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Long term endurance analysis of the effects on ring wear and lubrication oil of biofuel used in a DI diesel engine

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Abstract

In this study, the long-term endurance tests were carried out in an engine that was used 100% diesel and 90% diesel −10% bioethanol blend. The lubricating oil and ring wear were investigated in the direct injection diesel engine using two different fuels under partial load and for 110 h. As a result of long-term endurance tests, ash content, density, viscosity, acid number determination, and flash point values of engine lubricating oil were detected. Moreover, the metal residues (Fe, Al, Cu, Pb, Zn, Mg, Mn, Ni) were signs of wear in the lubricating oil were observed. Samples were taken from the lubricating oil at 55 and 110 h and examined by the Inductively Coupled Plasma-Mass Spectrometer method. Also, tribological and morphological analyses of the replaced piston rings were made for each fuel mixture. The piston rings (first ring, second ring and third ring) had been examined by using the Energy Dispersive X-ray Spectroscopy and Scanning Electron Microscopy. As a result, it was observed that the metal residues in the oil changed over time. Metal residues were showed that after the 55th hour there were more metal residues in the lubricating oil with B10, compared to diesel. While the TAN value of lubricating oil was measured as 3.08 mg KOH/g in the D100 operation, this value was 3.29 mg KOH/g in the B10 operation.

Keywords

Bioethanol, ring wear, long-term endurance, lubricating oil, engine

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Introduction

Biofuels are a common ground of issues such as environmental sensitivities, costs, and agricultural development.[1] Bioethanol stands out as an environmentally friendly alternative fuel produced from biological sources, renewable, with less impact on greenhouse gas emissions (Figure 1). Also, bioethanol provides significant advantages in combustion systems due to its high octane number and oxygen content.[2,3] Bioethanol fuel significantly reduces CO, HC and NO emissions.[4] However, the low calorific value of bioethanol fuel could cause a decrease in engine performance and an increase in specific fuel consumption. In addition, the low cetane number of bioethanol, compared to diesel fuel, also occurs some disadvantages in terms of combustion in diesel engines.[5,6] Wang et al. investigated the effects of biodiesel-ethanol-diethyl ether blends on a diesel engine. Distilled orange oil methyl ester was used as biodiesel. In this study, diesel and biodiesel fuels, B95E5 (95% biodiesel, 5% ethanol), B90E10, B95DEE5 (95% biodiesel, 5% diethyl ether) and B90DEE10 fuels were also used. As a result, the thermal efficiency of the engine using biodiesel-ethanol blends has increased compared to diesel fuel and biodiesel fuels. When using B90DEE10 fuel, CO emissions increased, while HC and NO emissions decreased.[7]

Different fuels used in engines affect many parameters such as combustion characteristics and exhaust emissions. Peterson researched the effects of ethyl and methyl esters in diesel engines. The experiments were carried out at different engine load and time intervals, and samples were taken from the lubricating oil at intervals of 50 h. When the oil analyses were evaluated, it was determined that the results were within the predicted limits. However, the viscosity values decreased over time.[8]

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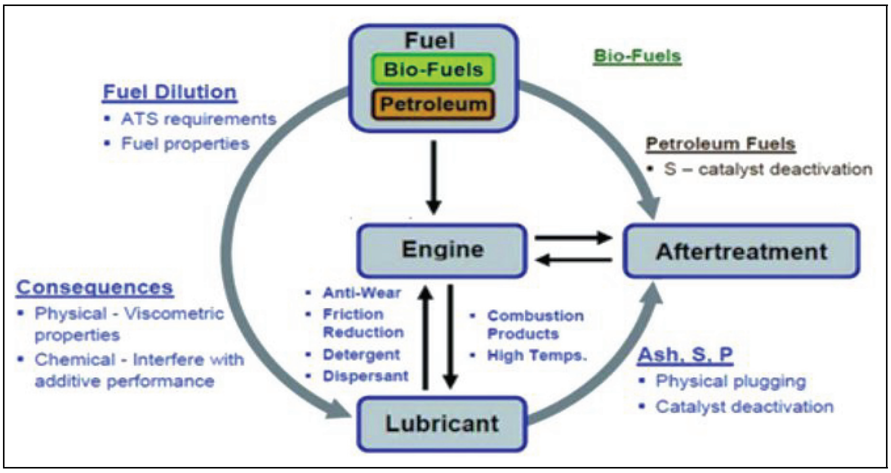

Figure 1. Biofuels cycle.

Thangarasu et al. experimentally investigated the effects of tribo-corrosion of different fuels on the direct injection diesel engine. Low corrosion rates had been achieved in the B50 blend fuel due to the low sulphur content.[9] Mujtaba et al. studied the lubricating properties of nanoparticle-doped diesel-biodiesel-ethanol fuels. When the SEM analyses were examined, weaker wear marks were found in the biodiesel blended fuel. Bioethanol added to biodiesel blends caused an increase in wear and friction coefficients, by reducing the lubricating properties of the fuel.[10]

The chemical content of bio-fuels affects the lubricating oil and cylinder-ring wear in engines. As a matter of fact, in many studies, it was emphasised that biofuels used as fuel in engines caused the deterioration of lubrication oil.[11–13] Suthisripok and Semsamran used biomass fuel in the engine operating a total of 800 h. In samples taken from oil every 100 h, it was observed that biofuel caused to decrease in the service life of the oil, viscosity, increase in TBN (Total Base Number), oxidation and nitration.[12] Hoang and Pham looked at the effects of lubricating oil in a diesel engine using diesel fuel and jatropha oil biofuel. The engine was operated for 300 h. In the oil samples taken every 25 h, the viscosity, density and metallic concentration values of the oil were compared. It had been determined that the metal residuals in the lubricating oil of the engine using biofuel were much higher compared to diesel fuel.[14] Particularly, physical and chemical changes such as acid formation, oxidation and hydrolysis in engine lubricating oil significantly change lubrication behaviour.[15] Kurre et al. studied the effect of diesel-bioethanol-biodiesel blends on lubricating oil. In the samples taken from the oil at 20, 40, 60, 80 and 100 h, compared to diesel fuel, Fe, Cu and TAN (Total Acid Number) of lubricating oil increased in blend fuels operations, while TBN, density and viscosity decreased.[16] The short-term use of biofuels is promising for users. However, fuels that cause high carbon accumulation could cause deterioration of the lubricating oil and increase of wear at long-term applications.[17] Many researchers, residual elements in the lubricating oil could determine by using many methods such as Atomic Absorption Spectrometers (AAS), Rotary Disk Electrode Atomic Emission Spectrometers (RDE/AES), Inductively Coupled Plasma of Optical Emission/Atomic mission Spectrometers (ICP-OES/AES/MS) and X-ray Fluorescence (XRF) Spectrometers.[18–22] In another study, the variation of metal elements in the lubricating oil depending on the operating hours are investigated by using the ICP/OES method. It has been emphasised that the increase rate of metals in the lubricating oil increases up to a certain operating hour and then decreases.[23] Iliev used different proportions of bioethanol fuel in the AVL Boost software. According to the results obtained, it has been shown that increasing the bioethanol ratio decreases engine power, CO and HC and increases the brake specific fuel consumption.[24] Praptijanto et al. investigated experimentally and numerically effects on a two-cylinder diesel engine of bioethanol (2.5%, 5%, 7.5% and 10% by volume) added to diesel fuel. As a result of this study, the used bioethanol caused a reduction in CO, soot and NO emissions.[3]

Today, it is possible to analyse internal combustion engines numerically with the help of many package programmes.[25–29] Asadi et al. carried out added biodiesel and bioethanol in the rates 10% (B10, E10) and 20% (B20, E20) to diesel fuel in the ESE Diesel part of the AVL FIRE software. As a result of the study, it was determined that the ıt decreased NO emission due to the increased bioethanol ratio in the blend.[30] Armas et al. investigated the effects of on fuel systems diesel fuel and diesel blended fuels containing 7% ethanol. Results show that the use of the ethanol blend tested produced a close effect on diesel fuel on the durability of the injection pump parts. However, it was seen that the effect on the injector nozzle was dissimilar.[31] This situation emerges as a function of combustion dynamics.[32]

