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DURABILITY OF A SMALL AGRICULTURAL ENGINE ON BIOGAS/DIESEL DUAL FUEL OPERATION[*]

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Abstract– Biogas from anaerobic digestion of organic waste is a potential alternative to the partial substitution of petroleum derived fuels because it is from renewable resources that are widely available. The effect of long term durability tests using biogas/diesel dual fuel operation on wear characteristics is evaluated and presented in this paper. Steady state tests were performed on a small, single cylinder, naturally aspirated, 4-stroke, direct injection diesel engine at a speed of 1500 rpm, coupled to a generator set to generate electricity for over 3500 hours. Lubricating oil samples were collected during the test run and were subjected to the analysis of various wear metal traces present and the changes in their properties. After completion of the endurance test, the engine was dismantled for physical inspection and wear assessment of vital parts. Formation of carbon deposits on in-cylinder surfaces was not found to be problematic. Injector tip coking did not occur. Surface wear and accumulations of metal debris in crankcase lubricating oil samples were analyzed and found to increase with time, but not at an unusual rate. Properties of used lubricating oils did not alter significantly from their original values. Wear was not significantly different in the test engine fueled with the biogas/diesel combination. An overall evaluation of the results indicated that the biogas/diesel duel fuel operation could be substituted for diesel fuel in electricity generation and worked satisfactorily under long term engine operation without any major troubles.

Keywords– Biogas, compression ignition, dual fuel, endurance test, renewable energy, wear

1. INTRODUCTION

It is common knowledge that the world's main energy resources will be depleted within the next several decades. The world is unavoidably faced with crises of fossil fuel shortage and environmental degradation as a direct result of growth in population, urbanization and industrialization [1]. Most countries find themselves under considerable energy constraints, while the growing demand for domestic energy use decreases fuelwood reserves and increases deforestation rates, foreign exchange earnings have to be spent on imported fuels. In Thailand, energy demand for gasoline and diesel fuels is as high as ever and imported petroleum products account for a large proportion of the country's energy imports [2]. The search for alternatives to partial or total substitution of fossil fuels has, therefore, been intensified in the last decade. Among the many different types of alternative fuels, biogas from anaerobic digestion of animal manure appears to be one of the most promising options [3]. Biogas technology has been developed steadily over the last 70 years [4]. It originates from the biodegradation of organic materials by bacteria under anaerobic condition and consists of mainly methane and carbon dioxide. The idea of biogas as a diesel fuel substitute is not new, but it is a very attractive alternative, especially in countries rich in agricultural products and poor in petroleum resources. There have been continuing efforts in research,

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development and demonstration to utilize biogas to provide heat and power agricultural engines in farms within the country for the past several decades [5]. Biogas can be used as an alternative to the partial or total substitution of gasoline and diesel fuels without requiring extensive engine adjustments or modifications [6]. Utilization of biogas will also help decrease farmers electricity use and reduce the expenditure of foreign exchange required for imported petroleum products.

To operate with gaseous fuels, diesel engines can be conveniently converted to a fumigated dual fuel engine which is the most practical and efficient method. Since biogas has a high octane number, it can be employed in a high compression ratio engine to maximize its conversion efficiency. In dual fuel operation mode, biogas is mixed with air prior to entering the combustion chamber. At the end of compression stroke, a pilot amount of diesel fuel is injected to ignite the mixture, as long as proper spray penetration and evaporation are achieved [7]. One advantage of this method is that the engine can be switched back to conventional diesel operation mode when the gaseous fuel supply is not available. Numerous research works have been done on dual fuel engines. These include natural gas [8-12], methane and propane [13-15], hydrogen [16, 17], producer gas [18] and biogas [19-22]. All investigations have concentrated on combustion characteristics, emissions and short term engine performance. Generally, relatively short term test results have confirmed their feasibility as fuels in engines with acceptable performance and emission quality. In comparison with conventional diesel, dual fuel operation tend to give higher exhaust gas temperature, higher lubricating oil and cooling water temperatures, higher equivalent ratio and lower energy conversion efficiency. However, information for long periods of operation time is scarce. The long term operation may pose problems including lubricating oil contamination, carbon deposits on engine surfaces and injection problems [23]. Sulfur content in biogas can be oxidized to form sulfur oxides in the engine combustion chamber. Sulfuric acid from a combination of sulfur oxides and water vapor will attack engine parts, giving rise to corrosion wear. The presence of biogas has the effect of decreasing the volumetric efficiency of air into the combustion chamber, leading to poor combustion and formation of deposits on the chamber wall, valve seat and injector. Some biogas or combustion products may be introduced into the lubricating oil, causing fuel dilution. Oxidation of the lubricating oil may occur and result in excessive thickening of the lubricating oil and the problem of inadequate engine lubrication over some portion of a temperature range [24].

