THE EFFECT OF BIODIESEL FUEL FROM RUBBER *(HEVEA BRASILIENSIS)* SEED OIL ON A DIRECT INJECTION (DI) DIESEL ENGINE

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Abstract

The extensive biodiversity of ASEAN countries includes many plants producing fatty-oils with yield potentials sufficient for biodiesel production. Seed of the rubber tree *(Hevea brasiliensis)* is perhaps one with significant potential because of the extensive areas of rubber plantations within ASEAN. Rubber seed oil is virtually unexploited commercially, probably because it is non-edible. Consequently, it has the potential to replace/substitute for edible oils such as palm oil, coconut oil, etc. as a raw material for biodiesel during periods of high food sector demand. Currently, the main product of the rubber tree is rubber milk, the raw material for latex and rubber industries. Rubber seed is a byproduct. The kernels constitute 50 to 60% of the seed and contain 40 to 50% brown oil.

In this study, the engine test bed procedure for testing coking of DI diesel engine injector nozzles was utilized to examine the effect of using neat Rubber seed oil biodiesel (RSB), and blends with diesel oil as fuel. The effect of the fuels on engine components and exhaust gas emissions such as Hydrocarbon (HC), Carbon Monoxide (CO), Smoke and Brake Specific Fuel Consumption (BSFC) was investigated. The performance and emissions of B5 fuel was comparable with diesel fuel; the use of B100 resulted in significantly higher BSFC (23%); higher emissions (20.83% CO, 27.78% THC, 20.80% opacity before commencement of the endurance test, 13.73% CO, 5.79% THC, 33.33% opacity after endurance test). Pure RSB and B5 reduced deposits on the cylinder head (38.74% and 35.82% respectively) but RSB increased deposits on the piston (37.42%).

Keywords: Biodiesel fuel, Brake specific fuel Consumption, Diesel engine, Direct injection, Exhaust emissions, Injector nozzle coking test, Rubber seed (*Hevea Brasiliensis*)

Introduction

In recent years, the use of biodiesels as alternative fuels has been extensively investigated with the objective of ensuring energy security and reducing the environmental impacts of diesel emissions. Rubber seed oil (RSO) has potential to become a prominent resource as it is non-edible. The rubber tree ***(Hevea brasiliensis)*** is a perennial plantation crop, originated from South America and cultivated as an industrial crop since its introduction to Southeast Asia in 1876. The rubber trees growth is most rapid at altitudes below 200 m and with monthly mean temperatures about 27 or 28°C which is appropriate in ASEAN countries.

Natural rubber producer in the world are Thailand (35%), Indonesia (23%), Malaysia(12%), India (9%), and China (7%). Cambodia now has planted these trees 70000 hectares in 2001. Normal seed production yields vary from 70 to 500 kg/ha/year [1] while the annual rubber seed production potential in India is about 150 kg per hectare [2]. Ramadhas et al. demonstrated that methyl esters of rubber seed oil could be successfully used in existing diesel engines without any modifications. Lower concentrations of biodiesel blends improved thermal efficiency. At higher concentrations of biodiesel in the blend, there was a reduction of smoke density in exhaust gas [2].

The main purpose of this investigation are to analyze and compare the effects of rubber seed biodiesel (RSB) fuel, which its properties are followed ASTM and SNI (Standar Nasional Indonesia), with conventional diesel (CD) using an endurance test to enable evaluation of the impact of blended fuels on critical components of a direct injection (DI) diesel engine [3]. Performance and emission parameters were also measured, analyzed and compared. The results add to the amount of information available on the effects of using biodiesel in diesel engines. It is also an example of the type of research basic for the development of other biodiesel resources in the agricultural countries of Southeast Asia.

Experimental Setup and Procedure

Engine Test Bed

All experiments were carried using a single cylinder, naturally aspirated, water cooled, horizontal type, 4- stroke DI diesel engine. The engine specifications are listed in Table 1. The engine was coupled to a 5kW, 220V, 50Hz electric generator that supply power to a series of heater elements to vary engine loads. A Stargas 898 analyser was utilized for exhaust gas emission measurement. Smoke emissions were measured with a Technotest Smokemeter 495/01. Figure 1 shows the schematic arrangement of experimental apparatus.

