Journal of Cleaner Production 221 (2019) 215–223

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Effect of bio-based lubricant towards emissions and engine breakdown due to spark plug fouling in a two-stroke engine

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ARTICLE INFO

*Article history:*
Received 23 May 2018
Received in revised form
28 January 2019
Accepted 20 February 2019
Available online 27 February 2019

*Keywords:*
Polyol ester
Biodegradable fully formulated lubricant
C18:1 oleic acid
Environmental-friendly lubricant
Lubricant in fuel

ABSTRACT

Two-stroke also known as two-cycle gasoline engine is a spark ignition engine. Its uniqueness to the four-stroke engine is that this engine does not require lubricant sump, which makes construction lightweight and simple. Its lubricant is mixed with gasoline and burnt together during combustion. There are reports which stated that higher spark plug fouling is due to carbon deposition on the spark plug electrodes on a two-stroke engine when compared to the four-stroke. While many factors could have affected this situation, however, in this paper, the effect of mineral and bio-based lubricants towards carbon deposition and emissions are studied and reported. Idle, half and full throttle operation modes had been conducted on a two-stroke, 43 cubic centimeter engine. To keep combustion temperature below self-cleaning temperature on all three modes of operation, a zero-load test was utilized. This situation accelerates the deposition process as low temperature causes incomplete combustion. This could lead to the accumulation of char, unburned fuel, as well as condensed water and acids as the by-products blanket the spark plug electrodes and the exhaust system. Five samples had been prepared with a commercially available mineral lubricant (T0) as reference. Trimethylolpropane Trioleate, TMPTO derived from plant origin was used as the bio-based candidate. It was then mixed with T0 which created another four lubricant samples namely T10, T15, T20 and T50 with 10%, 15%, 20% and 50% TMPTO accordingly. Results show that mineral lubricant T0 delivers the lowest hydrocarbon HC, carbon monoxide CO and smoke opacity during idle and half throttle operations. However, it exhibits a greasy deposit on the spark plug circumference and dry carbon deposits on its insulator tip. T0 also emits a liquid residue at the exhaust manifold. T10 and T50 show a wet deposit blanketing both electrodes. Severe deposition was recorded by T50 that caused the engine to fail half way with its emissions had the worst recording. T15 and T20 exhibit only dry carbon deposition on the spark plug circumference. However, T20 has outperformed T15 in terms of emissions with lower CO and $CO_2$ emissions during idling and half-throttling. With better emissions than T15 and better carbon deposition than mineral (T0), T20 could be proposed to be used as a commercial two-stroke lubricant.



## 1. Introduction

Commercial two-stroke (2T) lubes are mainly made of 1. mineral base oil and 2. Environmentally Adapted Lubricant (EAL) which are proven to emit almost the same polycyclic aromatic hydrocarbons (PAHs) and volatile organic compound (VOC). Both lubricants were also reported to have the same effect of pH to the fresh and salt water (Kelly et al., 2005). To overcome this, bio-based lubricant has been chosen to replace a fraction, if not all, the mineral and EAL base oils used in the commercial 2T lubes.

Bio-based lubricant is derived either from vegetable oil or fat from animals. It does not contain hydrocarbon-chain but instead contain a fatty-acid chain (Singh et al., 2017; Syahir et al., 2017). Bio-base oil was recently used as stock including Moringa oil (Singh

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https://doi.org/10.1016/j.jclepro.2019.02.224
0959-6526/

**Nomenclature**

| | |
|---|---|
| TMPTO | Trimethylolpropane Trioleate |
| HC | Hydrocarbon |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| $NO_x$ | Nitrogen oxides |
| T0 | Zero percent TMPTO, 100% mineral-based lubricant |
| T10 | 10-part TMPTO diluted in 100-part mineral-based lubricant (volume:volume) |
| T15 | 15-part TMPTO diluted in 100-part mineral-based lubricant (volume:volume) |
| T20 | 20-part TMPTO diluted in 100-part mineral-based lubricant (volume:volume) |
| T50 | 50-part TMPTO diluted in 100-part mineral-based lubricant (volume:volume) |
| 2T | Two-stroke |
| EAL | Environmentally-adapted Lubricant |
| PAHs | Polycyclic Aromatic Hydrocarbons |
| VOC | Volatile Organic Compound |
| FFL | Fully-formulated Lubricant |
| hBN | Hexagonal Boron Nitride |
| RON | Research Octane Number |
| v/v | Volume/volume |
| SI | Spark ignition |

et al., 2017) Castor oil (Sturms et al., 2017) and Mongongo oil (Singh et al., 2017). These researchers have reported the use of bio-based oils for four-stroke (4T) engine and diesel engine to exhibit superior physicochemical properties and tribological properties. Unfortunately, there are very limited reports on bio-based oil for two-stroke application are available.