Our research efforts are therefore directed to improvements in the use of biogas as fuel on a diesel engine with minimum engine modifications. Durability test of an agricultural engine operating on biofuel is of great interest to farmers and those in agriculture and horticulture. In this investigation, long term tests for engine durability operating on biogas/diesel dual fuel were carried out and reported. The main objective is to evaluate wear characteristics and changes in lubricants' properties of a small, naturally aspirated, agricultural, direct injection engine using dual fuel.

2. EXPERIMENTAL APPARATUS

The specific type of engine used in this project is a Mitsubishi DI-800 diesel engine. Setup of the experimental engine is illustrated in Fig. 1 and its specifications are listed in Table 1. The test engine was completed with its own cooling system. There was no modification of the engine, apart from installing a gas mixer upstream of the air inlet duct. The test engine was coupled to an alternator acting as a variable load system. The dynamometer used was an air-cooled, eddy-current type. Various instruments and gauges were employed to obtain different measurements. The engine speed was measured by a Digicon digital tachometer model DT-240P. Type K thermocouples utilizing TASK digital thermometers model TLDT-2 were used to measure inlet air and exhaust temperatures as well as coolant and cylinder wall temperatures. Air and biogas flow rates were regulated and measured by means of a Dwyer mass flow meter model GFC-1111 and a Chemec biogas meter, respectively. The fuel consumption rate was determined gravimetrically, and relative humidity and ambient temperature were monitored by a Dwyer humidity meter model 657C. Various sensors and analyzers were linked to a personal computer, while engine measurements were registered automatically by a data acquisition system.

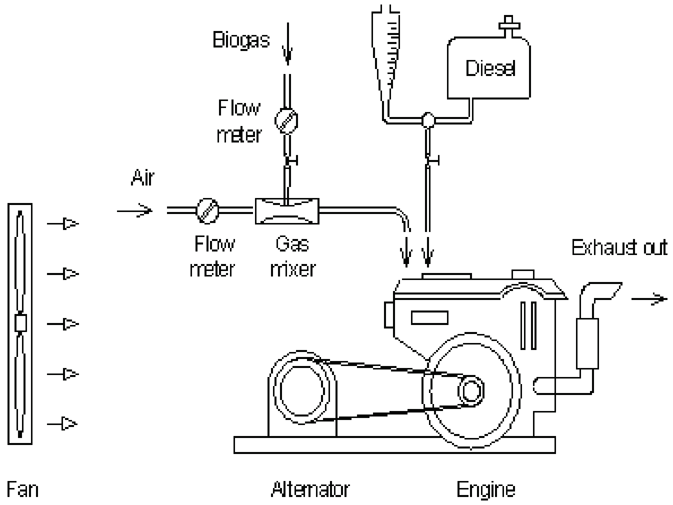


Fig. 1. Setup of the engine test rig

Table 1. Engine specifications

Engine	Mitsubishi DI 800
Type	Inline, 4-stroke, naturally aspirated
Combustion	Direct injection, compression ignition
Number of cylinders	1
Bore	82 mm
Stroke	78 mm
Displacement	411 cm^3
Rated power	5.5 kW at 2400 rpm
Maximum torque	25 Nm at 1900 rpm
Compression ratio	18:1
Injection timing	16^o BTDC
Dimension (L W H)	682 mm x 336 mm x 455 mm
Dry weight	82 kg
Governor type	Mechanical, variable speed
Cooling system	Water, pressurized circulation