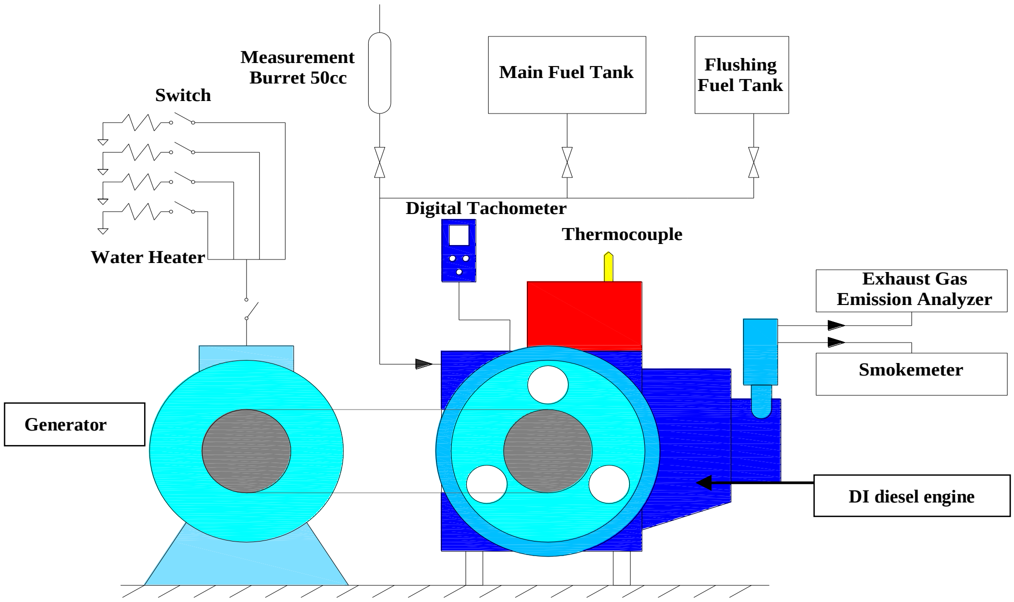


Figure 1. Schematic arrangement of experimental setup

Table 1. Engine Specifications

Engine Type	4 Strokes, Natural Aspiration , DI
Number of cylinder	1, horizontal type
Compression ratio	20:1
Bore x Stroke [mm]	Φ95 x 115
Displacement [liters]	0.815
Max. power [HPs/rpm]	14/2200
Fuel pump	BOSCH in line
Injection pressure [MPa]	12.75
Injector type	Multi-hole nozzle (4)
Rated power (kW/rpm)	8.8/2200
Injection timing	8^0 BTDC

The Fuels Tested

Three types of fuel were used to run the diesel engine to obtain data for comparing engine performance, including exhaust gas emissions, and to conduct endurance tests. The fuels used were: neat biodiesel fuel (B100), diesel fuel (B00) and a blend of 5 percent biodiesel by volume with diesel fuel (B5). The properties of these fuels were analyzed and are compared in Table 2. Differences in Cetane number (CN), viscosity, low heating value (LHV) and density influences the performance, exhaust gas emissions and wear of diesel engines. The viscosity of B100 was significantly higher than B00. Higher viscosities affect the atomization and combustion process and raise the potential for the formation of engine deposits and higher exhaust gas emissions levels [4]. In contrast to data found in the literature [2,3], the Cetane number of B100 recorded by the Lemigas Lab. was significantly higher than that of diesel fuel and is possibly erroneous. The lower Cetane numbers recorded in the literature reflect the higher levels of unsaturation in the carbon chain [2].

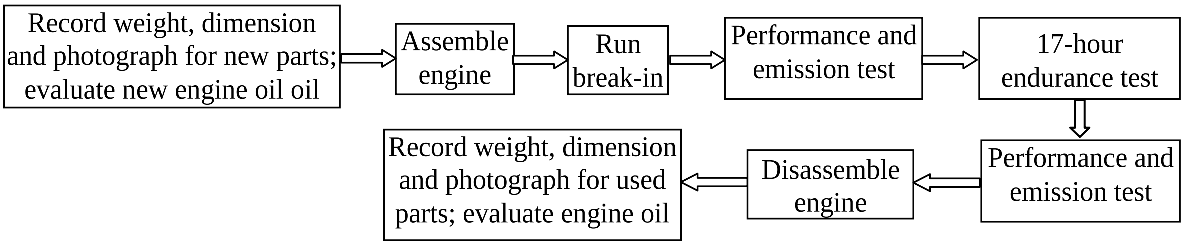
Table 2. Fuel Characteristics

Parameters	Unit	B00	B5	B100
Density at 15^0C	g/cm^3	841	843	874
Viscosity at 40^0C	mm^2/s	2.87	3.11	3.97
Flash point	^{0}C	56	-	182
Cetane number	-	54.23	-	69.56
LHV	MJ/kg	44.29	43,96	39,03
Total glycerol	%	-	-	0.08
Ester content	%	-	-	99.60
Cloud Point	^{o}C	15	-	10
Acid value	mgKOH/g	0.13	0.21	0.40

(Source: Thermofluid and Utility System Laboratory, LEMIGAS Laboratory and Thermodynamics Laboratory , Institut Teknologi Bandung)

Experiment Procedure

ads



zzzzz Figure 2. Schematic diagram of the test procedure for one sample

The endurance test was the core research element. All components of the engine influenced by the fuel both before (plunger and injector) and during the combustion process (cylinder head, valves, piston and piston rings) are changed with new parts. All of these parts were photographed, visually inspected and weighed to evaluate wear and deposits. Changes in weight and dimension were measured 5 times at each position and averaged for graphical plotting. The viscosity of lubrication oil was analyzed before and after each endurance test to check the effect of blow-by. After each test, the engine was cleaned and reassembled prior to testing the next sample.

Figure 2 is a schematic diagram of the test procedure. Before starting each endurance test, a break-in procedure of 24 hours was used to bed-in new parts, using only B00 diesel as the fuel. The break-in procedure, presented in Table 3, is specified by the Engine Builders Association (AERA).

Table 3. "Break-in" Process

Speed (rpm)	Load (kW)	Duration (hour)
850	0	2
1000	0	2
1500	0	12
1500	1	8

The procedure used for the endurance tests of the three samples (B00, B5 and B100) was as specified in the SAE Technical Paper 942010 [5], illustrated in Table 4. This operating sequence was run repeatedly for a period of 17 hours. In principle, the procedure used to check injector cleanliness follows the test method of CEC (PF-23) TB [Worldwide Fuel Charter, Sep.2006]. Reksowardojo et al. used this procedure in endurance tests for a single cylinder engine fuelled by Pure Coconut Oil, Pure Palm Oil and its biodiesel and Pure Jatropha oil and its biodiesel [6, 7, and 8].

Table 4. Operating Conditions

Speed (rpm)	Load (kW)	Duration (min)
1000	0	15
1500	4	10
2000	4	5

Before commencing the recording of performance and emission data, the engine was run until the coolant temperature reached 80^{0}C. The engine was then run at a constant speed of 1500 rpm with following loads: no load, 1kW, 2kW, 3kW and 4kW imposed by an electric generator, both before and after each endurance test. The same conditions, methods and procedures were applied for all three kinds of fuel.

