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Oil filter modification for biodiesel-fueled engine: A pathway to lubricant sustainability and exhaust emissions reduction

M.Gulzar[1], H.H Masjuki[2], M.A Kalam, M. Varman, I.M. Rizwanul Fattah

Centre for Energy Sciences, Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

Abstract

The widespread use of biodiesel in internal combustion engines promotes frequent lubricant drain intervals which in turn affects lubricant sustainability and engine performance. In this research two endurance tests were carried out to evaluate the novel approach of strong base oil filter with palm biodiesel (PME) fueled single-cylinder diesel engine. The effects of strong base filter on lubricant rheology, piston ring/cylinder wear losses, engine performance and exhaust emissions were investigated. The results of long duration engine testing showed that the strong base filter improved the lubricant's physical and tribological characteristics. Tribo-testing, using high stroke reciprocating test rig, proved that the mechanical energy losses due to piston ring-cylinder interaction were reduced significantly. Finally, the engine performance and exhaust emissions analysis for strong base filter testing showed an improvement in engine performance, average decrease of 2.78 percent in carbon monoxide (CO) emissions, 7.18 percent reduction in hydrocarbon (HC) emissions and 3.3% reduction in smoke opacity at full load engine conditions.

Keywords: Strong base filter, palm biodiesel, sustainability, drain interval, piston ring, engine emissions

[1] Corresponding author. Tel.: +60 3 79674448; Fax: +60 379675317. E-mail: mubashir_nustian@hotmail.com

[2] Corresponding author. Tel.: +60 3 7967 5245; Fax: +60 379675317. E-mail: masjuki@um.edu.my

1. Introduction

With the increasing environmental legislations, tribologists and researchers are looking for environment friendly lubrication alternatives. However industrial and transport sector is majorly dependent on petroleum based lubricants. As a result yearly millions of tons of oil wastes are exposed to environment which are toxic and non-biodegradable [1]. As the crude oil resources are depleting worldwide, the efficient use of lubricants is the requirement to meet the cost and environmental legislations [2]. The problem of short useful lubricant life is serious in diesel engines where the lubricant is degraded by contaminations such as soot, water, metal particles and acid by-products of fuels. During normal engine operations, the engine oil is exposed to combustion gases and carbon based acids. In such situations, the oxidation of base oil results in accumulation of the weak organic acids in the engine oil. The problem becomes more intense for biodiesel operated engines where the researchers have reported increased dilution and polymerization of engine oil which in turn requires more frequent oil changes [3-5]. The related problems include high carbon deposits, piston oil ring sticking, and increased engine oil viscosity [3, 6]. In order to improve the useful life and performance of engine oil, the neutralization of high concentrations of weak acids is required in biodiesel fueled engines. Currently in industry the acidity is the key factor to indicate the oil change in diesel engines and drain interval is mostly taken as engine oil ability to control the acids. With the widespread use of biodiesel as an alternative energy source, the lubricant drain interval is decreased. The esters available in biodiesels are hydrolyzed to increase the concentrations of weak acids in the lubricants [4, 5, 7]. The quality of lubricant affects the wear and friction of engine components as well as the engine performance and engine exhaust emissions [8]. The amount of unburned lubricant has been proved to be a predominant contributor to undesirable paraffins and hydrocarbons emissions [9]. Many techniques are in practice currently to maintain the lubricant physicochemical and tribological characteristics.

By pass filtration and slow additive release filters are two filter technologies currently being used to improve oil drain intervals [10]. In by pass filtration technique the contamination particles are removed mechanically, leaving the acidic contaminants untrapped. On the other hand, control over release rate is the main shortcoming in the filter technology which is based upon slow release of additives like detergents, dispersants and antioxidants etc. The accumulation of these additives increases ash content in lubricant. To address the issues mentioned in the currently practiced filter technologies, the effectiveness of novel approach of chemical modification of oil filter element has been highlighted by the various earlier researchers [10-14]. The technique found to be simple to adopt as well as economically suitable for various engines, fuels and lubricants. The related studies pointed out several benefits of strong base filter technique for diesel engines fueled with Ultra Low Sulfur Diesel (ULSD) [10, 13]. The major benefits include improvement in oil degradation rate, control of oil acidity, oil viscosity, total base number (TBN) retention and reduced engine wear and corrosion. Since the lubricant degradation rate is high for biodiesel engines so the effectiveness of strong base filter technology needs to be investigated for biodiesel-fueled engine. In this study, the strong base filter technique was assessed for palm biodiesel-fueled single cylinder CI engine. The study can be divided into following major parts.

1. Development and surface characterization of strong base (NaOH) filter.
2. Synthesis and physicochemical property analysis of palm methyl ester (PME) to be used as biodiesel.
3. Two long duration engine tests using standard and strong base filters in single cylinder diesel engine attached with emission analyzer.
4. Analysis of the effects of strong base filter on lubricant physicochemical characteristics and piston ring and cylinder liner wear losses.