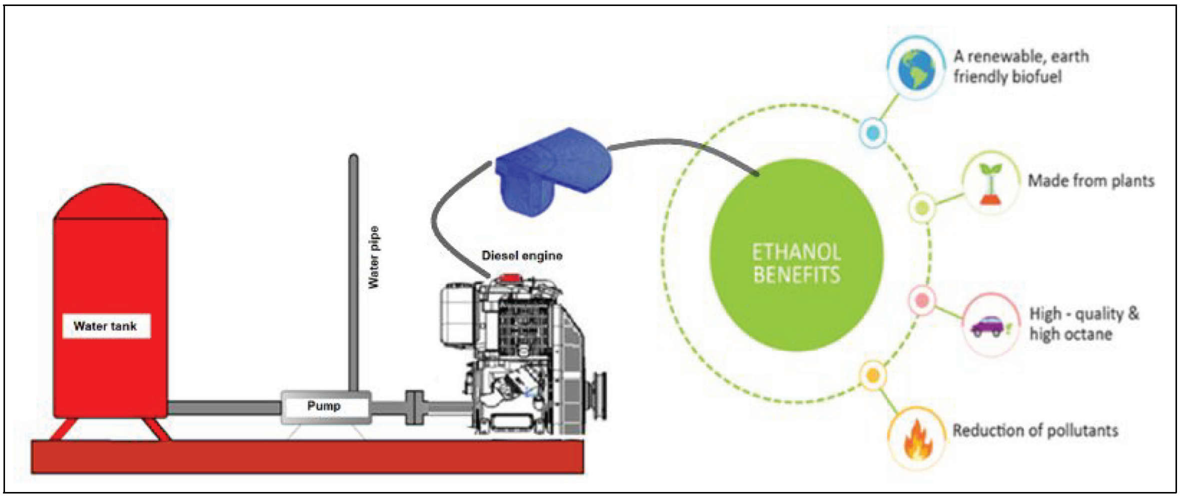

Figure 2. Experimental setup.

Table 1. Test engine specifications.

Engine type	4-Stroke, Air cooled, direct injection diesel engine
Number of cylinders	1
Cylinder volume	510 cm^3
Bore × Stroke	85 × 90 (mm × mm)
Compression ratio	17.5:1
Maximum power	8.8 (kW) @3000 (rpm)
Maximum torque	32.8 (Nm) @2000 (rpm)

From this point of view, it is necessary to reveal the effects of the combustion event on the in-cylinder equipment. The above-mentioned situation has been examined in this study. There are many studies in the literature on the use of bioethanol fuels in engines. However, it is seen that most of these studies are based on short-term engine performance and exhaust emissions. Since comprehensively examine the effects of bioethanol blended fuels on the engine, long-term tests need to be carried out. Examined in the literature, bioethanol fuels have been used at certain rates in diesel engines, due to some properties such as low cetane number and high vaporisation temperature. In this study, the tribological and morphological effects of bioethanol added to diesel fuel at a certain rate on piston rings resulting from long-term use were investigated. In the literature, the study on this subject is quite limited and it is thought that the study will contribute. In addition, the effect of diesel and mixture fuels on engine oil has been examined.

Experimental study

In the study, 100% diesel (D100) and 90% diesel-10% bioethanol (B10) as fuel were preferred. Figure 2 shows the experimental setup. ANTOR 3LD510 diesel engine was used in the study. Detailed technical properties of the test engine are given in Table 1. The engine were operated at part load and 2000 rpm engine speed, and the each fuel had been operated for 110 h. It was taken samples from the lubricating oil, for the element determination of oil at certain operation intervals. Firstly, the oil sample was taken for D100 fuelled engine at the 55th hour. Then, the engine was operated to the 110th hour, and end of this progress was taken the second oil sample. This process was repeated for B10 fuel. For both fuel types, the ended of 110 h operation, the lubricating oil and the engine's rings (first, second and third rings) were renewed. Rings belonging to this engine, first and second rings LG1 (Lamellar graphite cast iron – alloy pig cast) third ring (oil scraper) (Spherical graphite cast iron – nodular cast iron) were obtained. First ring surface is covered with Cr element. The total weight of these rings, which has a diameter of 85 mm, is 35 g. Three different analyses on this piston ring were performed. Firstly, the physical and chemical properties such as ash content, density, viscosity, acid number, flash point of engine lubrication oils were analysed. Secondly, the wear indicator metal residues of the oil samples that worked with different fuels were determined by the Inductive Coupled Plasma-Mass Spectrometer (ICP-MS) method. Finally, the tribological analyses of piston rings were made. The changes on piston rings were investigated by using Energy Dispersive X-ray Spectroscopy (EDX) and Scanning Electron Microscope (SEM). Properties of diesel and bioethanol fuels are given in Table 2.

Result and discussion

SEM/EDX analysis

Figures 3 and 4 shows the SEM/EDX images for first piston ring of the engine used D100 and B10 fuel, respectively. Examined the first ring surface, long abrasive wear lines that spread over the all ring surface were determined. In addition to abrasion wear, fatigue wear

Table 2. Properties of diesel fuel and bioethanol.[33,34]

The properties	Diesel	Bioethanol
Oxygen content (% by mass)	—	34.7
Density (g/cm^3)	0.83	0.789
Viscosity (mm^2/s)	2.6–4.1	1.19
Ignition temperature (°C)	315	235
Lower calorific value (kJ/kg)	42,500	26,800
Heat of evaporation (kJ/kg)	250	825
Cetane number	40–55	5–8
Air-Fuel ratio	14.6	9
Carbon content (% by mass)	87	52.2

was also observed on the first ring surface at the D100 fuelled engine operation. Examined SEM/EDX image of the first piston ring at D100 fuelled engine operation, it was seen that there were wear lines that spread to the entirety of piston ring surface compared to the B10 study. This situation was a more limited area with B10 fuel. Especially at the D100 operation, a large number of linear abrasions with a maximum length ranging from 385.97 to 383.12 μm that indicated by yellow lines, occurred (at 500x magnification). In study B10 operation, this value ranged from a maximum of 85.97 to 82.18 μm (Figure 4, yellow arrows seen at 2000x magnification). In the D100 operation, it was also detected that micro-joins were formed locally on the ring surface (red arrows at 500x and 2000x magnification). Moreover, cavities that are thought to be due to fatigue wear were also found in Figure 3 (blue arrows at 2000x magnification). One of the reasons for these differences in ring surface wear could be shown as the high calorific value of D100 fuel compared to B10 fuel. Because the high calorific value of the fuel and the increasing in-cylinder pressure and temperature distributions could be affect the behaviour of the lubricating oil. Especially the decreases at lubricating oil viscosity cause to weakening of oil film thickness and increases in wear. In addition, it could say that the high carbon content of D100 fuel triggers more soot formation during the combustion phase and this situation causes to decrease in the lubricating oil thickness,