Result and Discussion

Engine Performance

Brake Specific Fuel Consumption

Data for brake specific fuel consumption (BSFC) are presented in Figure 3. The BSFC versus engine load, measured as brake mean effective pressure (BMEP), was changed from 100 to 400 kPa at 1500 rpm. The average percentage increases in the BSFCs compared with B00 for B100 and B5 were respectively: 23.35 % and 3.44% before the endurance test; 23.39% and 5.41% after the endurance test. The average percentage increases in BSFCs after endurance test for B00, B100 and B5 were: 1.75%, 1.78% and 3.69% respectively. The BSFC of B00 was lower compared with both B5 and B100 biodiesel. The higher BSFC value of the biodiesel fuels can be attributed to lower heating value and higher viscosity. The fact that diesel has 11% higher caloric value, lower viscosity and better volatility than biodiesel ensures better fuel atomization and results in better combustion of the fuel as it is injected into the combustion chamber. Thus, less B00 fuel is needed to provide an equivalent amount of energy.

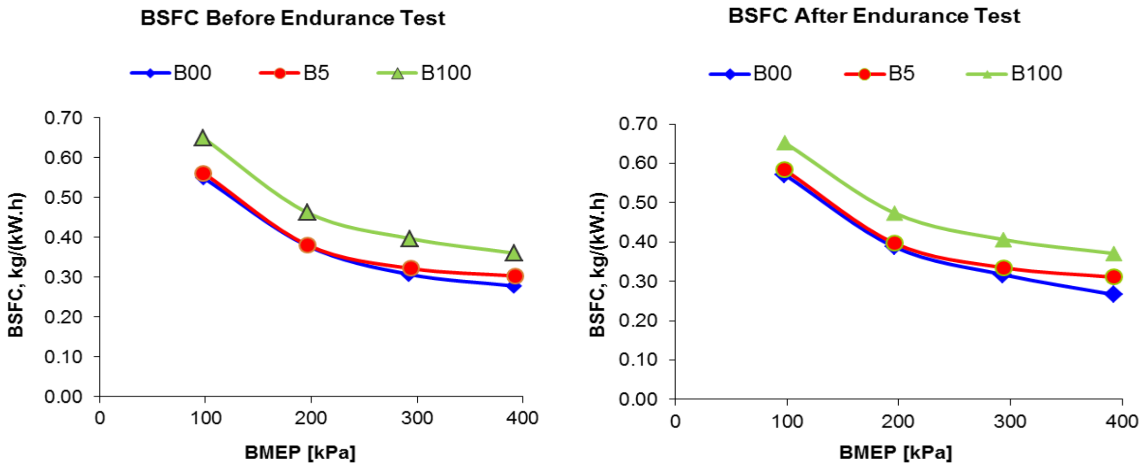


Figure 3. BSFC at 1500 rpm

Thermal Efficiency

Thermal efficiency is often referred to as the inverse of brake-specific energy consumption. Figure 4 shows thermal efficiencies before and after endurance tests for the three fuel samples. Differences in thermal efficiency were small at low load values, but became more obvious at higher load. The percentage differences of thermal efficiency for B100 and B5 compared with diesel fuel were respectively: -9.66% and -3.68% before endurance test and -11.10% and -6.48% after endurance test. A significant drop in efficiency was found with pure biodiesel when compared with diesel. This may be attributed to the poorer combustion characteristics of methyl esters due to higher viscosity. After the endurance test, the thermal efficiency of all test fuels decreased. The largest reduction was for B5

(-3.42%), followed by B100 (-2.12%) and B00 (-0.53%).

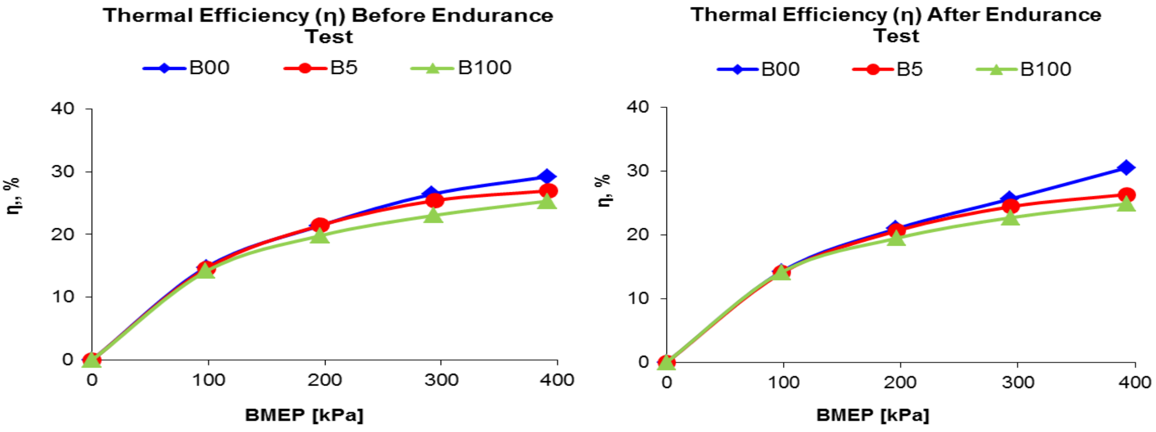


Figure 4. Thermal efficiency at 1500 rpm

Engine Exhaust Gas Emissions

Total hydrocarbon

Total hydrocarbon was measured by emission test for various blends of biodiesel and diesel at the rated engine speed of 1500 rpm under various load conditions. From Figure 5, it is evident that THC emissions increased for all fuels as the load increased. This trend is due to the presence of fuel-rich mixtures at higher loads. The percentage differences of THC emission for B100 and B5 compared with diesel fuel were respectively: 27.78% and -13.89% before and 5.79% and -12.40% after the endurance test. B100 produced the highest THC emission. Higher viscosity of the biodiesel results in less complete combustion, so increasing THC emission. Correction may require changes in injection pressure and/or injection timing.

B5 fuel produced lower THC emission than diesel fuel. This is probably due to the effect of the internal oxygen content of biodiesel fuel in the B5 blend tending to improve combustion. After the endurance test, the percentage differences of THC for B00, B100 and B5 were: 12.04%, -7.25% and 13.98% respectively. Increase of THC was due to insufficient combustion, caused by deposits and injector clogging.