5. Study of effectiveness of strong base filter on engine performance and exhaust emissions.

2. Experimental details

2.1. Flocculation of strong base on filter element

Strong base filter development was carried out as per the standard procedures. A variety of strong bases have been mentioned by researchers that can be effectively used as neutralizing agents [12, 15]. Sodium hydroxide (NaOH) was selected as strong base for this process. Reagent grade sodium hydroxide pallets with a molecular weight of 40 g/mol, pH=14 and purity of 99% were provided by the Chemistry lab, University of Malaya. High molecular weight Polyacrylamide (PAM) was used as flocculent. For the chemical process, 31.25 grams of PAM was added in 250 ml of filtered tap water. For uniform dispersion, the solution was constantly agitated by a magnetic stirrer for 30 minutes. NaOH slurry was prepared by diluting 5 grams of NaOH in 200 grams of filtered water. To this solution, 0.5 wt % of PAM dispersion was added by weighing into a container. For micro particle retention aid, 0.1 wt% of cationic starch (CATO302) was added. After filtration, the strong base flocs were transferred to the standard filter element and allowed to set overnight in oven at 105 ^{0}C. Schematic diagram for these processes is given in **Fig. 1.** The final form of strong base filter in comparison to a standard oil filter used in this study is shown in **Fig. 2.** Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) analysis provides strong base filter paper characteristics and elemental details in strong base filter showing primarily the contents of NaOH. **Fig. 3.** provides the related characteristics and elemental details for strong base filter paper.

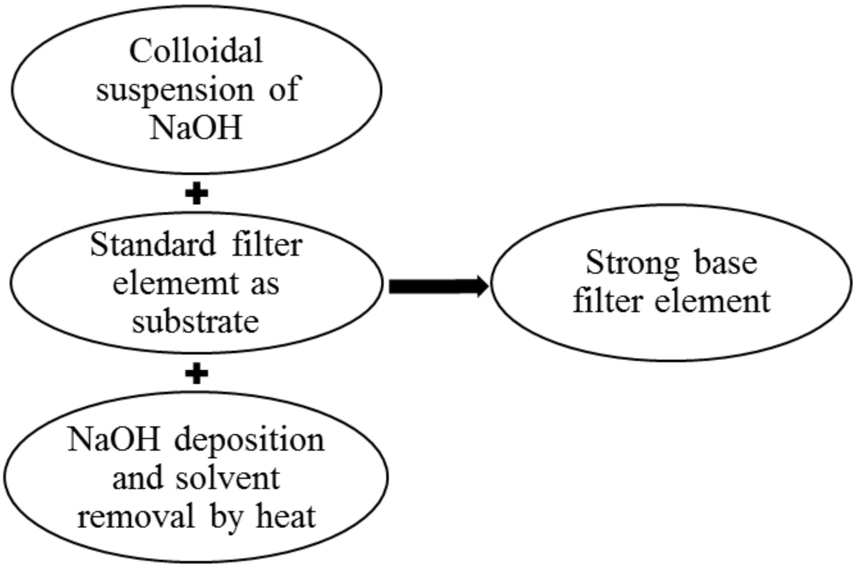


Fig.1. Schematic diagram for deposition of strong base on a standard filter element

Fig. 2. Standard filter element and strong base (NaOH) filter element

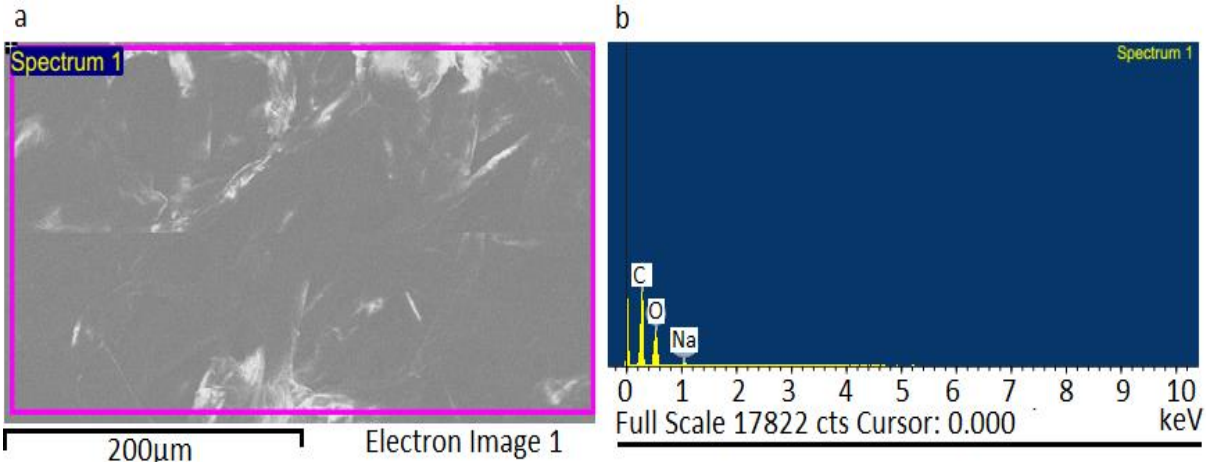


Fig. 3. (a) SEM analysis of strong base filter paper (b) EDX analysis showing elemental details

2.2. Production of palm methyl ester

The free fatty acids (FFA) content of crude palm oil used for the biodiesel production was about 0.25%. Since oils having FFA content less than 1% can undergo base-catalyzed transesterification reaction, [16] this process was adopted for production of palm methyl ester (PME). To carry out this process crude palm oil was reacted with methanol (25% v/v oil) and 1% (w/w oil) of potassium hydroxide (KOH) and maintained at 60°C for 2 h and 1000 rpm stirring speed. The selection of KOH as base catalyst was influenced by earlier research [17, 18]. The produced biodiesel was poured in a separation funnel for 12 h to separate the glycerin out from biodiesel after completion of the reaction. After phase separation, the lower layer that contained impurities and glycerin was drawn off. Then the methyl ester was washed gently with distilled water to remove the impurities and glycerin. To do that, 50% (v/v) of distilled water at 60°C was sprayed over the esters and shaken gently. This process was repeated several times such that the methyl ester became neutral i.e. pH = 7. The lower layer consisting of impurities was removed. Vacuum distillation was adopted for methyl ester distillation at 65°C for 1 h using rotary evaporator, to remove water and methanol. Finally, the product was dried using anhydrous Na_2SO_4 for 3 h and filtered using qualitative filter papers. The fatty acid composition analysis was carried out according to the procedure described in our earlier research [19]. PME contains 49.6% saturated methyl esters and 50.1% unsaturated methyl esters.

