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บทความวิจัย

Effect of the Ternary Blends (Ethanol-Biodiesel-Diesel) on Deterioration of a Stationary Agricultural Engine

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Abstract: This study determines the effect of ethanol in the ternary blend on the long-term use of the engine. A stationary agricultural engine is selected for the 500-hour endurance test because of the high feasibility of using ethanol blends as regular in the future. Ethanol 10 % (E10) is mixed with the blend of biodiesel 10% and 90% diesel (B10). So, the test fuel is B10E10. Commercial diesel, which has 7% biodiesel, is also used for the comparison. To simulate the actual application, the engine connected to a water pump was operated to circulate the water. The engine deterioration is evaluated through the change in performance and emissions when compared after 500 hours of use and before the beginning of the test. The engine wear is denoted by the metal contamination in lube oil. Also, the appearance and measured value of parts from the disassembled test engine are used to reveal the engine damage. Moreover, engine oil degradation was also checked by the oil condition and the additive depletion. The results found that torque and fuel consumption changed and indicated engine deterioration as usual. According to lubricant oil results, there is no effect of ternary blend superior to the commercial diesel. No evidence of severe wear can be detected. The engine can run smoothly throughout the test without any adverse consequences. Therefore, the use of ethanol-blended fuel in agriculture engines can expand.

Keywords: Ethanol; Biodiesel; Ternary blends; Diesohol

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1. Introduction

Due to the profound effect of global warming, greenhouse gas regulation is currently being tightened. The automotive sector is one of the most significant contributors to emitted greenhouse gases. Therefore, novel engine technology and alternative energy supply resources must be discovered. Regarding economy and efficiency, diesel engines are superior to gasoline ones, hence decreased CO_2 formation. However, based on the combustion mechanism, a compression ignition engine generates a trade-off between smoke and NO_X. Consequently, using renewable energy instead of petroleum-based fuel is the solution.

Oxygenated biofuels have been proven to significantly decrease particulate emissions in direct injection gasoline and diesel engines. The well-to-wheels greenhouse gas can also be reduced. Moreover, the dependency on imported crude oil can be alleviated. As a result, many countries have applied biodiesel blended with diesel. In addition, biodiesel can compensate for the ethanol blend properties by functioning as an emulsifier, lubricity, and viscosity enhancer [1]. Therefore, a ternary blend, ethanol-biodiesel-diesel blend, has been stimulated to investigate.

Previous research indicated that the miscible tri-blend with the higher ethanol concentration requires a higher biodiesel content [2]. Due to the lower heating value of ethanol and biodiesel, the fuel consumption increased compared to petroleum diesel fuel [3]. However, some researchers indicated higher thermal efficiency because oxygen molecules lead to more complete combustion [4]. The soot/particulate matter dramatically reduced while NO_X emissions seemed to increase [5]. Depending on the engine operating conditions, CO and HC vary [6].

Different ethanol concentrations have a distinct impact on engine output. Murcak et al. conducted the test with ethanol 0-15 % [7]. The results showed that when using 10% ethanol in the blend, the engine power, torque, and fuel consumption have more benefits than diesel for all engine operating conditions. Mohammadi et al. indicated that increasing ethanol up to 20% can decrease exhaust emissions, including the trade of NO_X and soot, with slightly increased thermal efficiency. Nevertheless, the fuel injection system needs modifications when using ethanol beyond 20% [8].

Concerning combustion features, a low cetane number (CN) of ethanol leads to the difficulty of auto-ignition in diesel engines. However, the pilot injection is an effective approach that helps the self-ignition of the main combustion [8]. Moreover, smoke-free combustion is possible with simultaneously lower NO_X by a large amount of exhaust gas recirculation (EGR). In addition, adding ethanol to diesel can induce puffing or

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micro-explosion incidents, thus accelerating fuel atomization, vaporization, and combustion [9].

Although the previous study showed the benefit of ethanol blended fuel, there is limited research on long-term use. Most of the research focused on the endurance of injection systems [10] and confined the binary blend (ethanol-diesel) [11]. For the ternary blend research, Kurre et al. [12] evaluated the oil degradation when the engine used a 10% ethanol-10% biodiesel blend with diesel for 100 hours. The results showed acceptable oil degradation but no comparison with regular fuel. Thawornprasert et al. [13] found that the injector was corroded, and then the malfunction happened after 100 hours when using the high blend of 60% biodiesel and 10% ethanol. Kandasamy et al. [14] showed that after 500 hours of an endurance test, engine torque and power reduction compared to 0 hours when using ethanol-blended fuel (20% ethanol + 5% biodiesel) is more significant than B5.

This study conducted the 500-hour durability test to expand the possibility of using ternary blend fuel for long-term use. Because 10% biodiesel blended with 90% diesel (B10) is sold as commercial diesel in many countries, 10% ethanol mixed with B10 is used as the test fuel. Due to its high strength and achievability in ethanol usage, the stationary agricultural-based engine has been selected for the endurance test. The deterioration of the engine is evaluated through the change in engine performance and exhaust emissions. Engine oil contamination and conditions are used to indicate engine wear. In addition, the disassembled engine parts are measured after use and observed.