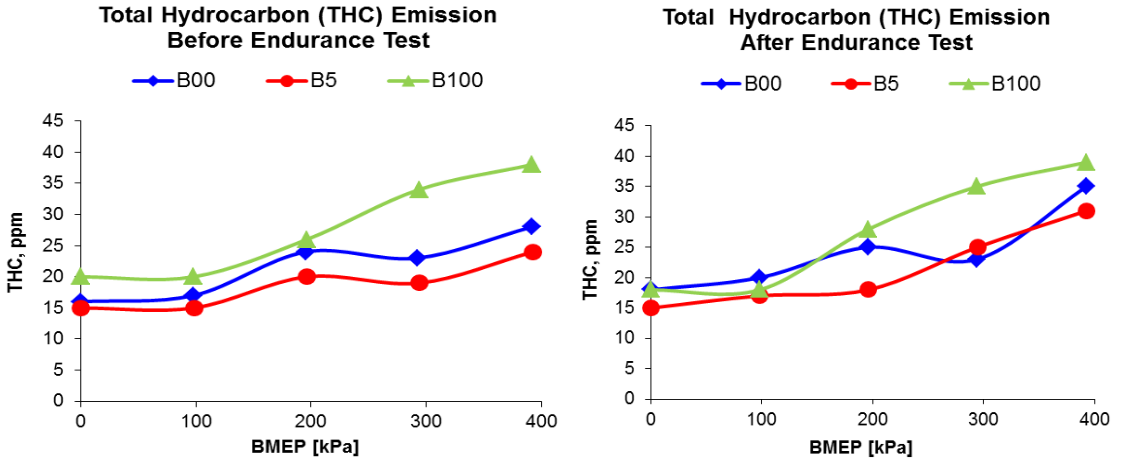


Figure 5. Total hydrocarbon emission at 1500 rpm

Carbon Monoxide

Figure 6 shows the percentage differences of CO emission for B100 and B5 compared with diesel fuel were respectively: 20.83% and -12.50% before endurance test; 13.73% and -19.61% after endurance test. It is noteworthy that, B5 produced less CO emission than B00 under all load conditions. Since RSB is an oxygenated fuel, it results in better combustion of blended biodiesel fuel and a resultant decrease in CO emissions, providing that the proportion of biodiesel is not sufficient to significantly increase the blend viscosity above that of B00. However, in case of B100, CO emission produced were higher than for diesel at the highest load level or at load levels approaching full load. The higher viscosity of B100 results in poorer combustion and higher CO emission especially at higher load levels. After endurance test, the percentage differences of CO emission for diesel, B100 and B5 were: 6.72%, 0 % and -2.38% respectively.

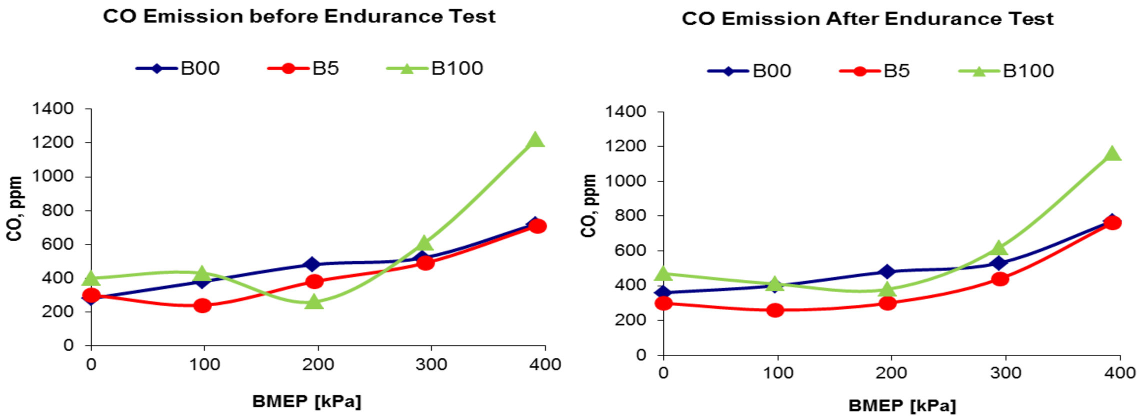


Figure 6. CO emission at 1500 rpm

Carbon Dioxide

Figure 7 shows the differences in CO_2 emission of B5 and B100 compared with diesel fuel which were respectively: 10.00% and 6.89% higher before and 17.57% and 20.42% higher after the endurance tests. Higher level of CO_2 emitted indicates better combustion of fuel. This is due to the presence of oxygen (11%) in the biodiesel fuel. After endurance test, the percentage differences of CO_2 emissions for diesel, B100 and B5 were: -12.05%, -0.91% and -6.01% respectively. Reduction of CO_2 emission was due to poorer combustion, caused by deposits in the combustion chamber and clogging of the injector.