2.3. Measurement of physicochemical properties of PME

The physicochemical properties of PME were experimentally evaluated according to ASTM D6751 standard using the equipment mentioned in **Table 1**. The following equations were used to evaluate the Iodine Value (IV), Cetane Number (CN) and Saponification Number (SN) [20, 21]:

$$IV = \sum\left(\frac{254 \times D \times A_i}{MW_i}\right)$$

(1)

$$SN = \sum\left(\frac{560 \times A_i}{MW_i}\right)$$

(2)

$$CN = \left(46.3 + \left(\frac{5458}{SN}\right) - (0.225 \times IV)\right)$$

(3)

Where A_i is showing component percentage, D is the number of double bonds, and MW_i is the mass of each component.

Table 1. Detailed physicochemical properties of synthesized palm biodiesel and lubricant.

Properties	Test standard	Test Equipment	Manufacturer	ASTM limits for biodiesel	PME	Diesel
Kinematic viscosity at 40°C (cSt)	D 7042	SVM 3000	Anton Paar, UK	1.9-6.0	4.87	3.60
Flash point (°C)	D 93	Pensky-martens flash point–NPM 440	Normalab, France	130	153	69
Oxidation stability (h)	EN14112	873 Rancimat	Metrohm Switzerland	3 h (min)	7.1	58
Density at 40°C (kg/m^3)	D 7042	SVM 3000	Anton Paar, UK	N/S	878	829
Calorific value (MJ/kg)	D240	C2000 basic calorimeter	IKA, Germany	N/S	39.40	44.80
Cloud point (°C)	D 2500	Cloud and pour point tester NTE 450	Normalab, France	Report	11.9	8
Pour point (°C)	D97	Cloud and pour point tester NTE 450	Normalab, France	N/S	13.1	7
Iodine value (g I_2/100 g)					49.93	-
Saponification number					209.23	-
Cetane number					61.15	-

Engine Oil	Physical properties	
	SAE Grade	15W40
	Viscosity @100 ^{0}C (cSt)	14.93
	TAN (mgKOH/g)	1.86
	TBN (mgKOH/g)	9.9

2.4. Engine tests

Naturally aspirated, single cylinder diesel engine was used for two long duration tests for standard and strong base filters. The engine specifications for relevant parameters of this study are given in **Table 2**. In order to use strong base filter, no modifications in the oil circuit was done. Both tests were run using single cylinder diesel engine at full load. The oil samples were collected at regular intervals and standardized oil analysis procedures were used to measure the lubricant quality. The exhaust emission gases were measured by connecting BOSCH exhaust gas analyzer with engine test rig. The specifications for exhaust gas analyzer are mentioned in **Table 3**.

Table 2. Engine specifications.

Parameter	**Specification**
Model	YANMAR TF 120-M
Configuration	Single cylinder
Air aspiration	Naturally aspirated
Maximum Power	7.7 kW at 2400 rpm

Fuel injection	Mechanical direct injection
Displacement	0.638 cc
Oil capacity	2.8 L
Oil change interval	200 hours

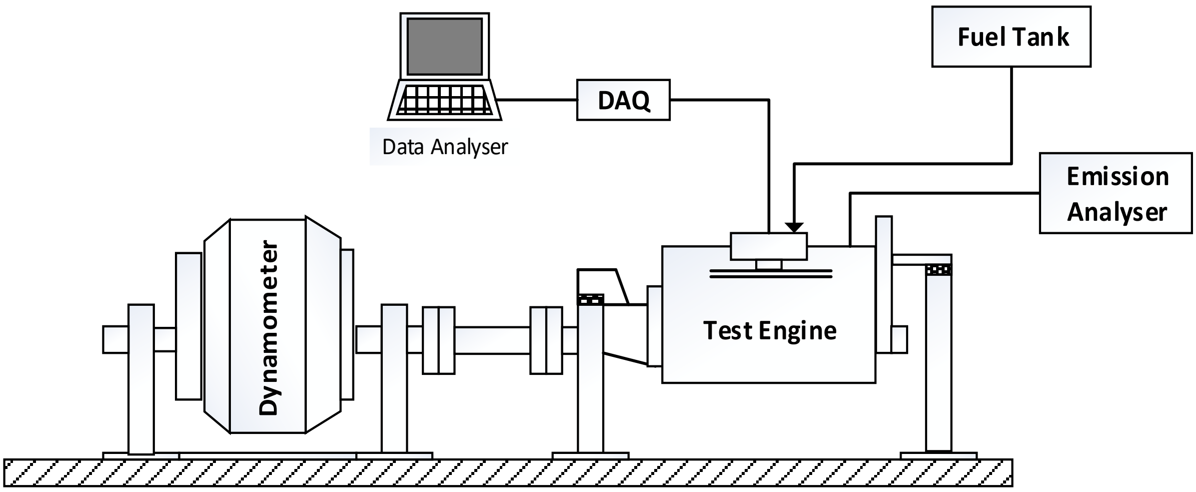


Fig. 4. Schematics of the engine test bench

Table 3. Details of the exhaust gas analyzer

Equipment	**Parameter Measured**	**Method**	**Accuracy**
BOSCH gas analyzer BEA-350	CO	Non-dispersive infrared (NDIR)	±0.01 vol%
	NO	Electro-chemical transmittance	±1ppm
	HC	Non-dispersive infrared (NDIR)	±1ppm
	Smoke	Hartridge principle	0.1%