In 2010, there were more than 5 million two-stroke mopeds operating in Italy alone and this number has kept increasing (Adam et al., 2010; Prati and Costagliola, 2009; Spezzano et al., 2008). Recent findings agree that impressive power-to-weight ratio, economically priced and almost free maintenance makes two-stroke engine a perfect choice for lightweight helicopter, snowmobile, outboard engine and dirt bike (Hooper, 2018; Kaya and Ozdalyan, 2017; Lawal et al., 2017; Lopez et al., 2017). This engine also works well with hydrogen-enriched air for better combustion quality (Zakaria et al., 2015).

Most of the two-stroke engines do not have oil sump like the four-stroke gasoline engine (M. H. M. Hanafi et al., 2013). Also, it does not acquire any active valve control. Intake and exhaust manifolds are open and closed solely via the movement of the piston thus making this engine so simple and lightweight. Two-stroke gasoline engine requires lubricant to reduce friction and to clean the engine at the same time. However, unlike the four-stroke lubricant, its lubricant has been premixed and burnt with gasoline in the combustion chamber. Due to these reasons, efforts had been taken to study the possibility of using bio-based lubricant in a two-stroke engine.

The chosen candidate is Trimethylolpropane Trioleate (TMPTO) derived from C18:1 oleic acid which originated from palm oil. Using two transesterification processes with alcohol and Trimethylolpropane (TMP) it becomes TMPTO. The chemical compound of TMPTO is $C_{60}H_{110}O_6$ which belongs to the polyol ester group. It had been reported that this was used to produce a chemically-stable lubricant as it exhibited comparable characteristics to the fully formulated lubricant (FFL) in terms of coefficient of friction (CoF) (Zulkifli et al., 2016).

As the candidate will be mixed with the commercially-available lubricant, it is, therefore, important for the candidate to exhibit a good mixing capability. TMPTO, in this case, has been proven to mix well with the commercial additive package as well as particle additive e.g. hexagonal Boron Nitride (hBN) to obtain a higher viscosity index as well as better tribological performance (Talib and Rahim, 2018).

## 2. Material and methods

### 2.1. Measurement of the physicochemical properties of lubricant blends

The mineral-based oil used was a commercial 2T lube already mixed with solvent and additives (T0). This will be used as a reference lube. T0 was then mixed with TMPTO with v/v ratio of 100:10 (T10), 100:15 (T15), 100:20 (T20) and 100:50 (T50). Various instruments (Table 1) had been utilized to measure the physicochemical properties and the result is as listed in Table 2.

### 2.2. Engine test set-up

An engine test was conducted using a 43-cubic centimeter (cc) brush cutter two-stroke engine. The gasoline-to-lubricant ratio was kept at 100:5 as recommended by the engine manufacturer. The fuel used was a RON95 unleaded gasoline. The engine test was conducted at the Engine Tribology Lab, Faculty of Engineering, University of Malaya in Kuala Lumpur, Malaysia. The recorded ambient lab temperature was 28 °C (82.4 °F) with a moisture level of 70%. Ambient air pressure was 1010 mmHg. The engine schematic is shown in Fig. 1 and its specification as well as the other test bed parameter are tabulated in Table 3.

There are two steps of measuring the emission of a two-stroke engine. First, is the carbon deposition on the spark plug. This is vital in order to observe the combustion quality of the blends. The second step is the measurement of gas emission at the tailpipe.

#### 2.2.1. Carbon deposition on spark plug

For carbon deposition, 1 L (0.26417 US gallon) of the gasoline-lubricant premix was used to run the engine at idling speed without load. Idling was chosen because in this state the engine operates at the slowest revolution per minute (rpm) with no load; which means no external stress is exerted on the engine. This relax situation might cause the combustion temperature not to reach the self-cleaning temperature of 450 °C (842 °F). Continuous operation below this temperature will allow the carbon and ashes from the combustion to cover the spark plug electrodes that lead to carbon fouling (NGK, 2018a). A good lubricant blend could burn completely around this temperature thus ensuring a clean operation throughout the engine operation range. After all, idling also eliminates unnecessary wear to the engine ring and liner in case of a faulty lubricant blend.

For each test, a new spark plug was used to investigate the carbon deposit on the spark plug. The carbon deposition pattern and other relevant behavior were also recorded and discussed.

#### 2.2.2. Exhaust emission measurement

Exhaust emissions were measured using the Bosch BEA350 Emission Analyzer and Test Smoke Opacity meter. The standard emissions measured were carbon monoxide CO, carbon dioxide $CO_2$ and unburnt hydrocarbon HC. As the lubricant was burnt in the combustion chamber, opacity had been measured as well to quantify the intensity of the smoke emitted at the tailpipe. For each test, a new spark plug was used. The characteristics of the emissions and other relevant behavior were also recorded.