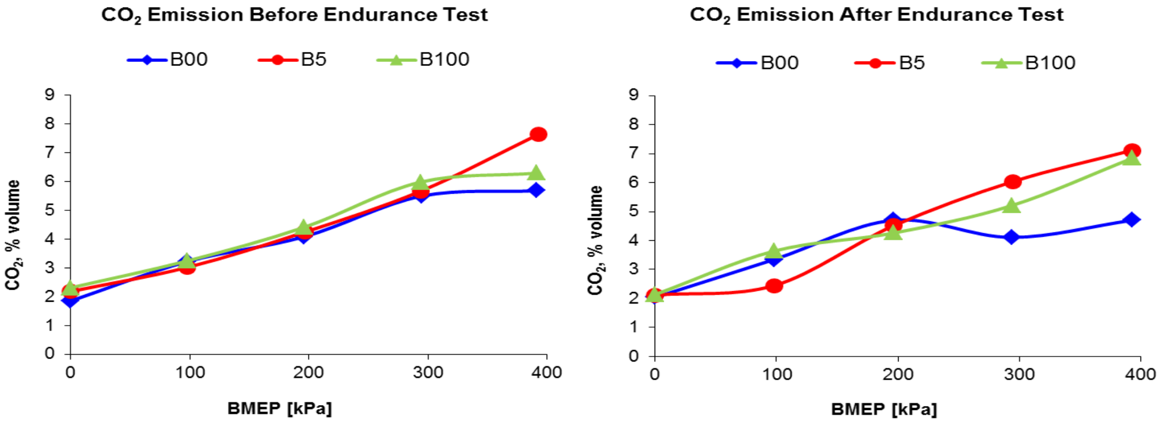


Figure 7. CO_2 emission at 1500 rpm

Smoke Emissions

Smoke formation results from unburned carbon and polycyclic aromatic hydrocarbon, and occurs for the same reasons as those for CO and HC - insufficient combustion air, poor mixing and low flame temperature. Figure 8 shows smoke opacity before and after endurance test for the three fuel samples and the engine operating at the rated engine speed of 1500 rpm under various load conditions. Smoke opacity increased with increase in load. The differences of B5 and B100 compared with diesel fuel were respectively:

-8.00% and 20.80% before endurance test; 8.33% and 33.33% after endurance test. The high viscosity of B100 RSB reduced fuel atomization and altered combustion, leading to poor mixing, increased fuel spray penetration and resulting in higher smoke levels compared with diesel especially at higher load levels. After endurance test, the percentage differences of smoke emissions for diesel, B100 and B5 were: -4.00%, 5.96% and 13.04% respectively. Increase of smoke emission was due to insufficient combustion, caused by engine deposits and clogging of injector tips.

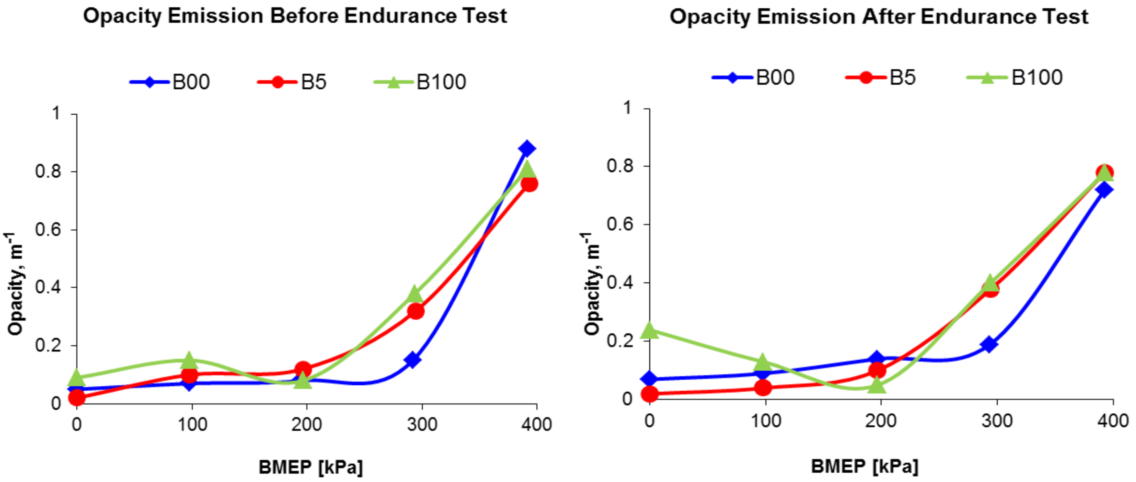


Figure 8. Opacity emission at 1500 rpm

Endurance Test

Component Wear

a. Plunger and plunger barrel

Change of diameter of plunger indicates lubrication properties of fuel. Figure 9 shows changes of diameter of plunger after endurance test. The lowest reduction of diameter occurred with B100, indicating that biodiesel fuel has better lubricating properties than B00, due to higher viscosity. Figure 10 shows changes of weight of plungers after test providing a general indication of wear for the three samples. Overall the trend in wear was greatest for B5 and least for B100.

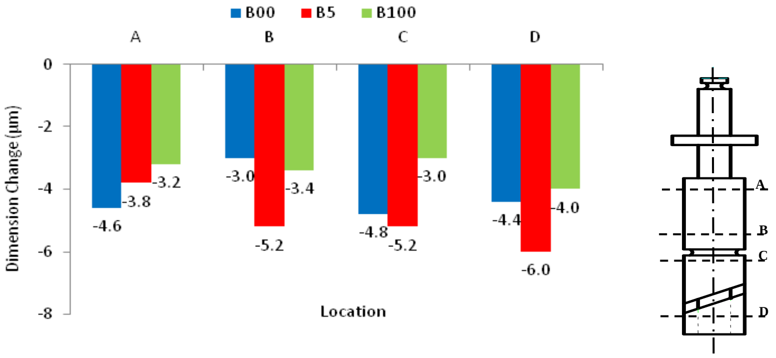


Figure 9. Change of diameter of plunger after endurance test

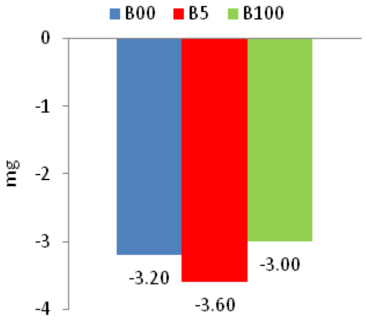


Figure 10. Change of weight of plunger after endurance test

Figure 11 shows changes of diameter of plunger barrel after the test. The lowest reduction of diameter was for B5, whereas B00 had higher wear than B100, again indicating that biodiesel fuel has better lubrication properties than B00. Figure 12 shows changes of weight of plunger barrel after test. The apparent wear trend was in descending order from B00 to B100 and then B5 respectively.