2.5 Experimental methodology

To evaluate the effect of filter chemical modification on the lubricant degradation and exhaust emissions, the engine was tested at full load and 2400 rpm. Two long duration tests were conducted with values of relevant test parameters as given in **Table 4**. In first test, new standard filter without chemical modification was used and engine was run for 200 hours as per the drain interval mentioned by the engine manufacturer [22]. In second test, the standard filter was replaced with strong base filter and 400 hours testing was performed and resulting parameters were compared with the standard filter results. In order to analyze the effect of strong base filter on oil quality, the oil samples were taken from engine sump after every 50 hours. Minimum volume required for oil analysis was extracted each time so that amount of fresh makeup oil was reduced. Dynomax-2000 software was used to operate the engine at required test conditions.

Table 4 . Engine test parameters

Parameter	Test 1	Test 2
Oil Filter	Standard oil filter	Strong base filter
Test Duration	200 hours	400 hours
Engine Load	Full load	
Engine Speed	2400 rpm	
Lubricant	SAE 15W40	
Fuel	Palm biodiesel (PME)	

3. Results and discussion

3.1. Effects on lubricant quality

Fully formulated lubricant 15W40 conforming to API specification CI-4 was used for both tests. The lubricant quality was tested using the standard tests. To test the lubricant quality, the change in oil viscosity, acidity and wear characteristics of engine oil after each test were measured. The effect of strong base filter on the oil degradation and piston ring/cylinder wear are compared to standard filter.

3.1.1. Oil viscosity

Lubricant viscosity is an important physical parameter to evaluate the lubricant degradation over time. In biodiesel fueled engines, acidic environment and related contamination results in thickening and gelling of the engine lubricating oil [3]. The increase in lubricant viscosity in biodiesel fueled engine has been reported by Ashraful A et al. [23]. The rate of increase of oil viscosity was measured for both long duration tests. The kinematic viscosity was measured at 100 °C using ASTM D445 standard. **Table 5** provides the rate of change of viscosity for both tests. The results show a decrease of 32 % in oil viscosity increase rate when strong base filter was used as compared to that of standard filter. It supports the idea of oil conditioning by using strong base filter to maintain its lubricity. For Ultra Low Sulfur Diesel (ULSD), Watson et al. have found similar improvement in maintaining the lubricant viscosity. In their study, the long duration engine testing showed 33.5% reduction in rate of viscosity increase by strong base filter compared to that of standard filter [10, 13].

Table 5. Change in viscosity SAE 15W40.

Filter Type	Kinematic Viscosity at 100°C (cSt)	Rate of

	[ASTM D445]			increase (cSt/hr)
	Fresh Oil	200 hrs	400 hrs	
Standard	14.93	18.02		0.01545
Strong base	14.93		19.13	0.0105

3.1.2 Total Base Number (TBN)

Total base number (TBN) indicates the quantity of alkaline reserve in the lubricant for controlling the acid contaminations. Lubricants with lower TBN are less effective in suspending the wear causing contaminants and results in engine damage due to corrosion by acid attack. For this reason, TBN is often considered as an indicator of oil degradation. In the formulated engine oil, over-based detergent neutralizes acids. Oils for most diesel engine applications typically have a TBN between 8 and 12 mgKOH/g. The effect of strong base filter on TBN retention has been discussed in previous research for ULSD as fuel. Watson et al. [11] reported that the rate of TBN depletion is reduced by 50% when magnesium oxide strong base filter was used for fully fomulated engine oil. In this study, standard test method, ASTM D4739 was used for TBN determination by hydrochloric acid titration. The TBN of CI-4 oil samples oil samples taken after 50 hours of intervals are plotted in **Fig. 5.** Chemically modified oil filter has a significant effect on TBN retention. The data plots of TBN indicates that the acid neutrallization rate of detergents in the CI-4 oil is slow when used with standard filter. An improvement in TBN retention was noticed for the oil samples taken after the strong base filter was installed in the oil circuit. The strong base filter assisted the acid control ability of the detergent by neutralizing the acid contaminants entering the engine oil . An average improvement of 7.11% has been noticed for extending the TBN retention from initial engine start up to end of endurance testing.