2. Apparatus

2.1 Engine

A brand new ordinary agricultural single-cylinder diesel engine equipped with a water pump was used in the current study. The cylinder positions horizontally, and the piston operates four-stroke cycles. With a naturally aspirated intake system, the fuel is injected directly into the combustion chamber by a mechanical pump system with a maximum pressure of up to 220 bars. The engine details are listed in Table 1.

Table 1 Engine specification

Specification	
Engine model	KUBOTA RT140
Engine type	Water-Cooled 4-Stroke Horizontal engine
Bore x Stroke	97 x 96 mm.
Dis. Volume	709 cm^3
Compression ratio	18:1
Int. & Exh. valve	1, 1 valve
Max. power	10.30 kW@2400 rpm
Max. Torque	49 Nm@1600 rpm

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The engine performance presented in Fig. 1 was acquired before the test started as the baseline and used to validate the engine conditions. The maximum torque is slightly less than the specification and occurs at 1600 rpm.

2.2 Engine load

A centrifugal pump was applied as the load for the engine durability test. The engine was connected to the pump via an extension belt. The pump sucks and discharges the water through the 4 inches pipe. Table 2 shows the details of the water pump.

2.3 Fuels

The effect of ethanol-blended fuels on engine deterioration was evaluated through B10E10 fuel, where E stands for ethanol, and B is biodiesel. Due to the miscibility problem, 10% ethanol must be mixed into B10, comprising 10% biodiesel as surfactant and 90% diesel. Commercial diesel sold in the gas station (mixed with 7% biodiesel, B7) was also used as the reference. The fuel specification is presented in Table 3.

2.4 Durability test procedure

The durability test was executed following Fig. 2. Before the test began, the engine run-in, also known as break-in, needed to be conducted for 12 hours. Then, engine performance and emissions when using B10E10 were measured at 0 hours as the baseline. Subsequently, the engine was equipped with a pump, which circulated the water

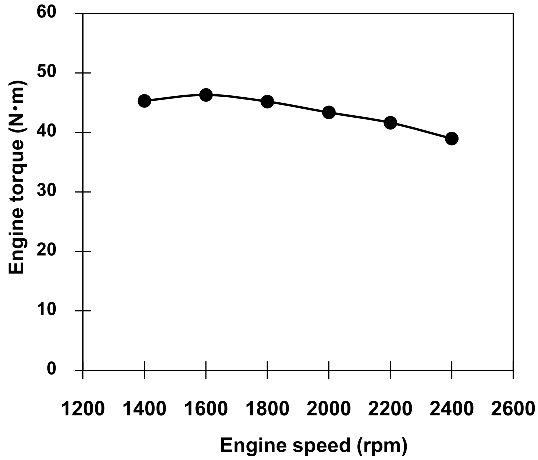

Fig. 1 Engine torque before the durability test

Table 2 Water pump specification

Specification	
Type	A centrifugal pump
Pipe dia.	4 inches
Max. Capacity	1700 liter/mint
Max. Head	27 m.
Output	10 hp.
Revolution	2000 rpm

Table 3 Fuel Properties

Properties	**B10E10**	**Diesel (B7)**
Ethanol (%)	10	0
Biodiesel (%)	9	7
Diesel (%)	81	93
Density (g/cm^3)	0.815	0.822
Viscosity (cSt)	2.8	3.2
Heating value (kJ/kg)	41.7	44.8
Lubricity (μm)	240	201

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with the pump head around 1 meter and ran for 500 hours. The engine speed was fixed at 1600 rpm. The lubrication oil was changed and evaluated every 100, 200, 300, 400 and 500 hours. After the engine running achieved 500 hours, engine performance and emissions were repeatedly determined. Furthermore, the engine was disassembled and monitored for deterioration and wear. Finally, the engine was overhauled before the test procedure was repeated, but diesel was used as the fuel. The new parts in the overhauled engine include a cylinder block sleeve, injector, piston, and rings. The valves are old ones but grinded.

Engine deterioration was determined by the torque, fuel consumption and emissions change as calculated in Eq. (1).

$$Percentage\ change\ (\%) = \frac{V_f - V_i}{V_i} \times 100 \qquad (1)$$

where V_f and V_i are the values at 500 and 0 hrs, respectively. The used lube oil conditions also indicate engine wear. According to ASTM D6595, the metal contamination in the used lubricants was determined by the rotating disc electrode atomic emission spectrometer. A surface acoustic wave-based instrument was used to measure fuel contamination. Fourier transform infrared spectroscopy measured the oil oxidation, nitration, soot and water according to the ASTM E2412 standard. The lube oil's total base number and viscosity were analysed using the ASTM D4739 and D445 test methods.