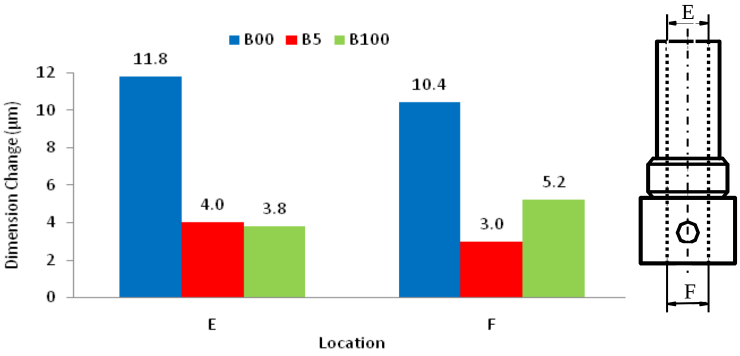


Figure 11. Change of diameter of plunger barrel after endurance test

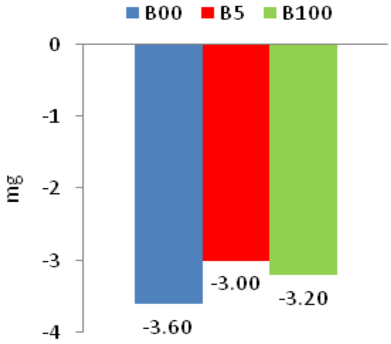


Figure 12. Change of weight of plunger after endurance test

b. Injector

Injection components investigated were the nozzle needle and nozzle, which are in contact with fuel as the lubricant. Deposits can occur in these components because of location in the combustion chamber. After completion of the endurance test, the injectors were removed from the cylinder head for visual inspection, tips were weighed, photographed and the thickness measured (nozzle tip diameter) for comparison. Figure 13, 14 and 15 show photographs, changes of diameter and weight of needle after endurance test. As in the case of the plunger, reduction in the diameter of the nozzle needle indicates the lubrication properties of fuel. B100 fuel gave the lowest reduction of diameter, again indicating that biodiesel fuel had better lubrication properties than B00. General information concerning differences in wear is provided by the weight of plunger. The trend in wear reduction was in descending order from B5 to B00 and then B100.

Diesel B5 B100

Figure 13. Nozzle needles before (left) and after endurance test (right)

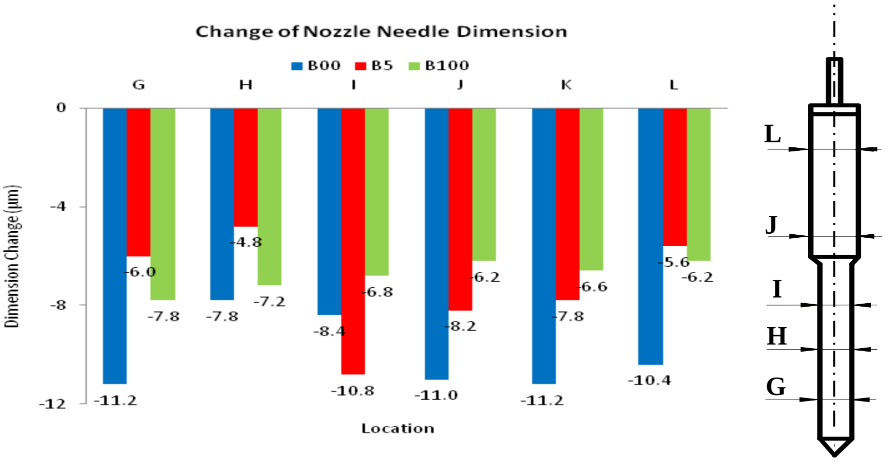


Figure 14. Change of diameter of nozzle needle after test

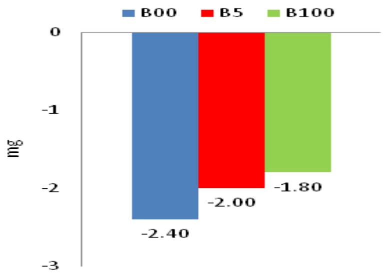


Figure 15. Change of weight of nozzle needle after test

Figure 16 to 18 show photographs, change of nozzle diameter and weight of nozzle. Deposit accumulation on liners of injector of B5 and B100 fuel was the greatest. The surfaces of the injector were dirtier after B5 and B100 use than for B00. However, greater carbon deposits were observed around the injector tip of diesel nozzle. There was no significant difference in the degree of coking around the injector tips of B5 and B100.

Diesel B5 B100

Figure16. Comparison of carbon deposits on injector nozzle before (left) and after endurance test (right)