Biogas used in the tests was supplied from a local swine farm. It was stored and compressed to about 250 Pa gauge in a closed, collapsible rubber dome from where it was fed to the engine intake port. Prior to entering the engine, biogas was passed through a condensation trap and a gas treatment unit to remove moisture and react with trace amounts of sulfur compounds present in biogas. Its compositions were regularly monitored. They were 66% CH_4, 26% CO_2, 6% N_2, 2% O_2 with some traces of H_2S. The biogas was also analyzed for its properties along with diesel obtained from a local commercial retailer. These are shown in Table 2.

Table 2. Properties of tested fuels

Properties	Diesel	Biogas
Heating value (MJ/kg)	45.91	24.50
Cetane number	50 minimum	-
Specific gravity @ 15°C	0.830	0.001
Viscosity @ 40°C (cSt)	3.34	-
Pour point (°C)	0	-
Sulfur content (%wt.)	0.037	0.12
Ash (%wt.)	0.001	< 0.001

3. ENGINE CONDITIONING AND TEST PROCEDURE

Prior to a durability run, the following engine conditioning procedure was undertaken. The engine was run idle through a 24 hour conditioning period to provide a properly “broken-in” engine at our engine laboratory. It was, afterwards, completely disassembled. Critical components such as cylinders, pistons, piston rings and a fuel injector pump were visually inspected and photographically recorded. The fuel injector pump was checked for its standard nozzle pressure. The engine was then reassembled in strict accordance with all furnished specifications and the fuel injector pump was readjusted and calibrated to its original state using a ZEXEL model 15 NP fuel pump tester. Once the engine had been reinstalled on the dynamometer test stand, additional 24-hour conditioning was run immediately following all engine oil changes. After the engine conditioning stage, all fuel filters, lubricating oil filters, lubricants and fuels were replaced with new ones and the engine was ready for durability testing. The lubricating oil used was of SAE 30 grade which was in similar grade to that recommended by the engine manufacturer and was obtained in a single batch in an amount enough for all tests. The oil change was carried out at every 250 hours as recommended by the engine manufacturer. Initially, the engine was operated on diesel fuel. Subsequently, the amount of diesel fuel was gradually reduced, while biogas was introduced to the engine. The amount of biogas was adjusted manually to achieve required speed and maximum possible power output. An effort was made to keep the pilot amount of diesel fuel as small as possible while maintaining smooth, trouble free operation.

A variable speed range from 1400 to 2000 rpm with wide-open throttle setting was chosen for performance tests prior to the durability test. A constant speed mode (1500 rpm) was later maintained throughout the durability test period. The engine was allowed to run continuously 24 hours per day, accumulating about 3500 hours durability tests in about six months. Periodic maintenance and oil change were performed at an interval of 200-250 hours according to the engine manufacturer. During the first 500, 900, 2000 hours and at the end of a 3500 hour endurance test, the engine was disassembled, components were again inspected. All components were reused until the end of the test except for minor spare parts. During the first 900 hours and at the end of the 2000 hour endurance test, the sample of lubricating oil was collected from the crankcase sump with a syringe while the engine was in operation. The same amount of fresh new lubricating oil equal to that collected was added up each time after sampling. All the samples of lubricant were then sent to the PTT Research and Technology Institute to analyze any change in their properties, including oxidation stability, total acid number, total base number and kinematic viscosity in accordance with the ASTM standard methods. Wear metal particles, Si, Pb, Fe, Cr, Cu and Al were also determined using a Perkin Elmer inductively coupled plasma spectrometer model Optima 3300DK.