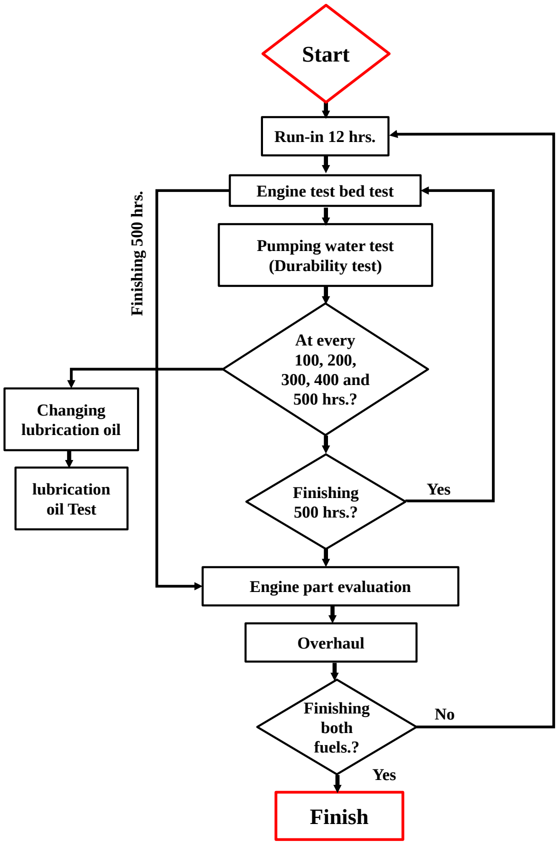

Fig. 2 Test procedure

2.5 Engine performance and emissions

The test was performed on the engine test bed, where a prony brake controlled the load. A chemiluminescent analyser, Horiba model FCA-266, was used to measure nitrogen oxides. The exhaust unburned hydrocarbon was measured by the Horiba model FCA-266 flame ionisation detector (FID) technology. A Horiba model AIA-260 non-dispersive infrared (NDIR) analyser was used to measure carbon monoxide. An AVL smoke meter 145SE was used to detect smoke levels.

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3. Result and Discussion

3.1 Performance and emissions change

The engine can run smoothly without any problem throughout the test period for B10E10 and diesel fuel. Fig. 3 presents the average fuel consumption calculated during the 500-hour test period (281 Liters for B10E10 and 267 Liters for diesel). The result shows that the fuel consumption is higher by 4.36 % than diesel B7 when using B10E10. The lower heating value of ethanol is the cause. However, the increasing percentage of fuel consumption is less than the decreasing percentage of the heating value (6.92%) of B10E10 fuel. Because of the more oxygenated molecules, complete combustion occurs for B10E10 fuel.

Fig. 4 exhibits the percentage change of torque after completing the test and initial condition of the engine when using B10E10 and diesel fuel. For more details, engine torque, fuel consumption, and exhaust emissions values before and after 500 hours were summarized in Table 4. Both fuels have a marginal effect on engine degradation. Engine torque decreased for all engine speeds. The percentage change varies with the engine speed without correlation. The engine using a ternary blend at low speeds seems worse than B7 but better at medium speeds. The torque change caused by B10E10 and diesel ranges from -0.60 to, -4.21 and -2.06 to -4.15, respectively. As a result the effect of ethanol on engine wear was not significantly observed when compared with commercial diesel.

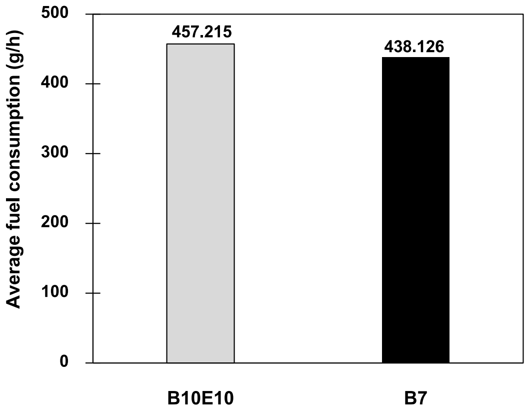

Fig. 3 Average fuel consumption when engine using B10E10 and diesel for 500 hrs.

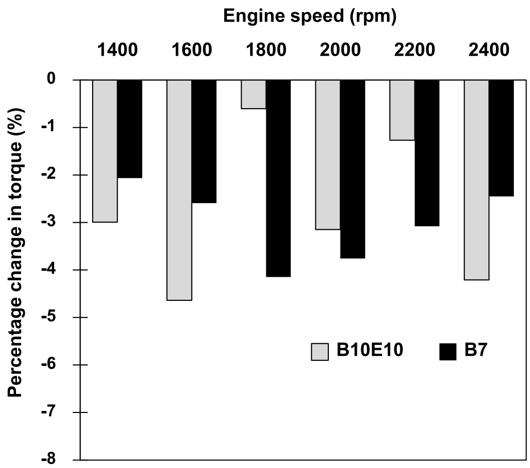

Fig. 4 Percentage of torque change when compared between 0 and 500 hrs.

As shown in Fig.5, long-term use slightly increased the engine's fuel consumption for both test fuels. The variation varied with the engine

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speed. The result could not indicate the domination effect of B10E10 fuel over diesel in terms of specific fuel consumption corresponding well with the decreasing torque.