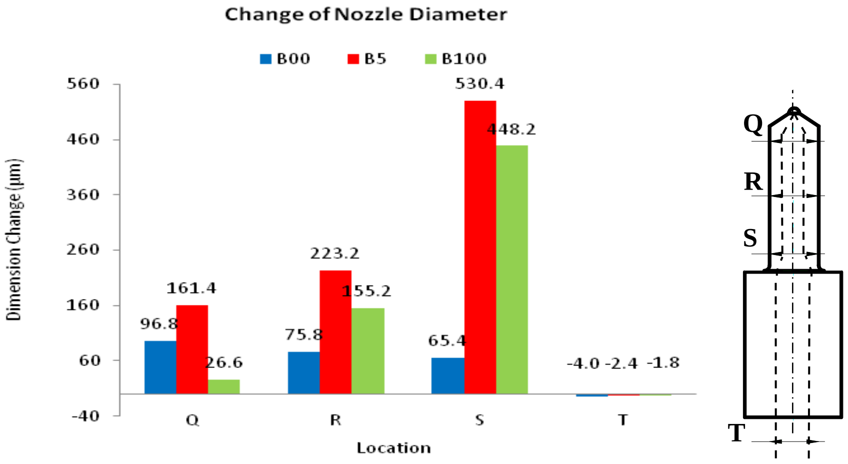


Figure17. Change of diameter of nozzle house after endurance test

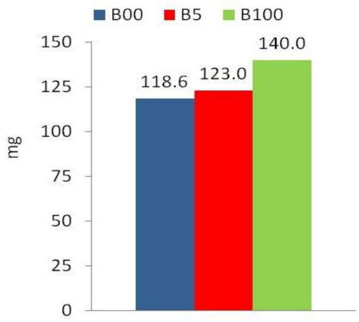


Figure 18. Change of weight of nozzle after test

Comparison Carbon Deposits

Deposits result from imperfect fuel combustion. In theory, as the flame front nears the engine wall late in the cycle, it begins to lose heat to the cooler surface, slowing the reaction rates and preventing the flame from travelling all the way to the wall. As a result, some of the fuel/air mixture in the flame quenching region does not experience temperatures high enough for complete oxidation and forms deposits [9].

a. Piston

After removal from the cylinder head, the piston surface was inspected. The variation and distribution of insoluble deposits on piston tops is indicated by figure 19 to 20. No heavy or sticky deposits were seen on the surfaces. Based on visual inspection of the piston tops, the deposits were dry and dark in case of B00, but wet and shiny in case of B100. B00 contains polycyclic aromatic hydrocarbons (PAHs) that are heavy and difficult to burn, and these may have been the main composition of deposits. In case of B100, quenching of the flame and condensation of fuel on the piston surface due to higher viscosity and density led to deposit formation. Deposits may also be the result of polymerization reactions. Biodiesel, particularly RSB, has high concentrations of unsaturated carbon chains that polymerize and can form long and heavy compounds at the very high temperature on piston tops. Hence, more deposit also developed on the B100 piston. The deposits in case of B5 were smooth, fine and shiny. This may have been due to leaner combustion conditions.

Diesel B5 B100

Figure 19. Carbon deposits in piston before (above) and after endurance test (below)

Deposit concentration is highest at impingement points. When fuel is injected and impinges on piston, the flame is extinguished and the fuel condenses on piston. This phenomenon resulted in heavier deposits from B100 than CD because of the higher viscosity and density of B100 which increase droplet size and momentum resulting in greater tip penetration. More B100 fuel impinges on the piston and more deposit accumulated.

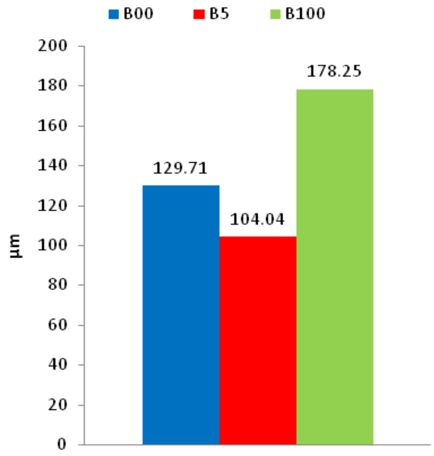


Figure 20. Deposits in piston after endurance test compared to new condition

b. Cylinder Head and Valves

Figure 21 to 22 show the average deposit thickness and the variations of distribution of deposits on the cylinder head. There were no heavy deposits on the cylinder head and valve surfaces or in the exhaust manifold. Deposit formation was lesser in the case of B5 and B100 than for B00. The cylinder head is in direct contact with cooling water so the combustion surface is lower in temperature than the piston. Accordingly, there is a reduction in the tendency for unsaturated carbon chains to polymerize on the cylinder head surfaces than on the piston.

The build-up of deposits in the combustion chamber appeared to be influenced mainly by the temperature and location. The highest deposit distribution was around the points furthest away from the high heat source and on the exhaust valve where temperature and exhaust gas concentration was the highest.

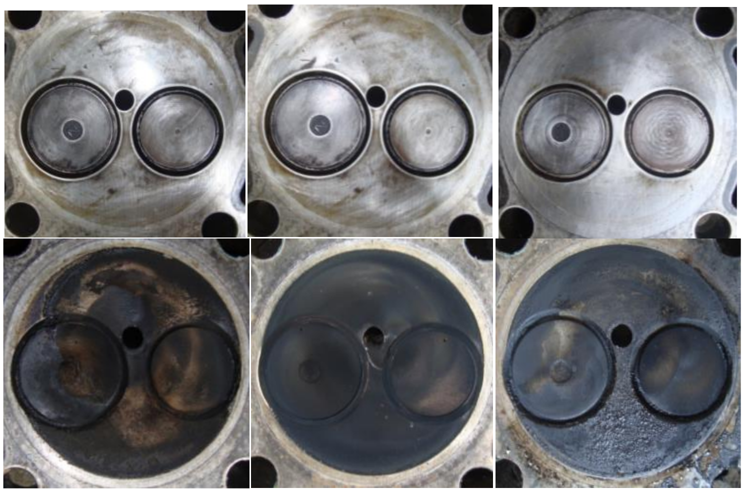


Figure 21. Carbon deposits in cylinder head before (above) and after (below) endurance test

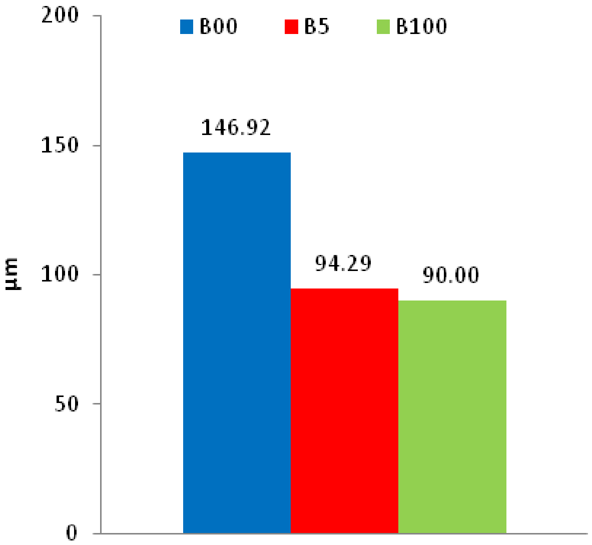


Figure 22. Deposits in cylinder head after endurance test compared to new condition

Engine Oil Analysis

Samples of lubricating oil were collected at the end of 17-hour endurance test for each fuel. The samples were analyzed in order to obtain viscosity, metallic concentration and total base number. The data obtained was used to examine the effect of B00, B5 and B100 fuels on lubricating oil performance.