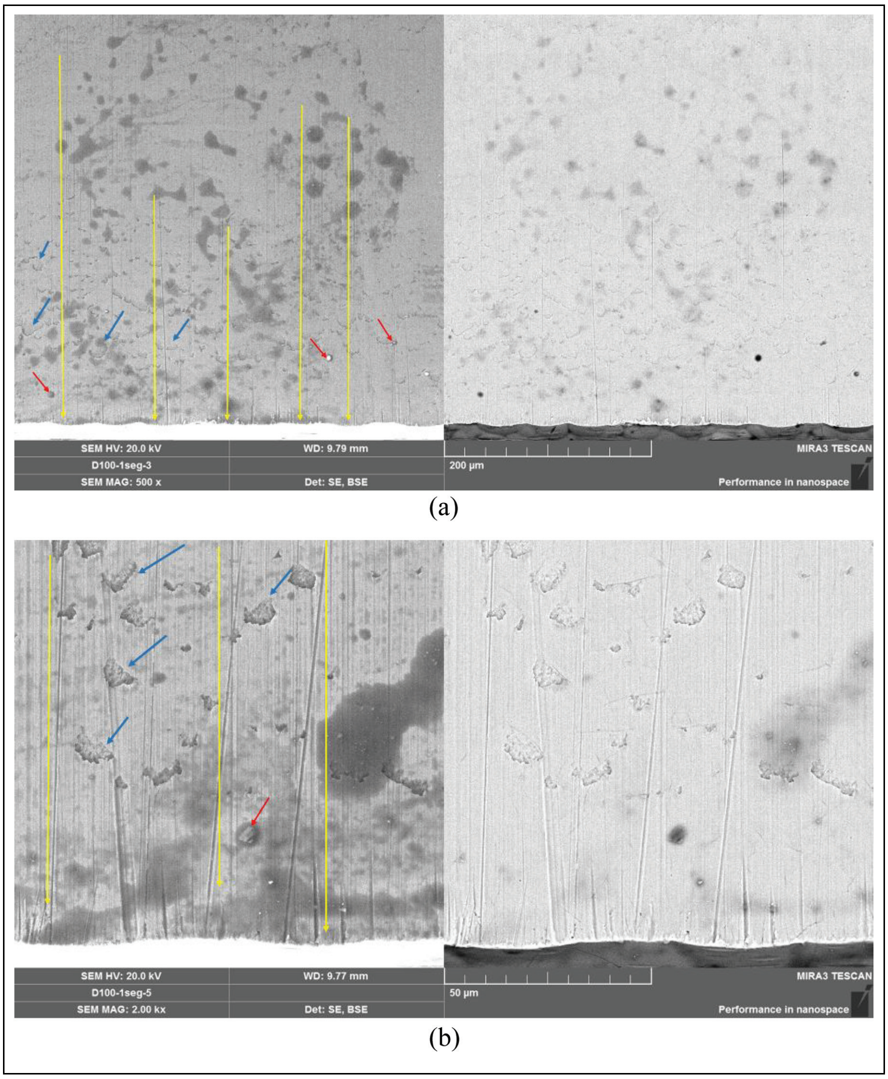

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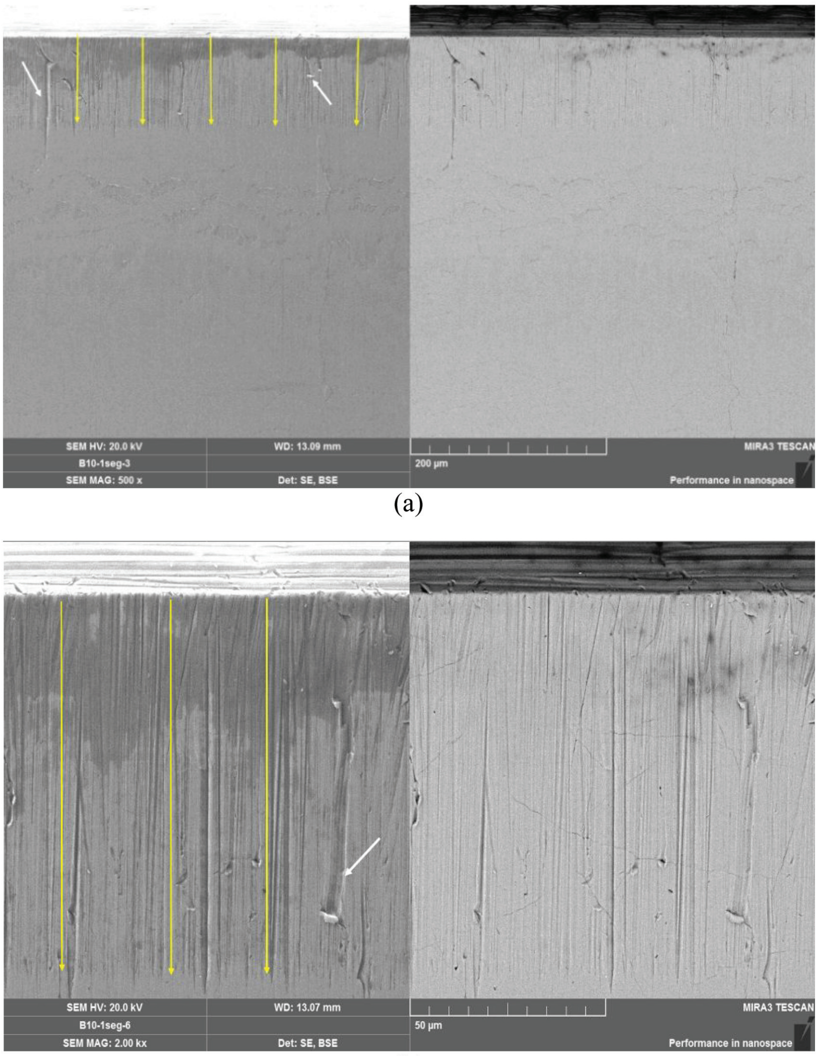
Figure 3. SEM/EDX image of the first ring of D100 fuelled engine at 500x (a) and 2000x (b) magnification.



(a)

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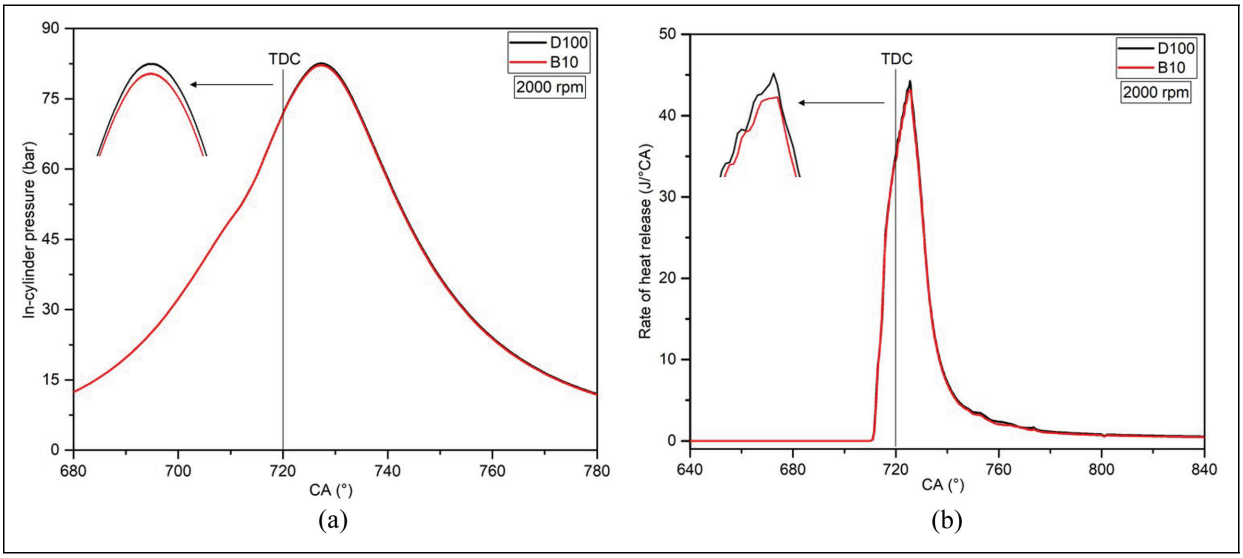
Figure 4. SEM/EDX image of the first ring of B10 fuelled engine at 500x (a) and 2000x (b) magnification.

compared to the B10 operation. Figure 5 show the variations in pressure/crank angle (a) and rate of heat release /crank angle (b) for test fuels at 2000 rpm engine speeds. Examined pressure distributions, it was seen that the in-cylinder maximum pressure decreased in bioethanol blends compared to D100 fuel. The maximum in-cylinder pressure was found to be about 81.1 bar for diesel fuel. Maximum pressure of B10 fuelled engine to compared diesel fuel decreased rate 2%. Bioethanol blend which has a low heating value cause to decrease in maximum temperature and pressure.[33–38] The heat release rates are also seen in Figure 5(b). It is seen that they are parallel with the in-cylinder pressure distributions.