The reduction in engine torque and increased fuel consumption after the endurance test of the brand-new engine/part may be inevitable because of cylinder wall deglazing. The rubbing parts, such as the piston ring and cylinder wall, have a rough surface at the beginning and are then polished to a smooth finish. The high level of metal contamination in the lube oil at 100 hours, which will be discussed later, is evident.

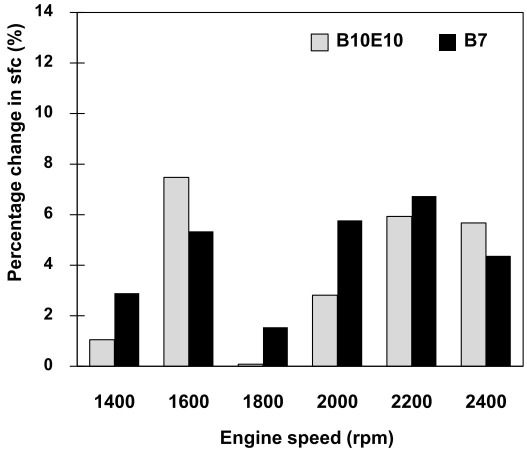

Fig. 5 Percentage change of specific fuel consumption (sfc) when using B10E10 and B7

Table 4 Engine torque, specific fuel consumption, CO, THC, NOx, and soot before and after 500 hours.

Detail	500 hr.	B10E10						B7					
		1400	1600	1800	2000	2200	2400	1400	1600	1800	2000	2200	2400
Torque (N·m)	Before	47.12	47.70	44.50	43.53	40.08	39.46	45.32	46.20	45.58	43.80	42.21	40.05
	After	45.71	45.49	44.23	42.16	39.57	37.78	44.38	45.00	43.70	42.15	40.90	38.97
SFC (g/kW·h)	Before	290.3	253.5	268.6	259.9	273.3	285.1	312.9	281.1	269.4	250.4	254.4	309.0
	After	293.4	272.5	268.8	267.2	289.5	301.3	321.3	296.0	273.6	264.9	271.5	324.6
CO (g/kW·h)	Before	7.09	3.02	1.00	0.37	0.23	0.18	10.17	5.47	1.69	0.57	0.45	0.35
	After	3.35	2.07	0.66	0.30	0.22	0.13	7.71	3.22	0.79	0.34	0.21	0.28
THC (g/kW·h)	Before	0.11	0.09	0.10	0.10	0.10	0.10	0.14	0.13	0.12	0.11	0.11	0.14
	After	0.07	0.07	0.07	0.07	0.07	0.11	0.08	0.07	0.07	0.06	0.07	0.08
NO_x (g/kW·h)	Before	0.51	0.47	0.63	0.61	0.56	0.47	0.58	0.61	0.62	0.59	0.59	0.58
	After	0.28	0.29	0.30	0.30	0.24	0.35	0.59	0.63	0.60	0.54	0.57	0.60
Soot (g/kW·h)	Before	7.51	6.07	4.52	3.75	3.12	0.50	7.86	6.10	4.88	3.28	2.27	0.73
	After	7.13	5.83	4.56	3.06	2.56	0.56	6.82	6.62	3.75	3.58	2.63	0.66

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The percentage change of CO, THC, NO_X and soot from 500-hour endurance is exhibited in Fig. 6. Unlike engine performance, no absolute trend of emission change exists. CO and HC tend to decrease after long-term use for both test fuels, but the change of NO_X and soot could not be concluded. One primary source of THC is the unburned hydrocarbon from the fuel escaping into the oil pan through the gap between the piston ring and cylinder wall. Likewise, unoxidized CO to CO_2 leaves from the crankcase enrich the CO emission. At the beginning of the test, more fuel and CO are easily blown through the coarse surface of the wall to the oil pan and then repel to the cylinder at the exhaust stroke, thus resulting in high THC and CO.

NO_X and soot strongly depend on the combustion characteristics. With the high combustion temperature, the level of NO_X increases and vice versa for smoke. Therefore, the uncertainty of the percentage change of these emissions is sophisticated. Combustion characteristics and spray behaviour should be further examined.

Although the exhaust gas change is an ambiguous indicator of engine deterioration in this study, the results confirm that ethanol in blended fuel has a similar effect to diesel fuel for long-term use. The change is opposite to the previous research [14], where CO, HC, soot and most NO_X emissions increased after the engine ran for 500 hours, and B5E20 had a more significant effect than B5 fuels. The discrepancy may result from the difference in the run-in period of 20 hours and the high oxygen content blended with the low concentration of biodiesel.

3.2 Lubrication oil

3.2.1 Wear elements

The engine oil was sampled at 100-, 200-, 300-, 400-, and 500-hour test periods and presented sequentially from left to right of each bar chart group and exampled in Fig. 7. Note that the actual age of engine oil is 100 hours, not the accumulated running hours, as the name indicates. Metal 1 and Metal 2 in Fig. 7 are representative of the graph pattern to present the result. They can be any metal, such as iron, molybdenum, or aluminum, which will be present later.