Viscosity is one of the most important properties of engine oils. Viscosity of engine oil was determined at 100°C being close to the average oil temperature during engine operation. Figure 23 shows the trend of crankcase oil viscosity during the endurance test. Oil viscosity in the case of CD and B5 fuels increased slightly but in the case of B100 fuel the viscosity of the engine oil was reduced. This decrease in viscosity was probably due to dilution of the engine oil by the fuel [10]. The higher viscosity and density of bio-diesel compared to diesel fuel may result in passage of bio-diesel through piston rings to the cylinder liner and hence to the crankcase. Neat biodiesel diluting the lubricating oil may result in a reduction in viscosity. Un-burnt biodiesel passing to the crankcase may reduce lubricant viscosity over time, reducing lubricant film thickness and ultimately increasing component wear.

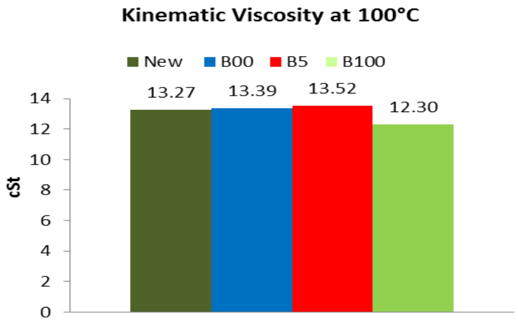


Figure 23. Kinematic viscosity of engine oil after endurance test

Engine wear was monitored by analyzing the lubricating oil for wear-metal levels. The concentrations of four metallic wear particles are shown in Figure 24. Copper, aluminum and chromium concentrations of three samples were minimal due to the change to new engine oil after finishing 24-hour break-in process. The only significant presence of metallic wear particles was for iron. The highest level of iron occurred in the case of biodiesel rising to 26 ppm, which correlates with the reduction in the viscosity of the lubricating oil, i.e. dilution of the lubricant oil resulted in a higher rate of wear. For B00 and B5 the concentrations of Fe were 11 and 12 ppm respectively, indicating the wear rates for these two fuels were comparable.

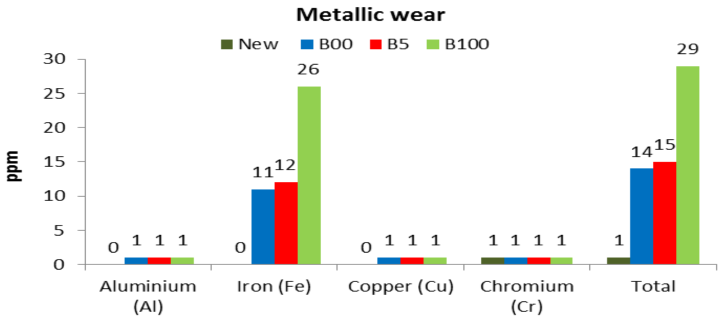


Figure 24. Variation of metallic concentration as a function of running hours

Total base number (TBN) is a measurement of the degree of acidity or alkalinity of the lubricant. After 17-hour endurance test TBN of all samples slightly increased, see Figure 25.

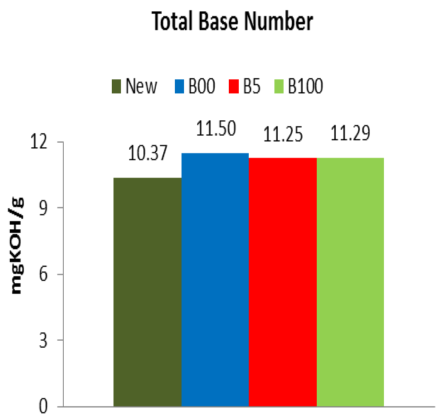


Figure 25. Total base number of engine oil after endurance test

Conclusions

The main conclusions from this research can be summarized as follows.

- BSFC for B5 fuel was comparable to that of diesel fuel. The BSFC was significantly higher (23%) than for diesel fuel. Brake thermal efficiency of B5 blend was better than B100 but still less than diesel, due to the lower calorific value of RSB than diesel.
- The B5 blend produced lower exhaust emissions including CO, THC and smoke opacity. Emissions for B100 were significantly higher than diesel (20.83% CO, 27.78% THC, 20.80 opacity before endurance test, 13.73% CO, 5.79% THC, 33.33 opacity after endurance test) because of poorer atomization due to high viscosity and poorer combustion due to the low heating value of RSB. According to results of CO and smoke emissions, it appears that the most favorable working condition of B100 fuel is at 200 kPa and 1500 rpm due to reduction of those emissions.
- RSB reduced wear of fuel-contact engine components due to its better lubricity.
- Pure RSB and B5 reduce deposits on the cylinder head but RSB increases deposits on the piston due to the high concentration of unsaturated fatty acids in the carbon chain.
- B5 does not significantly affect the lubricating oil viscosity.

Overall the results indicate that Rubber Seed biodiesel can be used as a partial substitute for diesel fuel. A 5 % blend of RSB with diesel fuel can be used to fuel DI diesel engines providing comparable performance, reduced emissions, wear reduction of engine components and neutral effect on lubricating oil. No significant engine modifications are required. The properties of RSB meet both ASTM and SNI (Standar Nasional Indonesia) standards for Biodiesel.

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