4. RESULTS AND DISCUSSION

Biogas/diesel dual fuel operation on the small, unmodified DI engine was found to run successfully. Biogas substitution or diesel replacement rate of over 90% by mass can be achieved. In the whole range of engine operation over 3500 hours, there was no major breakdown. The engine was able to maintain a speed of 1500 rpm and power output of about 1.5 kW electricity throughout the period.

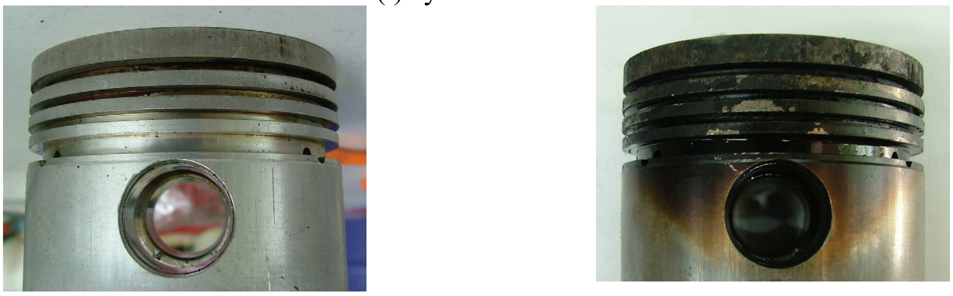
a) Carbon deposits

After completion of the endurance test, the engine was disassembled and the deposit formations on cylinder head, piston, injector tip, inlet and exhaust valves were examined. Figure 2 shows carbon deposits on the cylinder head, piston ring belt areas, injector, inlet and exhaust valve stems and landings, compared to the respective original parts prior to the test. Their surfaces were covered with deposits which were relatively heavy and appeared to be brownish black and hard. This indicated that some amount of fuels burned on the wall leaving the residue behind after a prolonged period of operation. Carbon residuals were also found on the piston ring and ring grove. Inlet and exhaust ports and valve stems were coated with rather thick deposits but can be easily removed. The injection nozzle tips were relatively clean, showing normal carbon residue. A routine check with a nozzle injection pressure tester showed negligible deviation from initial behavior. It should be noted that erratic operation from deposit accumulation and sticking was not encountered. The formation of carbon deposits did not unduly affect the overall performance of the engine.

b) Engine wear

Sliding contact between solid metallic components of any mechanical system is always accompanied by wear which results in the generation of minute particles of metal [24]. In a diesel engine, the components normally subjected to wear processes are the piston, piston ring, cylinder liner, bearing, crankshaft, cam, tappet and valves [25]. Wear of engine valve and seat insert include adhesive wear, surface fatigue wear, shear strain and abrasive wear [26]. Wear problems are associated with two regions within the engine, the combustion zone and the crankcase zone [25]. In the combustion zone, the combination of high gas temperature and high gas pressure may prevent effective formation of a lubricating oil film between the piston ring and the cylinder liner surface, resulting in metal-to-metal contact with subsequent damage. Sulfuric acid produced by the combination of sulfur trioxide and water vapor during the combustion process may also contribute to corrosion wear. Cold running may allow moisture to condense within the crankcase, which could lead to rusting when the engine is shut down. Abrasive wear may be caused by hard particles that are drawn into the engine or formed within the engine such as particulate matter, ash or wear debris [27]. From the experiment, the engine completed the durability test without any performance problem. Visual inspection of components at the end of the durability test showed little change, compared to its initial conditions. The engine liners showed no signs of wear and the same was true for the crankshaft, bearing and inlet valve stem. Cylinder head, intake and exhaust valves were in good working condition. The pistons and rings also showed no signs of excessive wear. These findings were surprising because wear was expected to occur due to the corrosive nature of the sulfur compounds present and the poor lubrication properties resulting from gas combustion. The engine wear did not vary significantly with running time. A number of engine parts were weighed. The percentage mass loss as an indication of wear after the durability test was calculated and the results are shown in Table 3. There was evidence of slight wear, but the magnitudes were generally small with less than 5% mass loss. Only a connecting rod bush gave a 21% loss rate, but this did not in anyway affect the engine performance and operation. The wear in engine components was not severe and most parts can be reused until the end of the endurance test.