Figures 6 and 7 shows the SEM/EDX images for the second ring of the engine used D100 and B10 fuel, respectively. SEM/EDX surface analyses showed that two different surface structures formed on the second ring surface for D100 fuelled engine operation. While the porous structure was formed in the first region, surface roughness and abrasive wear lines were observed in the second region (Figure 6). While wear lines similar to the first ring surface were occurred in the second region close to the combustion chamber, it was observed that this effect changed in the lower parts of the second ring. Besides, abrasive wear lines that occur at regular intervals in the direction of piston movement were also detected. When B10 fuelled operation is evaluated, it was seen that occurred two different surface structures similar to the D100 operation. However, it was determined that the porous structure seen only in a certain area on the second ring surface in the D100 operation occurred in a wider area in the B10 fuel. On the other hand, abrasive wear lines were found on the second ring surface with the B10 fuel operation. The B10 according to the D100 study, gradual surface wear was showed to the bottom parts of the second ring (towards the first region). Therefore, it could be said that there is less wear on the second ring in B10 operation than the D100 fuel. It had found shorter



(a)

(b)

Figure 5. The variation of in-cylinder pressures/crank angle (a) and rate of heat release/crank angle (b).

abrasive lines on the first piston ring in study B10. It could be said that parameters such as in-cylinder pressure and temperature, which changed depending on the different fuel used was effective on surface wear. The low calorific value and low cetane number of bioethanol blends compared to diesel fuel cause the combustion parameters to change.[33] For this reason, it has been interpreted as less wear on the mechanical parts in the combustion zone.

Figures 8 and 9 shows the elemental map of the second ring for the D100 and B10 fuelled engine, respectively. Examined the element distribution ratios of ring surface in D100 operation, it was seen that C, O, Zn, Mn and P elements concentrated in the first region. This result was considered as an indicator of the presence of lubricating oil inside the porous structure. On the other hand, according to the EDX element map, C, O, Mn and P elements were found in a larger area in the B10 study compared to the D100 fuelled operation. This was considered as an indicator of particles and oil that penetrated into the porous structure.

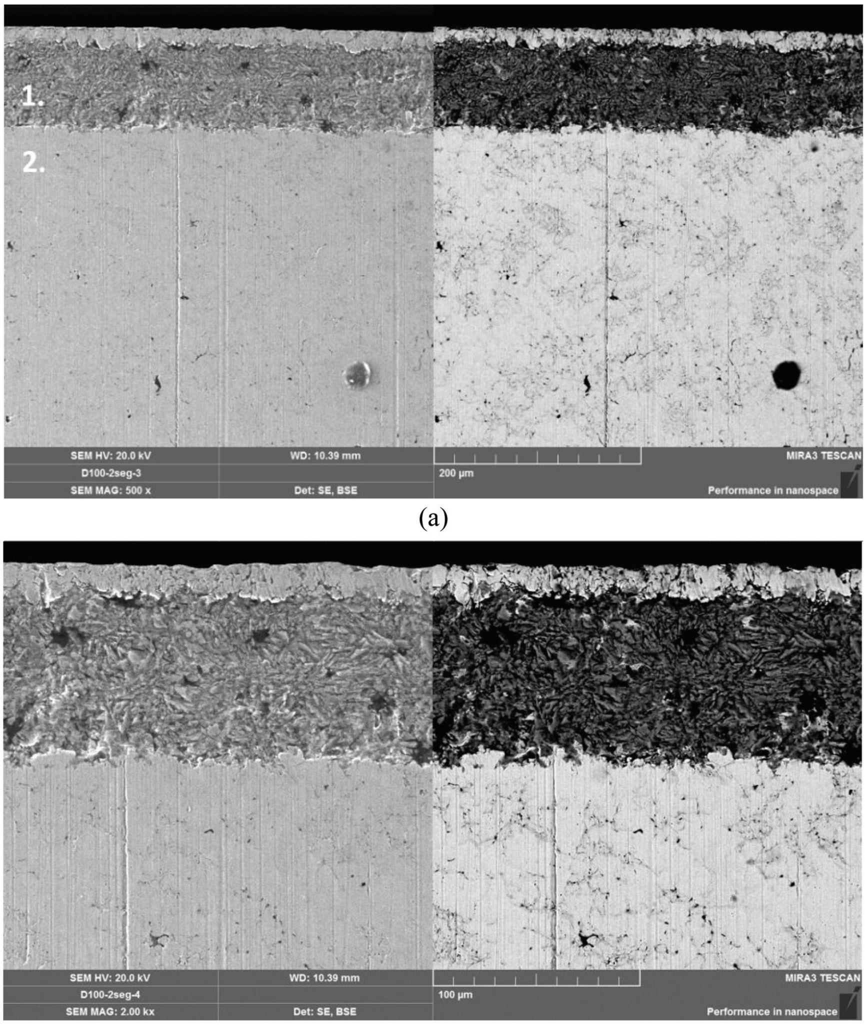
In this section, third ring analyses were performed. The low effect of the combustion chamber pressure and temperature in the third piston rings compared to the other rings was also reflected to the wear parameter. Moreover, it could be said that ıt was less the degree of wear due to the lubricating features of these rings compared to other rings. Figures 10 and 11 shows the SEM/EDX images for the third piston ring that used D100 and B10 fuel, respectively. As in the second rings, the surface roughness decreased and abrasive wear lines formed in the direction of the movement of the piston were observed on the third ring. It was thought that the higher oil film thickness between the third rings and the cylinder wall, compared to the other piston rings, caused the limited wear degree. The decrease in in-cylinder pressure and temperature in reciprocating engines significantly affects surface wear. As a matter of fact, the use of B10 fuel was effective in the third ring as well as in the first and second rings. It was seen that abrasive wear lines were more prominent in the direction of the movement of the piston in the third ring as in the second ring. When B10 fuel was compared to D100 fuel, it was seen that the wear lines on the third ring were more limited in number and depth.

Determination of oil's physical and chemical properties

Determination of engine oil properties gives important information about lubrication performance. In order to examine the effects of D100 and B10 fuels on lubricating oil, some physical and chemical properties of engine oil were analysed.

Various properties of the lubricating oil samples collected at the end of 110 h of operation of B10 and D100 fuels at constant regime are given in Tables 3 and 4, respectively. The density of the lubricating oil is affected by wear residues, fuel and moisture. Increased density at B10 fuel compared to D100 could be due to higher wear of engine components during 110 h. Indeed, ICP-MS analyses also supported this result. Fuel dilution decreases the density of lubricating oil because the density of fuels is lower than lubricating oil. The density of bioethanol and diesel was 0.789 and 0.83 (g/cm^3) respectively. Therefore, fuel dilution of lubricating oil by B10 causes a lesser reduction in density of lubricating oil compared to D100 fuel. This result could be an indicator that the D100 fuel mixed more at lubricating oil according to the B10 fuel.

Ash content is a parameter that indicates the presence of metal wear residues, particles and contaminants in the lubricant. As can be seen in Tables 3 and 4, after 110 h of operation with B10 fuel, the sulphate ash content in the lubricating oil was found to be higher than that of D100. Sulphated ash content was measured as



(a)

(b)

Figure 6. SEM/EDX image of the second ring of D100 fuelled engine at 500x (a) and 2000x (b) magnification.

0.785 by weight with D100 fuel, while this value was 0.819 for B10 fuel. The higher ash content of the lubricating oil in B10 fuel is an indication that the B10 fuel engine produces higher wear debris.

The viscosity of the lubricating oil is a significant parameter in an engine as it affects the lubrication effectiveness. Two main factors affect lubricant oil viscosity. Firstly, it can say that formation of resinous products because of oil oxidation, evaporation of lighter fractions, depletion of anti-wear additives and contamination by insoluble compounds tend to increase viscosity. Secondly, moisture formation and fuel dilution tend to reduce the oil viscosity. It has been seen that the values obtained as a result of the study in both fuels are close to each other. While the viscosity of lubricating oil at D100 fuelled operation was 68.08 mm^2/s at 40°C and 11.61 mm^2/s at 100°C, this value at B10 fuelled operation was 69.04 mm^2/s at 40°C and 11.6 mm^2/s at 100°C. After 110 h of operation, wear on the piston rings was higher in D100 fuel operation. Furthermore, SEM/EDX analysis showed that B10 fuel tends to reduce the wear between the piston ring and cylinder liner due to its lower calorific values. However, the lubricant oil kinematic viscosity variation of B10 fuels did not exceed the limits and caused a similar effect on lubricant oil kinematic viscosity than the D100 fuel.

