B100 - Pure biodiesel

TPO - Tyre Pyrolysis Oil

SEM - Scanning Electron Microscopic

TBN – Total Base Number

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REFERENCES

[1] Chandran, M.; Tamilkolundu, S.; Murugesan, C. Characterization studies: Waste plastic oil and its blends. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* **2020**, 42 (3):281–91. https://doi.org/10.1080/15567036.2019.1587074

[2] Chandran, M.; Tamilkolundu, S.; Murugesan, C. Investigation of the performance, combustion parameters and emissions analysis on DI engine using 2 staged distilled waste plastic oil-diesel blends. *Thermal Science* **2018**, 22 (3):1469–80. https://doi.org/10.2298/TSCI170501067C

[3] Ahmet Uyumaz; Bilal Aydogan; Hamit Solmaz. Production of waste tyre oil and experimental investigation on combustion, engine performance and exhaust emissions, *Journal of the Energy Institute* **2015**, 92 (5): 1406-1418. https://doi.org/10.1016/j.joei.2018.09.001

[4] Kapura Tudu; Murugan, S.; Patel, S.K. Effect of diethyl ether in a DI diesel engine run on a tyre derived fuel-diesel blend, *Journal of the Energy Institute* **2016**, 89(4):525-535. https://doi.org/10.1016/j.joei.2015.07.004

[5] Kandasamy Ragupathi; Ilangkumaran Mani. Durability and lube oil contamination study on diesel engine fueled with various alternative fuels: A review, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* **2021**, 43:8, 932-943. https://doi.org/10.1080/15567036.2019.1632987

[6] Agarwal A. K.; Dhar A. Wear, durability , and lubricating oil performance of a straight vegetable oil (Karanja) blend fueled direct injection compression ignition engine, *Journal of Renewable and Sustainable Energy* **2014**,44 : 631-38.

[7] Avinash Kumar Agarwal. Effect of straight vegetable oil utilization on carbon deposits and wear of CI engine components. Indian Institute of Technology Kanpur, Kanpur-208 016, **2018**, India.

[8] Tippayawong, N.; Promwungkwa, A.; Rerkkriangkrai, P. Durability of a small agricultural engine on biogas/diesel dual fuel operation, *Iranian Journal of Science & Technology, Transaction B: Engineering* **2010**; 34:167-177.

[9] Baumgardner M.E.; Lakshminarayanan A.; Olsen DB, et al. Durability testing of biomass based oxygenated fuel components in a compression ignition engine. ASME. Internal Combustion Engine Division Fall Technical Conference, Volume 1: Large Bore Engines; Fuels; Advanced Combustion V001T02A002. **2017**. https://doi.org/10.1115/ICEF2017-3551

[10] Suthisripok, T.; Semsamran, P. The impact of biodiesel B100 on a small agricultural diesel engine. *Tribiology Int* **2018**;128: 397–409. https://doi.org/10.1016/j.triboint.2018.07.042

[11] Mohanraj Chandran; Ramesh Chinnappan; Parthipan, N.; Chun Kit Ang. Effect of nano cerium oxide additive with tire oil blends on diesel engine combustion and emissions parameters with soot morphology analysis, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* **2020**. https://doi.org/10.1080/15567036.2020.1810179

[12] Mohanraj Chandran; Prabhu Rajamamundi; Ang Chun Kit. Tire oil from waste tire scraps using novel catalysts of manufacturing sand (M Sand) and TiO2: Production and FTIR analysis, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* **2017**, 39:18, 1928-1934. https://doi.org/10.1080/15567036.2017.1390010

[13] Murugan. S.; Ramaswamy, M.C.; Nagarajan, G. Performance, emission and combustion studies of a DI diesel engine using distilled tyre pyrolysis oil-diesel blends. *Fuel Processing Technology* **2008**, 89:152–59. https://doi.org/10.1016/j.fuproc.2007.08.005

[14] Senthil, R.; Ravichandiran, N.; Silambarasan, R. (2015). Performance and emission characteristics of a diesel engine with a zirconium dioxide-coated piston and nerium and mahua methyl esters used as fuels. Transactions of FAMENA, 39 (2), 87-96. Retrieved from https://hrcak.srce.hr/141795

[15] Murugan, S.; Ramaswamy, M.C.; Nagarajan, G. Influence of distillation on performance, emission, and combustion of a diesel engine using tyre pyrolysis oil diesel blends. *Thermal Science* **2008**, 12:157–167. https://doi.org/10.2298/TSCI0801157M

[16] Grujic, I.; Stojanovic, N.; Pesic, R.; Davinic, A; Narayan, S. (2020). Numerical analysis of IC engine operation with high-pressure hydrogen injection. Transactions of FAMENA, 44 (1), 55-66. https://doi.org/10.21278/TOF.44105

[17] Mrzljak, V.; Medica, V; Bukovac, O. Simulation of a two-stroke slow speed diesel engine using a quasi-dimensional model. *Transactions of FAMENA* **2016**, 40 (2), 35-44. https://doi.org/10.21278/TOF.40203

[18] Pipitone, E.; Costanza, A. An experimental investigation on the long-term compatibility of preheated crude palm oil in a large compression ignition diesel engine. *Biofuel Research Journal* **2018**, 20:900–08. https://doi.org/10.18331/BRJ2018.5.4.5

[19] Bietresato, M.; Friso, D. Durability test on an agricultural tractor engine fuelled with pure biodiesel (B100). *Turkish Journal of Agriculture and Forestry* **2014**, 38 (2):214–23. https://doi.org/10.3906/tar-1302-51

[20] Yüksek, L.; Kaleli, E.H.; Özener, O; Berk, Ö. The effect and comparison of biodiesel-diesel fuel on crankcase oil, diesel engine performance and emissions. *FME Transactions* **2009**, 37:91–97.

[21] Prabhu, A.; Venkata Ramanan, M.; Venu, H.; Jayaprabakar, J.; Anish, M.; Joy, N. Emission and performance characteristics of a diesel engine using copper oxide nanoparticles in palm oil biodiesel-diesel blends. Transactions of FAMENA **2021**, 45 (3), 29-44. https://doi.org/10.21278/TOF.453012919

[22] Ku, Y.; Liao, C; Shih, Y; Chang, M. The impact upon durability of heavy-duty diesel engine using low percentage biodiesel (B2). **2013**, https://www.artc.org.tw/upfiles/ADUpload/knowledge/tw_knowledge_364209377.pdf.

[23] Nowruzi, H.; Ghadimi, P.; Yousefifard, M. (2014). Large eddy simulation of ultra-high injection pressure diesel spray in marine diesel engines. Transactions of FAMENA, 38 (4), 65-76. Retrieved from https://hrcak.srce.hr/135878

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