(i) cylinder head



(ii) piston

(iii) injector tip

(iv) inlet valve

(v) exhaust valve

Fig. 2. Carbon deposits on main engine components before and after 3500 hours durability test

Table 3. Engine component wear shown as percentage mass loss over 2000 hours of operation

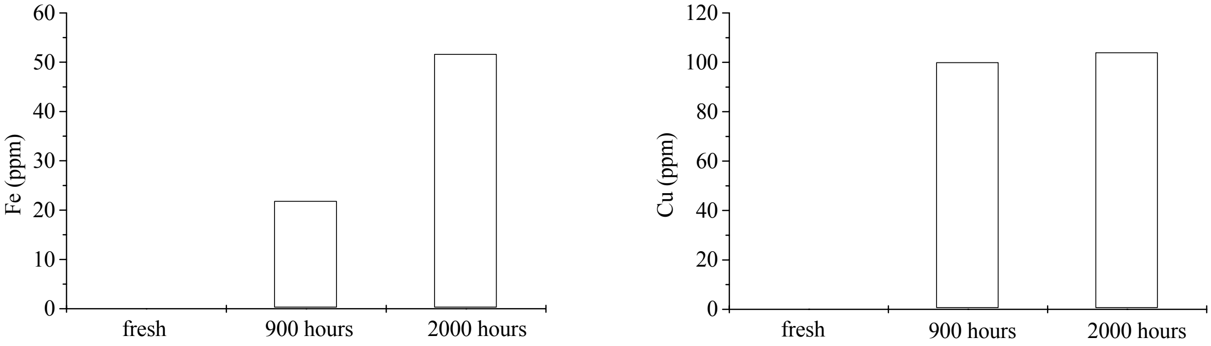
Engine components	% Mass loss
Intake valve	0.8
Exhaust valve	1.2
1st piston ring	4.3
2nd piston ring	2.0
Compression ring	0.1
Connecting rod bush	20.7
Connecting rod bearing	0.5