The flash point is known as an important parameter that showed the dilution rate of the fuel. While the flash point temperature of ethanol fuel is 15°C, this value is 78°C for diesel oil.[29] While the lubricating oil flash point at D100 fuelled engine was 154°C, this value was determined as 198°C at B10 fuelled engine (Tables 3 and 4). This result was an important indicator that the D100 fuel mixed more at lubricating oil compared to the B10 fuel. As is known, diesel fuel also has good lubricating properties. Less wear that seen in the D100 study compared to the B10 operation after 110 h. It was evaluated as a result of this feature (as seen in ICP-MS analyses).

Total Acid Number (TAN) indicates the ability absorb acids that cause to corrosion. The total alkalinity number is the ability of the lubricating oil to prevent the formation of sulphuric acid, which occurs due to the sulphur content in the fuel and causes corrosion.

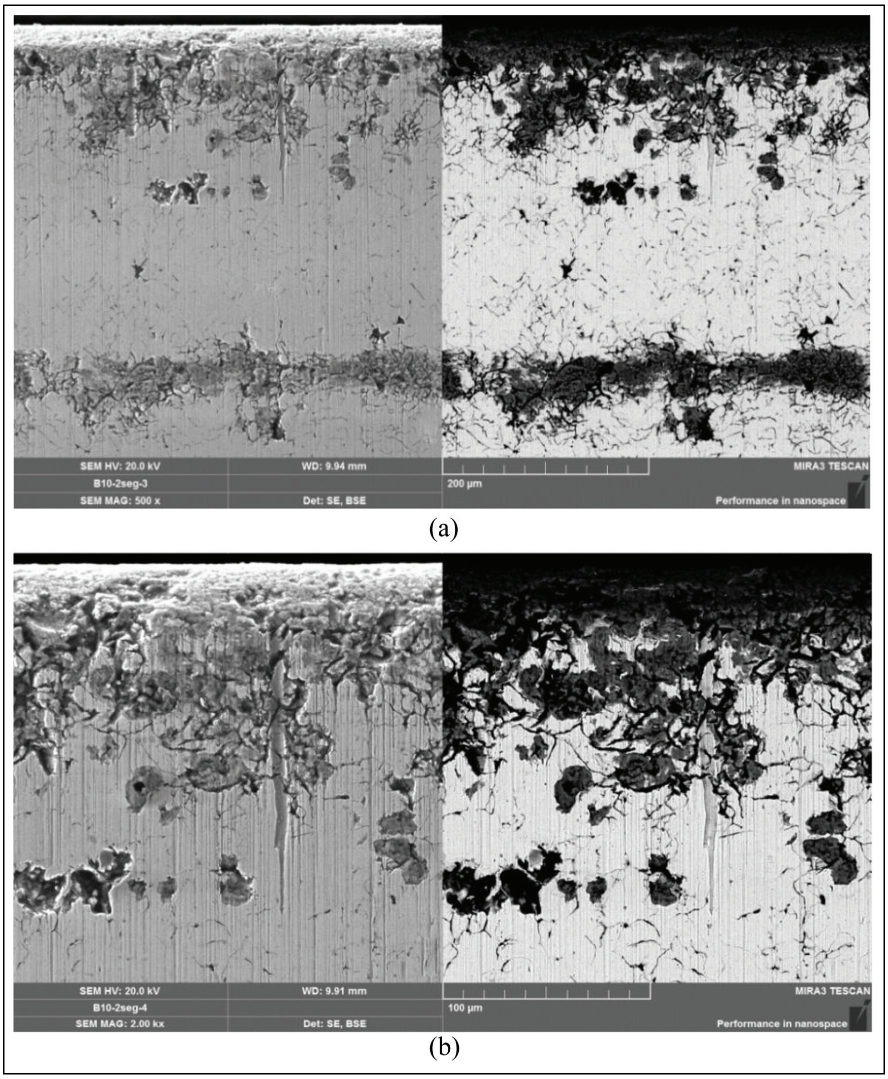


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Figure 7. SEM/EDX image of the second ring of B10 fuelled engine at 500x (a) and 2000x (b) magnification.

In addition, it also shows the ability of the lubricating oil to clean the combustion residues adhering to the machine parts. The TAN is important in terms of showing the concentration of acidic molecules in the oil. The TAN value is an important parameter that gives the number of acid or acid derivatives in the lubricant. While the TAN value was measured as 3.08 mg KOH/g with the D100 fuel, this value was 3.29 mg KOH/g after working with B10 fuel. A lower TAN indicates better performance and lower corrosion potential for the lubricating oil. It shows that the corrosive and moisture-retaining properties of bioethanol fuel are reflected in this value when blended with the lubricating oil.

Spectrometric analysis of lubricating oil (ICP-MS)

Thermo Scientific ICP-MS iCAP Q brand device was used to detect wear elements in engine oil. Thermo Scientific ICP-MS iCAP Q brand device was used to detect wear elements at engine oil. Engine oil could not be directly used in the ICP-MS device due to organic compounds and high carbon content. For this reason, it was subjected to acid digestion under high pressure and temperature in a microwave device.

The disjunction process was performed by using the EPA3051(for oil) method. Spectrometric oil analysis is a preventative maintenance tool used to determine the amounts of worn metals in lubricating oil. It is to determine in advance whether there is an abnormal situation such as wear, corrosion, scratching and fragmentation that may occur in the system with spectrometric oil analysis. Looking at the metal residue results in the engine lubricating oil, it was seen that; more wear elements in samples taken from lubrication oil at 55th hour were found at D100 fuelled operation compared to the B10 fuelled operation. This result is thought to affect the combustion event due to the chemical properties of B10 fuel. Since D100 fuel has a higher calorific value than B10 fuel, it caused an increase in in-cylinder pressure and temperatures. Increased temperatures and pressures led to increased wear on the piston rings. These results were also supported by SEM/EDX analyses of the piston ring. Combustion formation changed

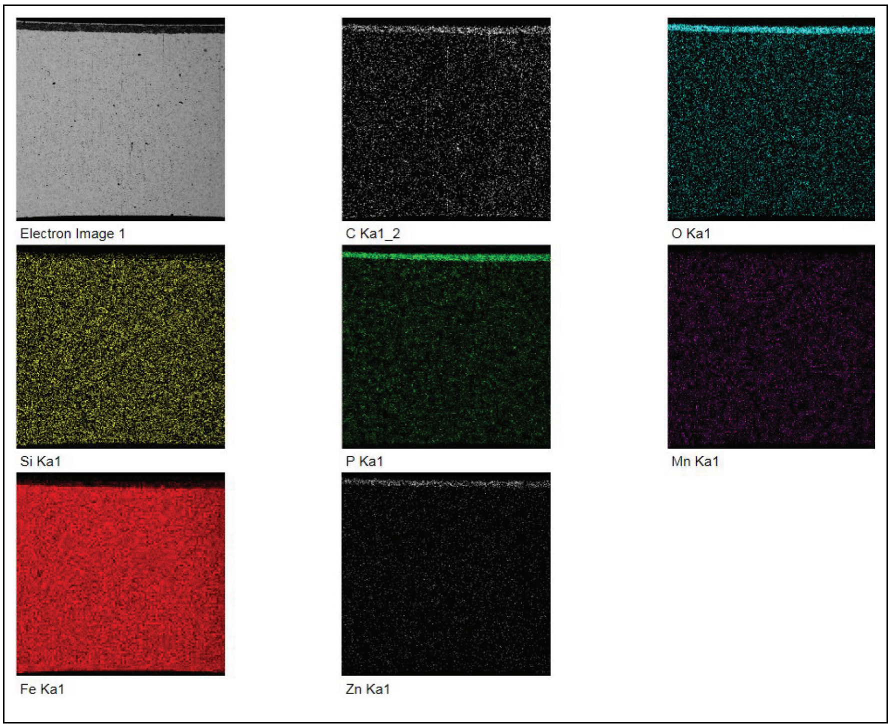


Figure 8. The elemental map of second ring at D100 fuelled engine operation.