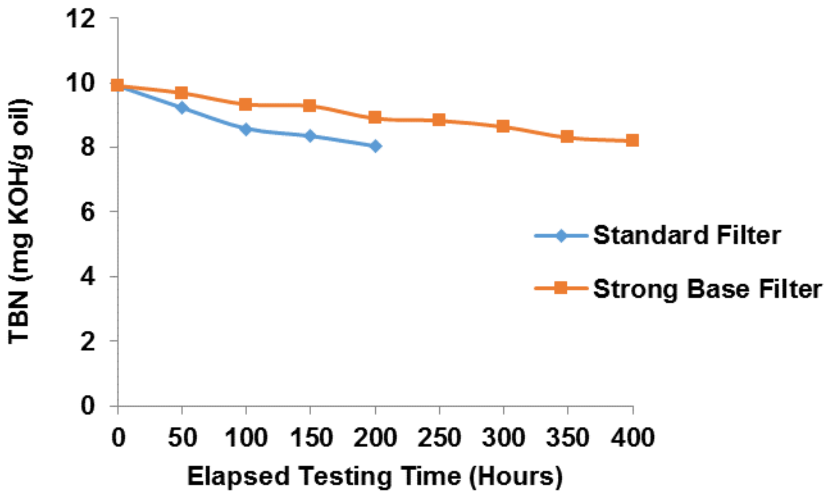


Fig.5. TBN retention of degraded oils after long hour tests

3.1.3. Total Acid Number (TAN)

Lubricant degradation is mostly related to the rate of increase of lubricant acidity over the time. It is the main indicator of the oil change timing in the engines. Low acidity of lubricant is desirable to avoid corrosion, viscosity change and lubricant oxidation [24]. The total acidity, mentioned as the TAN, is a representation of the mutual concentrations of organic and inorganic acids. TAN typically has an increasing trend over the lubricant life. In this study, TAN was determined with two standard test methods; ASTM D664 and D974. Calorimetric titration procedure was used to calculate the values of TAN for fresh and used engine oils. Two grams of oil from each sample was taken and an alcoholic solution of potassium hydroxide was added till the acid content of oil was neutralized. **Fig.6.** shows the results for the oil samples taken after 50 hours of intervals. The profiles clearly show significant improvement in the case of strong base filter. The rate of TAN increase is reduced significantly by the use of strong base filter. From the engine start-up to the total running time, the acidity of the lubricant obtained by strong base filter test was lower as compared to standard oil filter test. An average improvement of 7.69% has been noticed for controlling the TAN increase rate. In case of ULSD as fuel, similar trends have been reported previously [11, 14]. The tendency for lowering the value of TAN can be related to the chemically active filter employing a strong base material that is capable of neutralizing weak acids in the fluids which come into contact with the strong base particles. Such control over TAN not only enhance lubricant drain interval but are also helpful in maintaining low corrosive environment in engine.

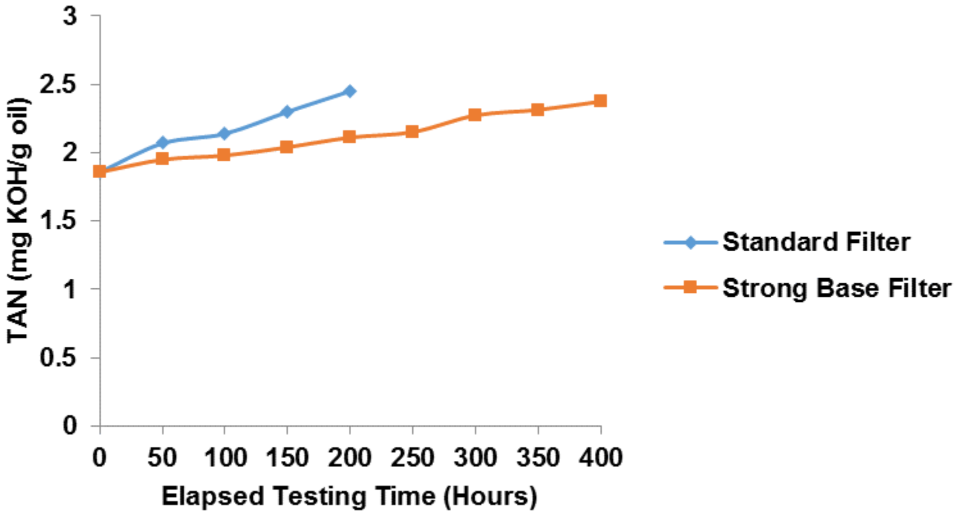


Fig.6. Total acid number of degraded oils after long hour tests.

3.2. Lubricant conditioning mechanism of strong base filter

Strong base filter works by cyclic regeneration of the weak base (detergent additives) in fully formulated lubricant. The proposed mechanism for action of strong base oil filter has been discussed previously by different researchers [24, 25] and is illustrated in **Fig. 7.** Strong base filter displaces the weak base from combustion acids-weak base complex. The combustion acid-weak base complex forms at piston ring zone by interaction between combustion acids and lubricant detergent additives and travels within the lubricant. While passing through the strong base filter, the weak base is displaced from combustion acid-weak base complex resulting in formation of combustion acid-strong base complex. This displacement happens via ion exchange as NaOH disposed on strong base filter exchanges with weak base in the combustion acid-weak base complex. It results in regeneration and recycling of weak base in lubricant to travel back and neutralize additional acid in piston ring zone. This cyclic process helps in extending the alkaline reserve provided by over-based detergents which are most often used in fully formulated diesel lubricants.

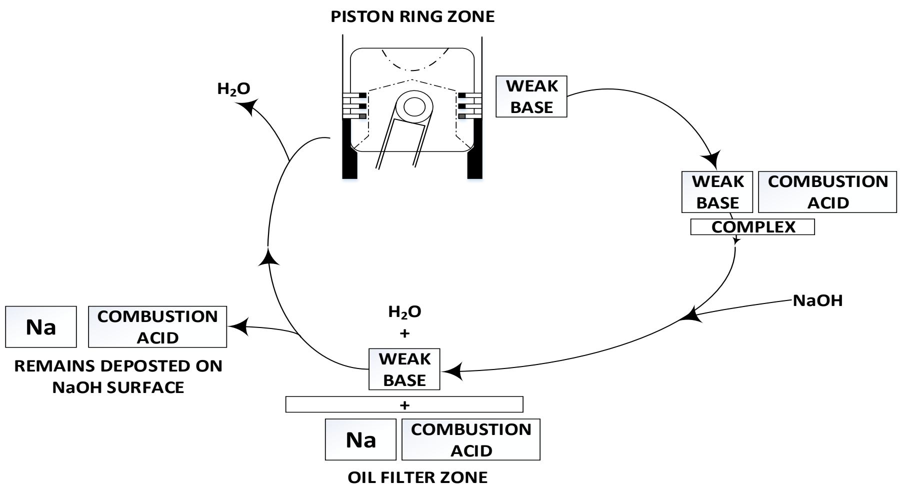


Fig.7. Mechanism for lubricant conditioining by strong base filter [24].