c) Wear metal debris

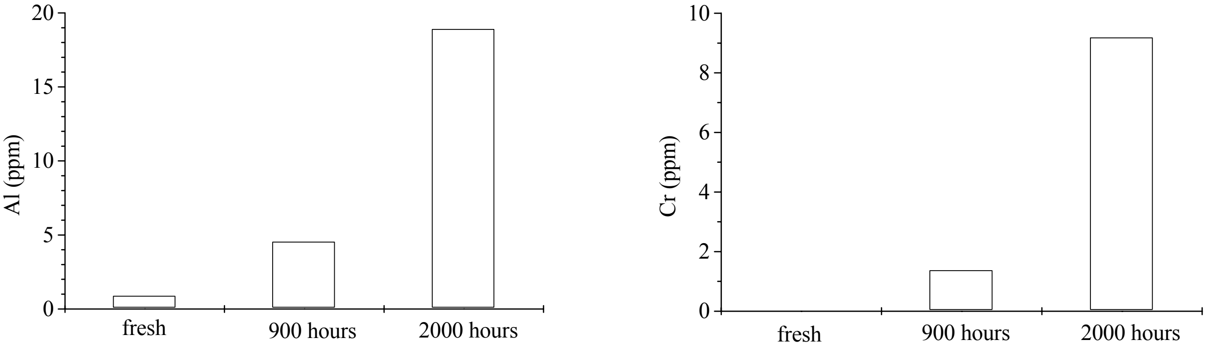
Wear particles generated from sliding contact of solid surfaces are suspended in the lubricating oil. By analyzing a sample of lubricating oil from the engine after a certain running period, it is possible to gain information on the operation and condition of the engine. Literature reveals that various contaminant metals present in used lubricating oil may have a number of possible sources in the engine [25, 26]. Table 4 lists typical sources of metallic elements in wear debris from used lubricating oil. In this investigation, variation in the concentration of wear metals debris including Fe, Cu, Al, Cr, Pb and Si in the used lubricating oil with engine operation time was obtained using ASTM D 5185 standard method [28]. Results are presented in part per million by weight of metal to lubricating oil. Analysis results were illustrated in Fig. 3. From the results obtained, there was a marked increase in Fe concentration in the lubricant from the initial value of 0.4 ppm to about 22 and 50 ppm at the 900th hour and 2000th hour, respectively. The iron in wear debris could be from the cylinder liner, piston, rings, valves, valve guides, gears, shafts, rust and crankshaft. Similar ascending trends of wear metals concentration for Al and Cr were also observed. They showed an increase in concentration at a higher degree between 900-2000 hours than the first 900 hours. The aluminum and chromium in lubricating oil come from wear of piston, bearings, cylinder liner, compression rings and crankshaft. Silicon exhibited a small but constant rise in concentration with engine age. With respect to Cu and Pb, the rate of wear tended to be initially high and in time decreased to a lower value. The copper and lead in wear debris may originate from bearings, bushings, paints and grease additives. Overall, wear metals did not increase beyond the usual values encountered in the durability tests.

Table 4. Typical sources of metallic elements in wear debris

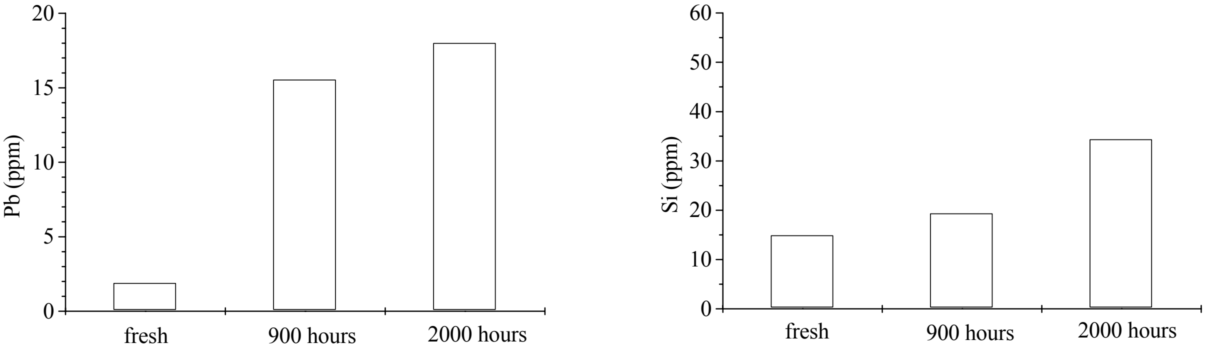
Cylinder liner	Fe, Cr
Piston rings	Fe, Cr, Mo, Cu
Piston	Al, Si, Fe, Sn, Pb
Crankshaft	Fe, Cr
Bearings	Pb-Sn, Cu-Pb-Sn, Al-Si, Al-Sn
Camshaft	Fe
Valve train	Fe, Ni
Auxiliary drive	Cu-Pb, Fe