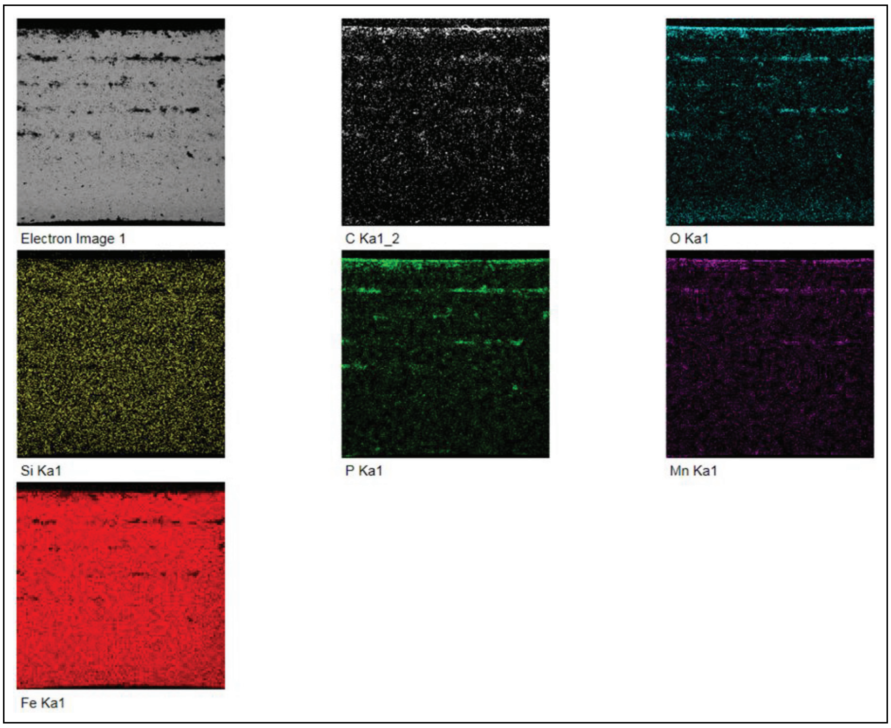
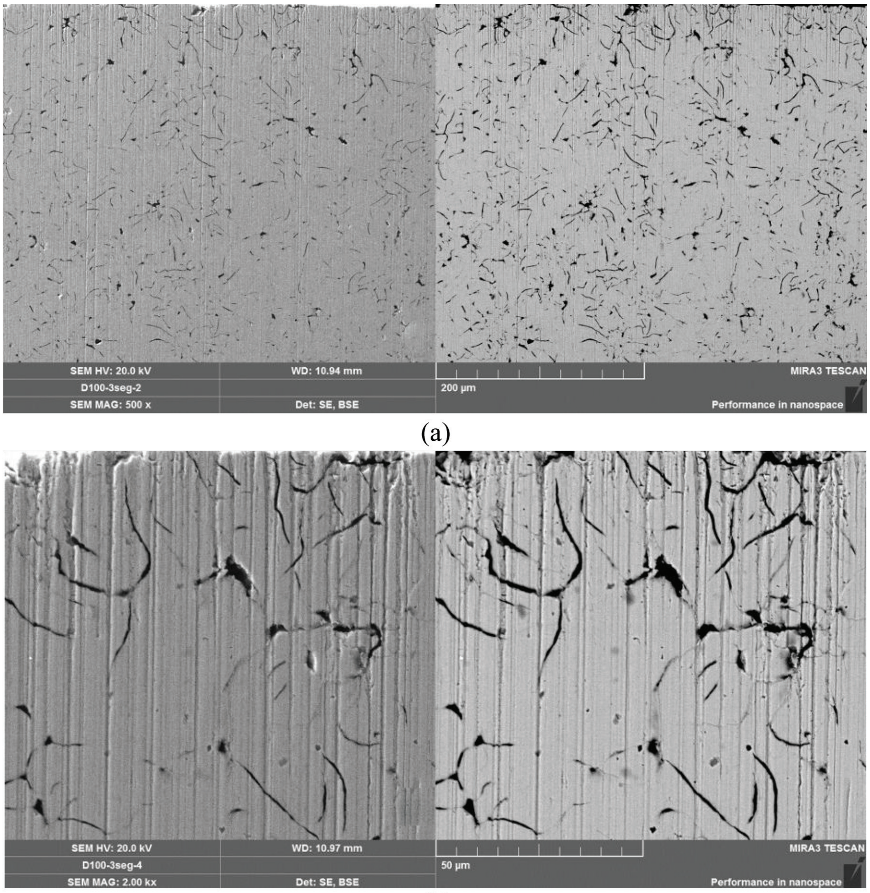


Figure 9. The elemental map of second ring at B10 fuelled engine operation.

by using different fuels at engine changes the pressure forces applied to the ring-cylinder structure, piston pin, connecting rod and crank bearing. Also, the different temperature distributions create thermal changes on engine parts and lubricating oil. When the element results in the lubricating oil were examined after 55 h, it was shown that combustion events were effective on the lubricating oils.

Figure 12 shows the Mn, Fe, Mg, Ni, Al, Cu, Zn, Pb concentrations in lubricating oil samples with usage. After 110 h of operation, it has been observed that manganese (Mn), iron (Fe), nickel (Ni), copper (Cu), lead



(a)

(b)

Figure 10. SEM/EDX image of the third ring of D100 fuelled engine at 500x (a) and 2000x (b) magnification.

(Pb) concentration in B10 fuelled engine is high compared to D100 fuelled engine. In the other elements (such Al, Zn), it was seen that the results in both fuel operations values close to each other were obtained. It was evident that Mg content in lubricating oil samples drawn from D100 fuelled engine was slightly higher than lubricating oil samples of B10 fuelled engine. The bioethanol fuel could provide poor lubricity due to its dilution with lubricating oil resulting in a higher generally wear rate of metal element concentration. Higher metal elements in the lubricating oil samples of B10 fuelled engine shows a higher extent of lubricating oil oxidation and polymerisation that could be resulted in more lubricating oil contamination by bioethanol dilution. The ability moisture absorption and the corrosive effect of bioethanol blended with lubrication oil can also affect the properties of the lubricant. As a matter of fact, it is thought that bioethanol mixed with lubricating oil increases the oxidation of the oil over time and causes the loss of its lubricating property.

Conclusions

A diesel engine was operated for 110 h at 2000 rpm and part load, and the effects of D100 and B10 fuels on ring tribology and lubricating oil were investigated. Density, viscosity, sulphated ash content, flash point and TAN values of the lubricating oil were analysed. In addition, metal residues in two different oil samples were detected by the ICP-MS method. If the obtained results are listed as items;

(1) When the SEM/EDX image of the first piston ring was examined, it was seen that there were wear lines that spread over the entire surface of the ring on D100 fuel than the B10 fuel. This situation was a more limited area at B10 fuelled engine operation.
(2) In bioethanol blend compared to D100 fuel caused the accumulation of more wear elements at the lubrication oil.
(3) In the physical and chemical analysis of engine lubricating oil, the flash point, ash content and TAN value of the lubricating oil are higher in B10 fuelled operation. Density and kinematic viscosity values gave close results in both fuels.
(4) According to the flash point results, the presence of diesel fuel in the lubricating oil could be important one reason the occurred of the lower wear residue because diesel fuel has a lubricating feature. It also could be said that the corrosive and moisture-retaining properties of bioethanol fuel