3.3.. Wear characteristics

The wear characteristics of lubricants obtained from both tests were investigated using high stroke reciprocating test rig. In internal combustion engines, piston assembly is one of the engine parts which contribute major wear and frictional losses [26-28]. Thus, the specimen of actual piston ring and cylinder were used at simulated engine conditions. These specimen were extracted by using CNC, EDM wire cutting, so that the surface finish and profiles must not be damaged. The size for piston rings and cylinder spercimen were selected in such a way that the conformity of surfaces must be established. **Fig. 8.** shows the extracted specimen and oil bath used for wear testing. Lubrication condition establishing parameters like running speed, normal load, oil temperature, and lubricant feed rate were controlled by the testing system. Test conditions are mentioned in **Table 6**. Weight loss method was used to determine the wear rate for fresh and used oils. For each test, new specimen were used. Samples were cleaned ultrasonically and weighed to an accuracy of 0.1 mg, before and after each test. Prior to each test, the piston ring on liner surface was run in for two hours so that the sharp asperities were shaved off. **Fig. 9.** shows the weight loss for piston ring and piston liner using fresh and degraded oils. Even after increasing the drain interval twice (400 hours) for strong base filter, better wear characteristics were observed. For engine oil conditioned by NaOH filter, tribo testing showed that the piston liner wear was reduced by 7.03% in comparison with oil conditioned by standard oil filter. For ULSD, the ability of strong base filter to reduce the wear of interacting surfaces was also experimentally validated for single cylinder Lister Petter TR1 diesel engine [10]. Standard four ball wear tests were performed to evaluate the wear scar diameters for the fresh and used engine oils. The results indicated that the strong base filter provided superior wear protection even though the oil was aged for over twice the length of time as comapre to standard filter [10, 11, 14].

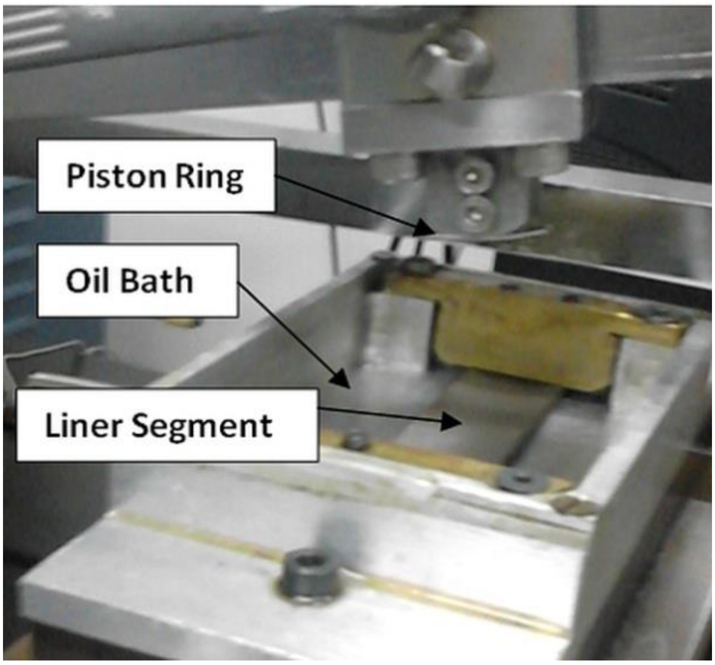
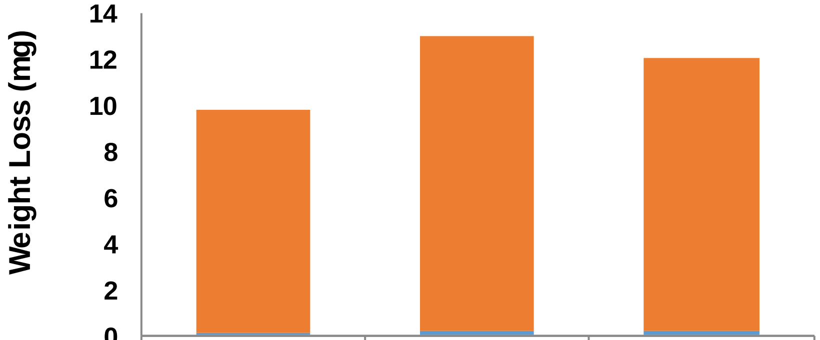


Fig. 8. Piston ring and liner specimen in reciprocating test rig

Table 6

Test conditions for ring on liner reciprocating test rig.