Metal contamination in used-lube oil, including Iron (Fe), Molybdenum (Mo), Aluminum (Al), Copper (Cu), Chromium (Cr), Lead (Pb), Tin (Sn), and Nickel (Ni), both fine (size < 8 μm detected by rotating disc electrode) on the left and coarse (size of 5 -150 μm measured by rotating filter spectroscopy) elements on the right is illustrated in Fig. 8. Iron is the primary material used for the crankshaft, camshaft, and cylinder block. The engine piston and bearing have an aluminum constituent. Copper is the constituent part of the valve, and chromium is used to cover the cylinder ring and block. The fine particle has a higher

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amount than coarse pieces for most metals. In the first 100 hours, the amount of debris for all metals, except for molybdenum, torn from the engine parts is the highest due to the run-in period, particularly iron, which is above the warning level. However, after 100 hours of accumulation, the quantities of wear metal decreased and remained stable afterwards in the acceptable range. It indicates that the break-in period should be over 12 hours to evaluate the deterioration results.

The oil at the first 100 hours, drawn from the engine using B10E10, contaminated higher metal elements than diesel fuels. However, the wear debris from the brand-new part using B10E10 during the run-in duration significantly contributed to the result, not the test fuels. The new parts used

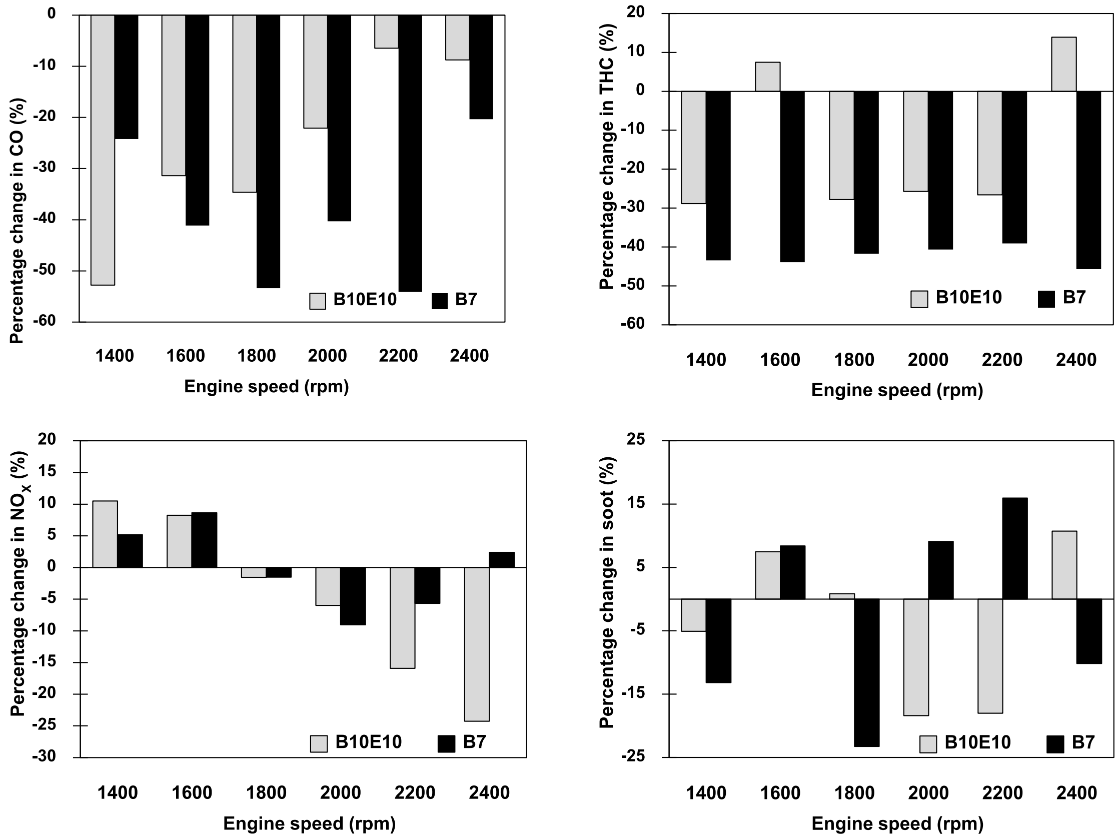

Fig. 6 Percentage change of CO (upper left), THC (upper right), NO_X (lower left) and soot (lower right) emissions from the 500-hour endurance test

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in the overhauled engine using B7 include the cylinder block sleeve, piston, piston ring and grind valve. Other parts, such as the crankshaft, camshaft and bearing, had already passed the break-in period and were less detached when tested with B7. Moreover, compared to 200-, 300-, 400-, and 500-hour tests, the level of metal contamination is no different between B10E10 and diesel fuel.