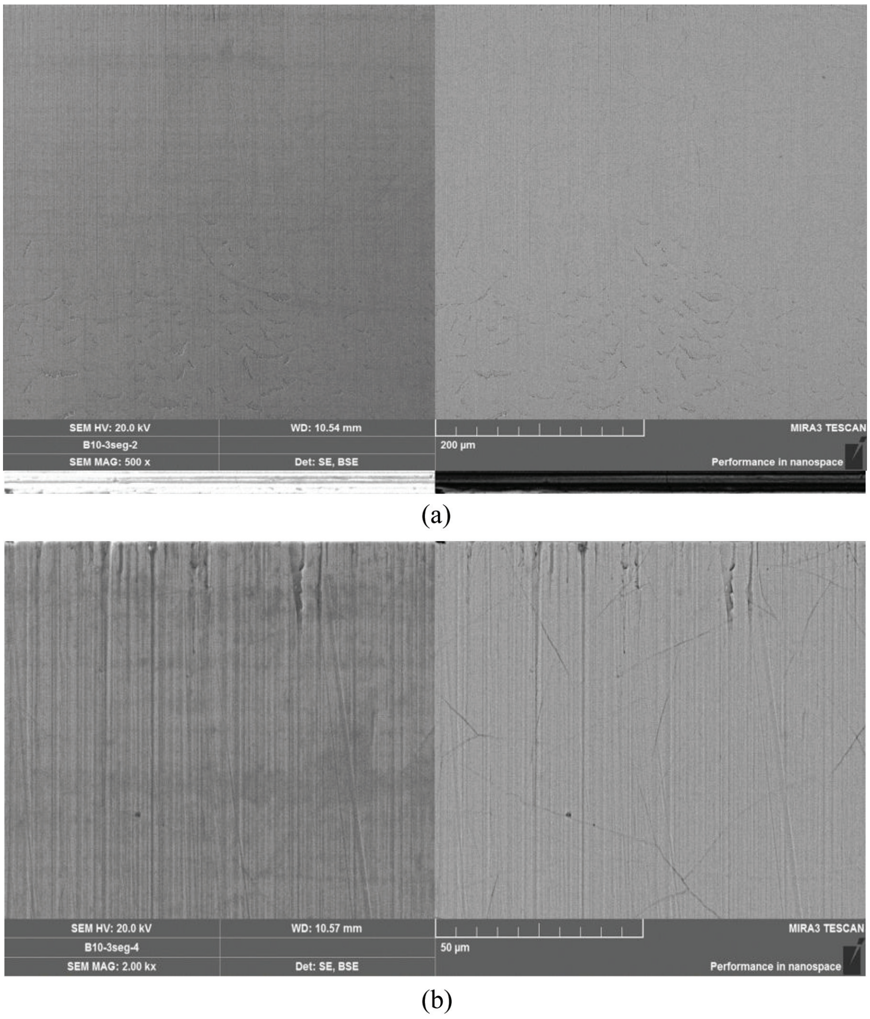


Figure 11. SEM/EDX image of the third ring of B10 fuelled engine at 500x (a) and 2000x (b) magnification.

Table 3. Engine oil analysis results at D100 fuelled engine operation.

The properties	Method	Measurement uncertainty	Value
Density (kg/m^3, 15°C)	ASTM D4052	±0.1	856.9
Flash point (Pensky-Martins open cup,°C)	ASTM D92	±3.4	154
Kinematic viscosity (mm^2/s, 40°C)	ASTM D445	±0.125	68.08
Kinematic viscosity (mm^2/s, 100°C)	ASTM D445	±0.017	11.61
TAN (mg KOH/g)	ASTM D 664	±0.66	3.08
Sulphate ash (% Weight)	ASTM D874	±0.047	0.785

Table 4. Engine oil analysis results at B10 fuelled engine operation.

The properties	Method	Measurement uncertainty	Value
Density (kg/m^3, 15°C)	ASTM D4052	±0.1	860.2
Flash point (Pensky-Martins open cup, °C)	ASTM D92	±4.4	198
Kinematic viscosity (mm^2/s, 40°C)	ASTM D445	±0.127	69.04
Kinematic viscosity (mm^2/s, 100°C)	ASTM D445	±0.017	11.6
TAN (mg KOH/g)	ASTM D 664	±0.7	3.29
Sulphate ash (% Weight)	ASTM D874	±0.049	0.819

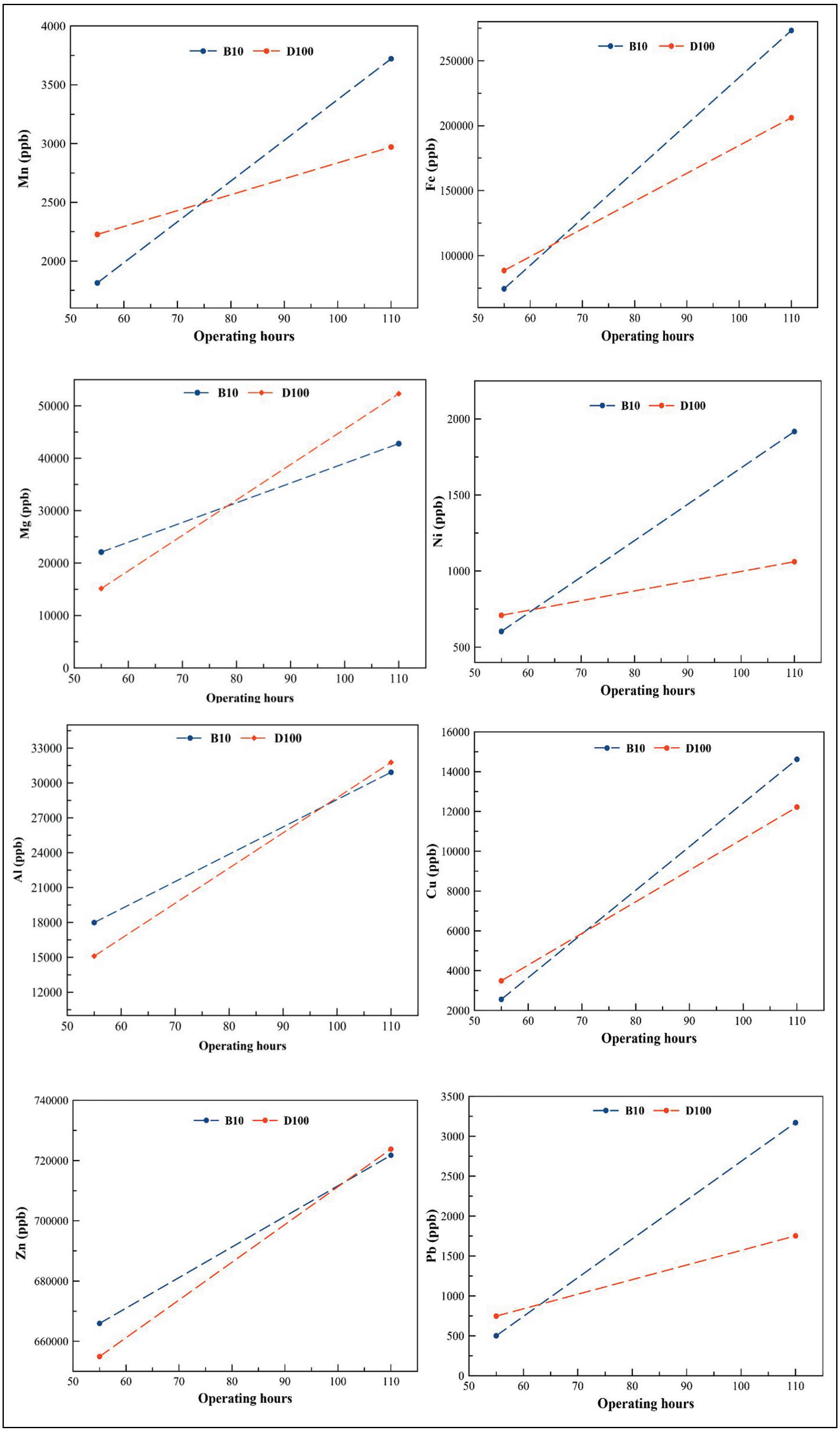


Figure 12. The metal residual concentrations in lubricating oil samples at different operating hours.

could be weakening the lubricating functions of the lubricating oil and thus cause more wear residues. This corrosive feature was also reflected in the TAN value, and the TAN value in the oil taken from the B10 fuel study was higher than the D100 fuel. This corrosive feature was also reflected in the TAN value.

(5) Wear residues of bioethanol fuelled operation formed parallel to the ash content results.

Author contributions

İlker Temizer: Conceptualisation, Supervision, Writing-original draft, Validation. Ayşegül Arı: Conceptualisation, Writing-original draft, Validation, Data curation, Formal analysis.