Normal load	160 N
Temperature	70 °C
Stroke	84 mm
Contact width	25.4 mm
Speed	240 rpm
Lubricant feed rate	5 mL/hr
Test duration	2 hrs



	Fresh Oil	Standard Filter (200 hrs)	Strong Base Filter (400 hrs)
Liner	9.7	12.8	11.9
Ring	0.1	0.2	0.2

Fig. 9. Piston ring and cylinder wear

3.4. Oil drain interval

The positive effects of strong base filter on lubricant quality and tribological performance suggests that the strong base filter is helpful to extend engine oil drain intervals in CI engines fueled with palm biodiesel. In the considered case, the lubricant acidity was controlled by extra alkaline reserve of strong base filter and the lubricant life was enhanced. The lubricant degradation affects the piston ring zone due to high combustion temperatures and increase of lubricant acidity. For this reason, top ring specimen wear was tested against piston cylinder specimen under engine simulated conditions**.** Although the engine testing time for strong base filter was doubled yet the better oil quality and improved engine wear was observed in comparison to standard oil filter test. The reason for extended oil drain intervals is the ability of strong base filter to preserve the alkali reserve in the lubricant and reduces lubricant acidity. This effect postpones the point when TAN exceeds TBN in the oil, a situation that often triggers an oil change [29]. Thus oil conditioning with the chemically active filter preserves the functionality of the engine oil over a longer period of time.

3.5. Engine performance and exhaust emissions analysis

For both of the tests, engine performance was measured in terms of brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE). The exhaust emissions for CO, HC, NO and smoke opacity were monitored at frequent intervals. The results are provided over the test duration for both tests.

3.5.1. Brake specific fuel consumption

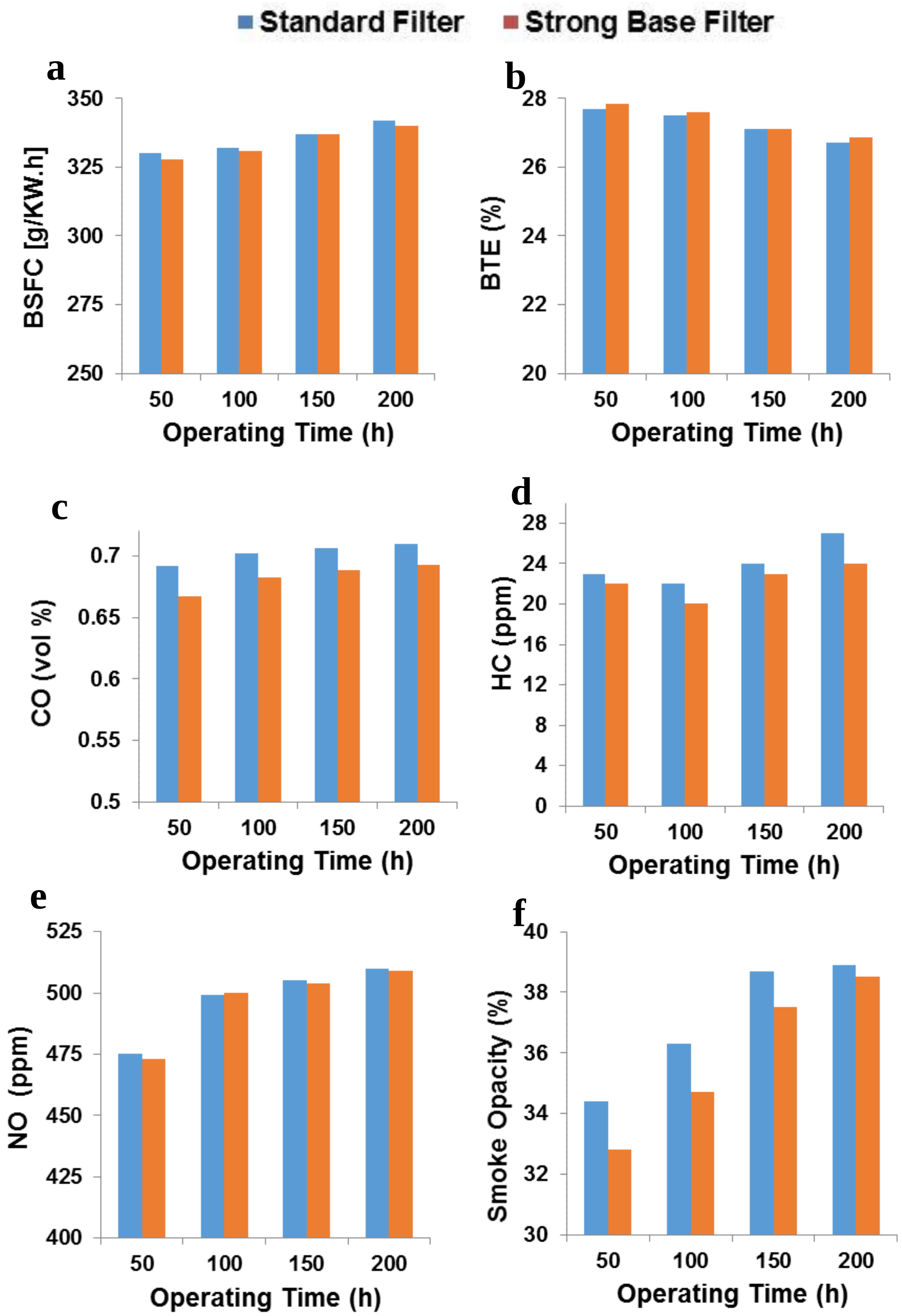
Brake specific fuel consumption (BSFC) is the ratio between the fuel mass flow rate and engine power [30]. BSFC rates for the considered engine tests are shown in **Fig. 10a** over the running time for both tests. It can be clearly seen from **Fig. 10a** that initially no change in BSFC was observed at 50 hrs values. But later on an improvement was observed for the engine tests using strong base filter. By comparing the data an average decrease of 0.37% in BSFC was observed. Such an improvement was also observed for MgO treated strong base filter with Ultra Low Sulfur Diesel (ULSD) for single cylinder CI engine [10].