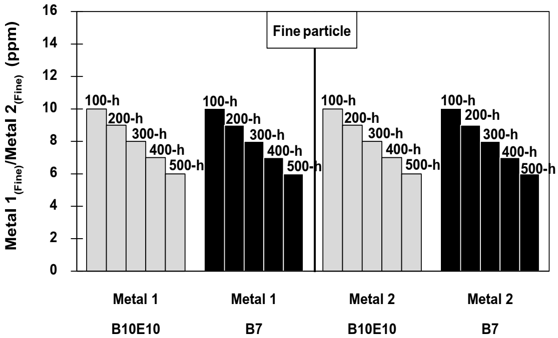

Fig. 7 Example to indicate the engine oil results

3.2.2 Oil condition

Fig. 9 exhibits the used engine oil conditions (viscosity, total base number (TBN), nitration, and oxidation) sampled every 100 hour-accumulation. For all sample oils, the viscosity decreased and closed to the lower warning bounds after 100 hours of use. Both test fuels have a relative effect on oil viscosity. The fuel/water dilution shown in Fig. 10 is the cause of viscosity reduction. In order to prevent engine failure, the engine oil should be changed every 100 hours as the manufacturer recommends.

Typically, TBN should be decreased because of the acid formation from by-products of combustion, nitration and oxidation. In addition, the acidity of biodiesel resulting from the fuel dilution can reduce the alkalinity. Interestingly, the TBN of motor oil used in this study is comparable to that of new oil except for the oil drained at 200 hours when using B10E10 and 500 hours when using B7. The alkaline additive in the lubricant, such as calcium, neutralizes the acidity. It can be noticed that the calcium concentration in Fig. 11 was identically reduced, with the TBN substantially decreased at 200 and 500 hours.

Nitration is formed by the reaction of oil and nitrogen oxide compounds, while oxidation is the product of oil oxidized with oxygen. Both substances typically lead to increased viscosity and acidity. The result shows that nitration and oxidation increased after 100 hours of usage compared to the new oil. B10E10 slightly increased higher than B7. Because of higher oxidative agents in tri-blend fuels, the oxidation reaction with lube oil occurs more quickly. More oxide of nitrogen emitted from the B10E10 may be the cause of marginal higher nitration. However, the effect of nitration and oxidation on the viscosity and TBN could not observed as discussed above.

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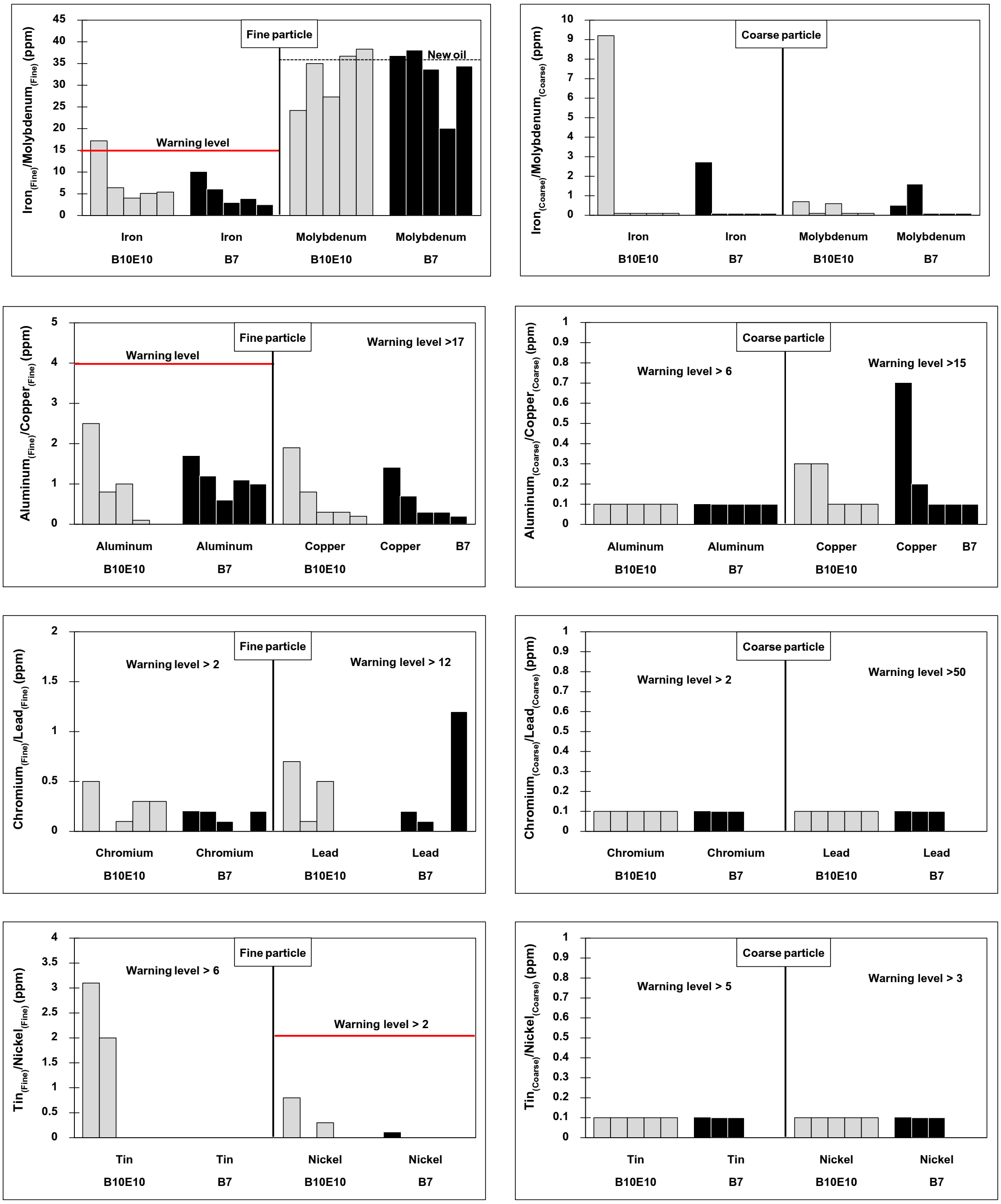