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References

1. Kwanchareon P, Luengnaruemitchai A and Jai-In S. Solubility of a diesel–biodiesel–ethanol blend, its fuel properties, and its emission characteristics from diesel engine. *Fuel* 2007; 86(7–8): 1053–1061.
2. Nagdeote D and Deshmukh M. Experimental Study of diethyl ether and ethanol additives with biodiesel-diesel blended fuel engine. *Int J Emerg Technol Adv Eng* 2012; 2: 3.
3. Praptijanto A, Muharam A, Nur A and Putrasari Y. Effect of ethanol percentage for diesel engine performance using virtual engine simulation tool. *Energy Proc* 2015; 68: 345–354.
4. Mofijur M, Rasul MG, Hyde J, Azad AK, Mamat R and Bhuiya MM. Role of biofuel and their binary (diesel–biodiesel) and ternary (ethanol–biodiesel–diesel) blends on internal combustion engines emission reduction. *Renew Sustain Energ Rev* 2016; 53: 265–278.
5. Temizerİ. The combustion analysis and wear effect of biodiesel fuel used in a diesel engine. *Fuel* 2020; 270: 117571.
6. Shafi WK and Charoo MS. Avocado oil mixed with an antiwear additive as a potential lubricant – measurement of antiwear and extreme pressure properties. *Proc IMechE, Part C: J Mechanical Engineering Science* 2021; 235: 2087–2098.
7. Wang S, Viswanathan K, Esakkimuthu S and Azad K. Experimental investigation of high alcohol low viscous renewable fuel in DI diesel engine. *Environ Sci Pollut Res* 2021; 28: 12026–12040.
8. Peterson LC. *Performance and durability testing of diesel engines using ethyl and methyl ester fuels, for the National Biodiesel Board*. Idaho: Department of Biological and Agricultural Engineering, University of Idaho Moskow, 1996.
9. Thangarasu V, Balaji B and Ramanathan A. Experimental investigation of tribo-corrosion and engine characteristics of Aegle Marmelos Correa biodiesel and its diesel blends on direct injection diesel engine. *Energy* 2019; 171: 879–892.
10. Mujtaba MA, Muk Cho H, Masjuki HH, et al. Effect of alcoholic and nano-particles additives on tribological properties of diesel–palm–sesame–biodiesel blends. *Energy Rep* 2021; 7: 1162–1171.
11. Dandu MSR and Nanthagopal K. Tribological aspects of biofuels – a review. *Fuel* 2019; 258: 116066.
12. Suthisripok T and Semsamran P. The impact of biodiesel B100 on a small agricultural diesel engine. *Tribol Int* 2018; 128: 397–409.
13. Hoang AT, Tabatabaei M, Aghbashlo M, et al. Rice bran oil-based biodiesel as a promising renewable fuel alternative to petrodiesel: A review. *Renew Sustain Energ Rev* 2021; 135: 110204.
14. Hoang AT and Pham VV. A study of emission characteristic, deposits, and lubrication oil degradation of a diesel engine running on preheated vegetable oil and diesel oil. *Energy Sources A: Recovery Util Environ Eff* 2019; 41: 611–625.
15. Gulzar M, Masjuki HH, Varman M, et al. Effects of biodiesel blends on lubricating oil degradation and piston assembly energy losses. *Energy* 2016; 111: 713–721.
16. Kurre SK, Pandey S, Khatri N, et al. Study of lubricating oil degradation of CI engine fueled with diesel-ethanol blend. *Tribol Ind* 2021; 43: 222–231.
17. Vikram K and Avinash AK. Friction, wear, and lubrication studies of alcohol-fuelled engines. In: Kumar V, Agarwal AK, Jena A and Upadhyay RK (eds) *Advances in engine tribology*. Singapore: Springer, 2021, pp.9–29.
18. Agarwal AK and Dhar A. Karanja oil utilization in a direct-injection engine by preheating. Part 2: experimental investigations of engine durability and lubricating oil properties. *Proc IMechE, Part D: J Automobile Engineering* 2010; 224(1): 85–97.
19. Agarwal AK and Dhar A. Wear, durability, and lubricating oil performance of a straight vegetable oil (Karanja) blend fueled direct injection compression ignition engine. *J Renew Sustain Energy* 2012; 4(6): 063138.
20. Dhar A and Agarwal AK. Experimental investigations of effect of Karanja biodiesel on tribological properties of lubricating oil in a compression ignition engine. *Fuel* 2014; 130: 112–119.
21. Singh SK, Agarwal AK, Srivastava DK and Sharma M. Experimental investigation of the effect of exhaust gas recirculation on lubricating oil degradation and wear of a compression ignition engine. *ASME J Eng Gas Turbines* 2006; 128: 921–927.
22. Nantha Gopal K and Thundil Karuppa Raj R. Effect of pongamia oil methyl ester–diesel blend on lubricating oil degradation of di compression ignition engine. *Fuel* 2016; 165: 105–114.
23. Zzeyani S, Mikou M and Naja J. Physicochemical characterization of the synthetic lubricating oils degradation

under the effect of vehicle engine operation. *Eurasian J Anal Chem* 2018; 13(4): 1–16.

24. Iliev S. A comparison of ethanol and methanol blending with gasoline using a 1-D engine model. *Procedia Eng* 2015; 100: 1013–1022.
25. Mohan B, Yang W, Yu W, Tay KL and Chou SK. Numerical simulation on spray characteristics of ether fuels. *Energy Proc* 2015; 75: 919–924.
26. Soni DK and Gupta R. Numerical analysis of flow dynamics for two piston bowl designs at different spray angles. *J Clean Prod* 2017; 149: 723–734.
27. Soni DK and Gupta R. Numerical investigation of emission reduction techniques applied on methanol blended diesel engine. *Alex Eng J* 2016; 55: 1867–1879.
28. Temizer İ and Cihan Ö. Analysis of different combustion chamber geometries using hydrogen / diesel fuel in a diesel engine. *Energy Sources A: Recovery Util Environ Eff* 2021; 43: 17–34.
29. Rajak U, Nashine P and Nath Verma T. Numerical study on emission characteristics of a diesel engine fuelled with diesel-spirulina microalgae-ethanol blends at various operating conditions. *Fuel* 2020; 262: 116519.
30. Asadi A, Kadijani ON, Doranehgard MH, et al. Numerical study on the application of biodiesel and bioethanol in a multiple injection diesel engine. *Renew Energy* 2020; 150: 1019–1029.
31. Armas O, Mata C and Martínez-Martínez S. Effect of an ethanol–diesel blend on a common-rail injection system. *Int J Engine Res* 2012; 13(5): 417–428.
32. Yu M, Qiu Z, Lv B, Wang R and Liu K. Transient simulation of cavitation evolution process in a diesel engine injector. *Int J Engine Res*. Epub ahead of print 29 April 2022. DOI: 10.1177/14680874221095839
33. Sezer I. Experimental investigation the effects of ethanol and diethyl ether addition into diesel fuel on engine performance and exhaust emissions. *J Therm Sci Technol* 2017; 37 1: 61–68.
34. Paul A, Bose PK, Panua R and Debroy D. Study of performance and emission characteristics of a single cylinder CI engine using diethyl ether and ethanol blends. *J Energ Inst* 2015; 88: 1–10.
35. Temizer İ, Gücer F and Cihan. A numerical approach in the investigation of the effects of diethyl ether and ethanol mixtures on combustion characteristics and NO emissions in a DI diesel engine. *Eur Mech Sci* 2022; 6(2): 110–118.
36. Asad U, Divekar PS and Zheng M. High efficiency ethanol–diesel dual-fuel combustion: analyses of performance, emissions and thermal efficiency over the engine load range. *Fuel* 2022; 310: 122397.
37. Chaudhari VD and Deshmukh D. Fuel flexibility study of various fuels with charge dilution and high compression ratio for medium-load operating RCCI engine. *Fuel* 2022; 310: 122163.
38. Kaminski P. Experimental investigation into the effects of fuel dilution on the change in chemical properties of lubricating oil used in fuel injection pump of Pielstick PA4 V185 marine diesel engine. *Lubricants* 2022; 10(7): 162.

Appendix

Notation

D100	%100 diesel fuel
B10	90% diesel fuel + 10% bioethanol (in vol.)
SEM	Scanning Electron Microscopy
EDX	Energy-dispersive X-ray spectroscopy
TAN	Total Acid Number
ICP-MS	Inductively Coupled Plasma-Mass Spectrometer
KOH	Potassıum Hydroxıde
ASTM	American Society for Testing and Materials