3.5.2 Brake thermal efficiency

Brake thermal efficinecy (BTE) is defined as work output of a heat engine as a function of thermal input through fuel injection. BTE is simply the inverse of the product of the specific fuel consumption and the lower calorific value of the fuel [30]. **Fig. 10b** shows BTE for endurance tests using standard filter element as well as strong base filter element. The trend of the plotted values of BTE can be related to the **Fig. 10a** as the values are inversely related to the BSFC values. The maximum value of BTE was 27.86% which was observed at 50 hours for the case of strong base endurance test. An average improvement of 0.37% has been achieved by using the strong base filter.

3.5.3. Emissions analysis

The strong base filter ability to sequester acids from oil not only improved the lubricant quality but also shows better trends have been observed for exhaust emissions. The major constituents of particles from diesel combustion are elemental carbon in the form of soot and organic compounds, which consists mainly of unburned lubricating oil, unburned fuel and partly oxidized compounds from oil and fuel [9]. Thus, controlling the lubricant acidity can help in reducing partly oxidized compounds due to unburned engine oil and fuel. It has been reported in earlier research that the engine oils with low TAN increase rate show low CO and HC emissions at high power [8]. In this study, the exhaust emission data was taken at frequent intervals during each long duration test to highlight the significant effects of strong base filter. **Fig. 10c, 10d, 10e** and **10f** show the data obtained for CO, HC, NO and smoke emissions for standard filter and strong base filter. The emission analyzer was used to get the provided data while engine was operated at full load condition. **Fig. 10c** provides the percentage values of CO emissions over the 200 hours of testing. CO emission occurs due to the incomplete fuel combustion and depends on different engine parameters with major influence of in-cylinder temperature and equivalence ratio [31]. Maximum percentage of CO reduction can be observed at 50 hours which is about 3.47% and minimum CO reduction can be seen at 200 hours which is about 2.33%. An average reduction of CO emissions for the 200 hours testing was 2.78%. HC emissions are related to engine operating conditions, fuel quality and fuel spray characteristics [32, 33]. Engine operating conditions can get affected by engine speed, lubricant quality and lubrication regime. For HC emissions, **Fig. 10d** provides the related data obtained by the emission analyzer for the both tests. Over the 200 hours testing an average reduction of 7.18% was observed for HC emissions. The reduction of HC and CO emissions can be related to the tendency of strong base filter to absorb the acids originating from biodiesel dilution of the oil and reducing the acidic emissions due to unburned fuel and lubricant [9, 10]. NO emission was nearly same for both cases as shown in **Fig. 10e**. Such effects are due to predomination of "thermal" and "prompt" mechanisms for NO formation in biodiesel combustion [19]. The role of lubricant quality was not of much significance in the considered testing conditions. The fuel effect is of major dominance in case of NO emissions and the lubricant degradation effect is negligible for this case. For smoke opacity measurement, the data was recroded using smoke-opacity measurement module RTM 430. The smoke opacity of exhaust gases is an indication of particulate matter emissions [34, 35]. The smoke opacity data was collected after 50 hours of intervals for both endurance tests. **Fig 10f** shows the smoke opacity percentages for tested conditions. In comparison to standard base filter, the smoke opacity of strong base filter was low. From the collected data at regular intervals, an average reduction of about 3.3% has been achieved. The reduction of smoke opacity can be correlated with the ability of strong base conditioned oil to absorb more soot content as compare to standard filter element [10].



Standard Filter
Strong Base Filter
a
BSFC [g/KW.h]
350
325
300
275
250
50
100
150
200
Operating Time (h)
b
BTE (%)
28
26
24
22
20
50
100
150
200
Operating Time (h)
c
CO (vol %)
0.7
0.65
0.6
0.55
0.5
50
100
150
200
Operating Time (h)
d
HC (ppm)
28
24
20
16
12
8
4
0
50
100
150
200
Operating Time (h)
e
NO (ppm)
525
500
475
450
425
400
50
100
150
200
Operating Time (h)
f
Smoke Opacity (%)
40
38
36
34
32
30
50
100
150
200
Operating Time (h)

Fig.10. Fuel consumption and exhaust emissions during the long hour tests.

4. Conclusions

For biodiesel engines, the use of strong base filter technology was adopted to neutralize the acid contaminants. By filter chemical modification, the improvement in lubricant drain interval and exhaust emissions was experimentally investigated by two long duration tests. The following important results were obtained

- For the adopted test conditions and using palm biodiesel as fuel, the strong base filter showed significant and positive effect by decelerating the lubricant degradation rate. Even the drain interval was double for strong base filter; the chemically conditioned oil reduced viscosity increase rate to 32%.
- Lubricant acidity was reduced by using the strong base filter and continuous acid neutralizing effect enhanced the lubricant useful life. An average improvement of 7.11% in TBN retention was achieved and TAN increase rate was decelerated to an average of 7.69%.
- Wear rate of engine components was also reduced significantly. For piston ring and cylinder contact the energy losses due to sliding wear were reduced significantly. An overall improvement of 7.03% was observed for piston liner wear reduction using oil conditioned with strong base filter.
- Strong base filter improved the engine performance for palm biodiesel fueled single cylinder CI engine. An improvement of 0.37% was achieved for BSFC and BTE for the considered testing conditions.
- Exhaust emissions were reduced for the engine test with strong base filter. A reduction of 2.78% ,7.18% and 3.3% were

observed for CO, HC and smoke emissions respectively for strong base filter compared to that of standard filter.

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