Fig. 8 Metal contamination, Fe, Mo, Al, Cu, Cr, Pb, Sn, and Ni from top to bottom, fine size on the left and coarse on the right

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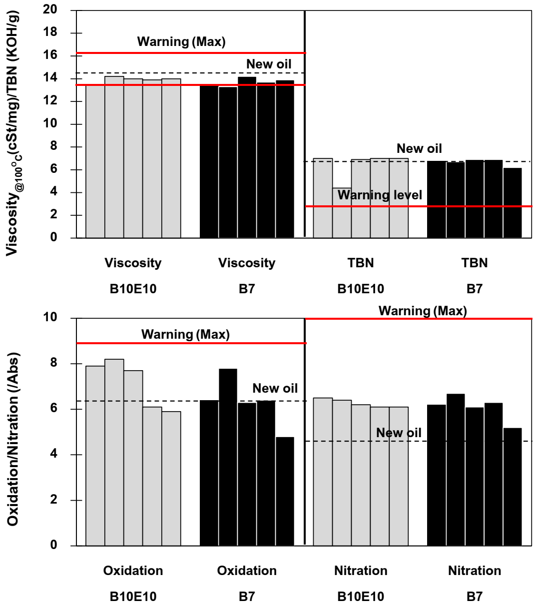

Fig. 9 Used lube oil conditions including viscosity & TBN (top), and oxidation & nitration (below)

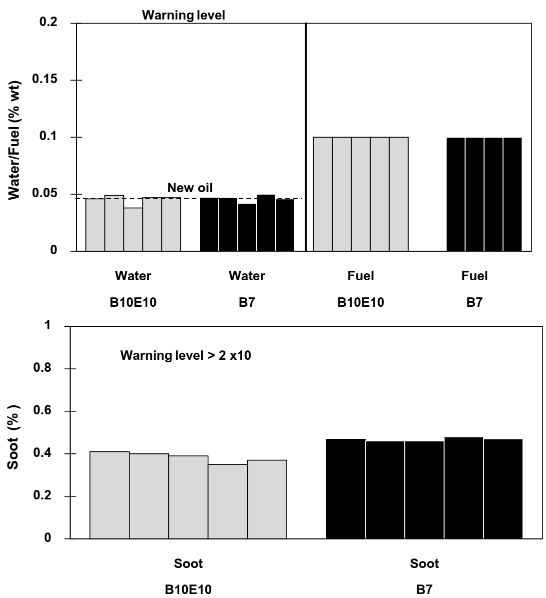

Fig. 10 Contamination of water, fuel, and soot in used lube oil at every 100 hours

3.2.3 Contaminations

The contaminants comprised of water, fuel, and soot diluting in the engine oil are presented in Fig. 10. All contaminant levels are below the upper warning limits. There is no sign of water leakage from the cooling system into the lubricant—the water level in the used oil is comparable to the fresh. However, the fuel can vent through the oil pan and dilute the oil, leading to decreased viscosity (shown above). The effect of both test fuels on fuel dilution is equivalent. Soot concentration when using ethanol-blended fuels is marginally inferior to commercial diesel. The cause is the suppressed soot formation during in-cylinder combustion by a higher amount of oxygen [5].

3.2.4 Additive elements

As shown in Fig.11, the additive elements are zinc, phosphorus, and calcium. Zinc and phosphorus come from an organic compound multifunctional additive, zinc dialkyl dithiophosphate (ZDDP), which is in charge of antiwear and antioxidants. When ZDDP works, an additional temporary lubricant layer that acts as an antiwear property is created between two mating surfaces. This mechanism consumes and depletes ZDDP in the lube oil. Therefore, the phosphorus and zinc reduction levels are correlated [15]. However, of particular interest are the discrepancies between the change of zinc and phosphorus when using different test fuels. The difference in the amount of oxidation shown above may be the cause. Consequently,

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further investigation into the antioxidation of ZDDP and the vaporization process, which is another cause of consumed additives [15], should be conducted.