(i) Iron (ii) Copper



(iii) Aluminium (iv) Chromium



(v) Lead (vi) Silicon

Fig. 3. Concentration of wear metal debris in lubricating oil as a function of engine operation time

d) Change in lubricating oil properties

The lubricating properties of engine oil change with running time were due to the effects of oxidation, thermal degradation, reaction with sliding surfaces, contamination by engine blow-by and additive depletion [29]. During engine operation, a small amount of fuel may be diluted in the lubricating oil. This is especially important during engine starting when the ambient temperature is low and the fuel/air mixture is rich. Four important properties of lubricating oil were considered in this study, namely, oxidation stability, acid number, base number and kinematic viscosity at high temperatures which were determined according to relevant ASTM standards. Viscosity is the most important property of lubricating oil because it affects the engine friction and wear rate of engine components. Change in viscosity of the lubricating oil is undesirable. Very high viscosity increases frictional loss through the shearing forces of the lubricant preventing the formation of a protective film. Reduction in oil viscosity has an adverse effect on the formation of protective film, diminishing load bearing ability. Results summarized in Table 5 showed a monotonic drop in viscosity values from 14.6, 11.3 and 7.4 cSt as the operation time increased. Even though no noticeable oil thickening or thinning was physically observed, smaller than original value of viscosity of the lubricant may have led to excessive wear, low oil pressure and poor oil economy during the remaining life of the engine. A decrease in viscosity may be attributed to fuel dilution, which is a direct consequence of clearance between the piston rings and the cylinder liner. The higher degree of ring wear will result in an increase in clearance, hence, higher dilution.

Table 5. Change in properties of lubricating oil with operation time

Property	Test method	Fresh lube oil	900 hours	2000 hours
Kinematic viscosity at 100°C (cSt)	ASTM D 445	14.59	11.34	7.36
Oxidation stability (min)	ASTM D 2272	249	71	86
Acid number (mgKOH/g)	ASTM D 664	3.57	3.80	3.56
Base number (mgKOH/g)	ASTM D 2896	10.09	7.84	3.90

A test for the oxidation stability of the lubricating oils was performed. Results showed a sharp decline in oxidation stability from about 250 min for fresh oil to around 80 min for used lube oil, indicating a degradation of the lubricating oil. Variations of acid and base numbers with the operating time are also shown in Table 5. Acid and base numbers are the measures of oil alkalinity and acidity, indicating its ability to counter corrosive effect due to oxidation [30]. While an acid number shows acidic presence, a base number value indicates the absence of free strong acids. A higher base number refers to a higher degree of stability for the lube oil. From the results obtained, fresh oil showed a relatively high acid number value. It was also found that change in the acid number with running time was generally small, lying within the range of 3.56 – 3.80 mgKOH/g. On the other hand, the base number proved to undergo a marked reduction. It was originally at 10.1 mgKOH/g and dropped sharply to about 7.1 and 3.9 mgKOH/g at 900th and 200\0th hour, respectively. Results from oxidation stability, acid and base number analyses appeared to lead to a similar conclusion, however, it should be noted that even though the lubricating oil was expected to experience some degree of oxidation, the evaporation of lighter oil components, contamination by foreign particulates and depletion of its additives, the severe degradation of the lubricating oil's properties was not encountered in the durability tests.

5. CONCLUSION

In this research study, evaluation of engine durability test operating on biogas/diesel dual fuel in a small DI diesel engine at constant speed and load condition over 3500 hours has been carried out. The results were investigated in terms of performance and wear. The following conclusions may be drawn from the present study.

1) Carbon deposits were observed on in-cylinder surfaces but their amounts were not substantial. Rate of wear in terms of percentage mass loss was small for most parts except a connecting rod bush which can be easily taken care of during routine maintenance.
2) Low concentrations of metallic elements were present in lubricating oil samples and exhibited an increasing trend with operation time. Oil analysis also revealed changes in lubricating oil properties, noticeably a decrease in oxidation stability, base number and viscosity. Nonetheless,

unusual increase in wear metal debris and the deterioration of the lubricating oil's properties were not observed.

3) Biogas can potentially be utilized in a dual fuel operation and performed satisfactorily without any engine hardware modification under long term engine operation. No significant problems were observed during the entire engine durability test.

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