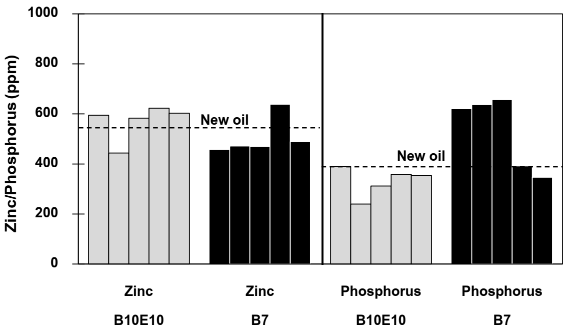
The duty of calcium is a detergent additive used to suspend contamination such as deposits. Moreover, calcium can also neutralize the acidity of combustion products. Calcium forms a thin film to envelop the coagulation deposits and hold them to the oil filter. Therefore, calcium diminished from the used oil compared to the fresh lubricant. Surprisingly, calcium precipitously fell from the oil sampled at 200 hours, resulting in a relatively low TBN, as discussed above.

The low calcium level coincides with the low level of zinc and phosphorus but does not obviously relate to other properties. Moreover, there is no sign of severe engine wear, implying the fast calcium drop.

3.3 Engine parts

All dismantled parts (not shown here) are in normal condition. No severe wear and damage appeared on any parts. Fig. 12 and 13 demonstrate the piston and cylinder head from the disassembled engine after a 500-hour endurance test. The result indicates that the engine using B10E10 has less soot depositing on the piston and head than the diesel B7, which corresponds well with the lower soot contamination in lube oil.

The lists in Table 5 are the parameters and values measured from the long-term used parts. Unfortunately, the assessment before testing could not be provided for comparison. Therefore, the manufacturer's standard specifications are given for reference. Except for the valve seat size, all parts have the measured value in the acceptable range. The parts dismantled from the engine using B10E10 have comparable value to diesel, even the valve seat.



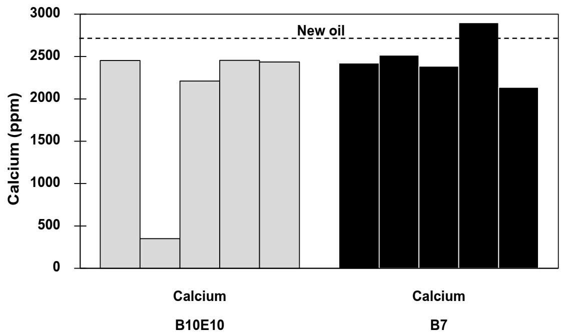


Fig. 11 Concentration of additive elements (Phosphorus, Zinc and Calcium) in used lube oil

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B10E10 **B7**

Fig. 12 Piston after long-term use

B10E10 **B7**

Fig. 13 Cylinder head after long-term use

Table 5 Parameter and measured value of the parts dissembled from the test engine

Part	Detail	Specification		Measured value	
				B10E10	Diesel
Cylinder head	Distortion	(mm./100 mm.)	< 0.05	< 0.05 mm.	< 0.05 mm.
Valve	Valve seat size	Intake (mm.)	1.4	1.6	1.6
		Exhaust (mm.)	1.4	1.55	1.55
Cylinder block	Size	(mm.)	97.010-97.032	97.048	96.956
		Limit (mm.)	< 0.2		
Piston	Wrist pin size	(mm.)	27.000-27.021	27.02	27.01
		Limit (mm.)	< 27.04		
	Pin size	(mm.)	27.002-27.011	27	27
Piston rings	1^{st} ring gap	(mm.)	0.2-0.4	0.45	0.35
	2^{nd} ring gap	Limit (mm.)	< 1.2	0.35	0.35
	3^{rd} ring gap			0.55	0.45
	4^{th} ring gap			0.35	0.35
	Side clearance between 2^{nd} rings and groove	(mm.)	0.02-0.052	0.05	0.05
	Side clearance between 3^{rd} rings and groove	Limit (mm.)	< 1.5	0.05	0.05

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4. Conclusion

The endurance of a stationary agricultural diesel engine is evaluated through 500-hour long-term use to expand the feasibility of using the ethanol-biodiesel-diesel blend (B10E10). Commercial diesel is also used for reference. The change in performance and emissions indicates engine deterioration. The engine wear is analyzed through lubrication oil. In addition, dismantled engine parts are observed and measured. The conclusions are:

- Torque reduction and increased fuel consumption specify inherent characteristics of engine deterioration when using both test fuels. However, the change in emissions could not confirm the results. Nevertheless, all changes indicate that the ethanol blend has a similar extent of worsening the engine as commercial diesel.
- The effect of the run-in period demonstrates the highest level of metal contamination at the first 100 hours of engine running when using both test fuels. Therefore, the break-in period should be longer than 12 hours to clarify the engine deterioration.
- According to lube oil analysis, a ternary blend of ethanol has a comparable effect on engine endurance and oil degradation to a binary blend of biodiesel B7.
- The dissembled engine part confirms the normal condition of the engine after long-term use for both test fuels.

From all results, it can be concluded that a stationery can apply the ternary blend as the regular fuel.

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