**Table 1**
List of instruments used to measure the physicochemical properties of the lubricant blends.

| Property | Instrument | Manufacturer | Standard test method |
|---|---|---|---|
| Flash point | Pensky Martens closed-cup flash point tester | Normalab France SAS | ASTM D93A |
| Kinematic viscosity | SVM 3000™ Stabinger viscometer | Anton Paar, USA | ASTM D2270 |
| Density at 15 °C | SVM 3000™ Stabinger viscometer | Anton Paar, USA | ASTM D2270 |
| Acidity | Titration | – | – |

**Table 2**
Physicochemical properties of the mineral base oil and bio-based lubricants.

| Properties | T0 | TMPTO | T10 | T15 | T20 | T50 |
|---|---|---|---|---|---|---|
| Kinematic viscosity cSt 40 °C | 44.263 | 50.947 | 43.747 | 44.387 | 44.921 | 45.921 |
| Kinematic viscosity cSt 100 °C | 7.5121 | 10.005 | 7.5975 | 7.7747 | 7.8979 | 8.3024 |
| Density at 15 °C | 0.8659 | 0.9157 | 0.8705 | 0.8729 | 0.8739 | 0.8839 |
| Flash point | 125 °C | [a]>280 °C | 128.5 | 124.5 | 130.5 | 134.5 |
| Acidity (mg/KOH) | 1.68 | 0.78 | 0.56 | 0.47 | 0.37 | 0.12 |

[a] From manufacturer.

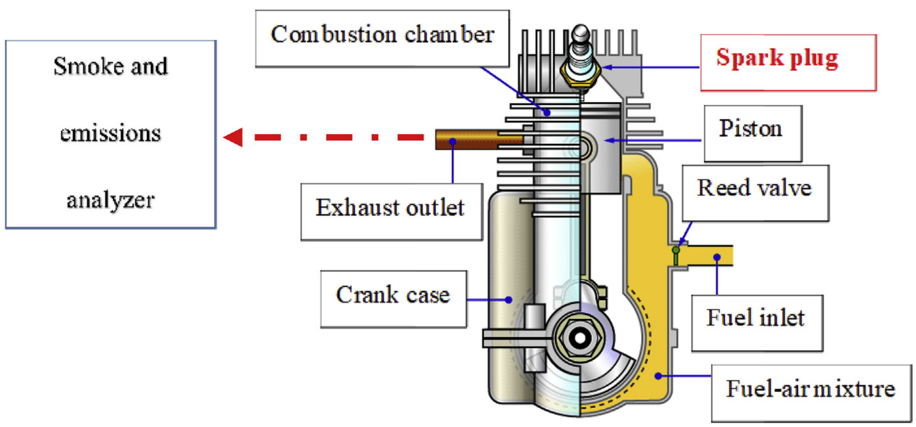


**Fig. 1.** Schematic diagram of the two-stroke engine.

**Table 3**
Engine specification and setup parameter.

| Specification | Parameter |
|---|---|
| Engine | 1E40F-5C, two cycle, air-cooled, vertical piston valve |
| Piston | Cast aluminum alloy, 40 Ø x 39.2 mm dome head, non-tapered, dual rings |
| Cylinder liner | Cast aluminum alloy, 40.12 mm inner diameter, dome shape roof, spark plug port at 30° horizontal |
| Displacement [cc] | 42.7 |
| Bore x stroke [mm] | 40 Ø x 34.2 |
| Idling speed (rpm) | 2500 ± 150 |
| Half throttle (rpm) | 5000 ± 150 |
| Full throttle (rpm) | 7000 ± 150 |
| Maximum output (kW/rpm) | 1.25/6500 |
| Carburetor | Float type |
| Spark Plug | NGK BM6A, 14 Ø x 9.5 mm. Nickel electrodes with 0.8 mm electrode gap. Short thread. |
| Fuel | Unleaded gasoline RON95 premixed with 2T lube at 100:5 v/v |

## 3. Results and discussion

### 3.1. Carbon deposition

For each test, the engine was kept running idle until it ran out of fuel, or until it stopped due to spark plug fouling and in this case is carbon fouling (NGK, 2018b). The area of interest for carbon deposits are the center electrode, side electrode, insulator tip and side electrode circumference which are exposed to the combustion (Fig. 2). Testing on carbon deposition was also done for half and full throttles but undistinguishable results between samples were observed. This can be accredited to the increase in exhaust temperature and higher velocity of exhaust gas at half and full throttles which enable the conversion of char into soot. This is evident with the higher opacity recorded during half and full throttles which was discussed in the volatile emissions subchapter. After all, this finding was also observed by (M. H. B. Hanafi, Nakamura, Hasegawa, Tezuka and Maruta, 2018).

As seen in Fig. 3, the duration of all combustions was almost the same but not identical. Longest operation was recorded by T0 and T15 at 7 h and 5 min. T20 recorded 7 h and 4 min, just 1 min less. T10 ran for 7 h and 1 min. T50 was recorded to consume 512 ml and

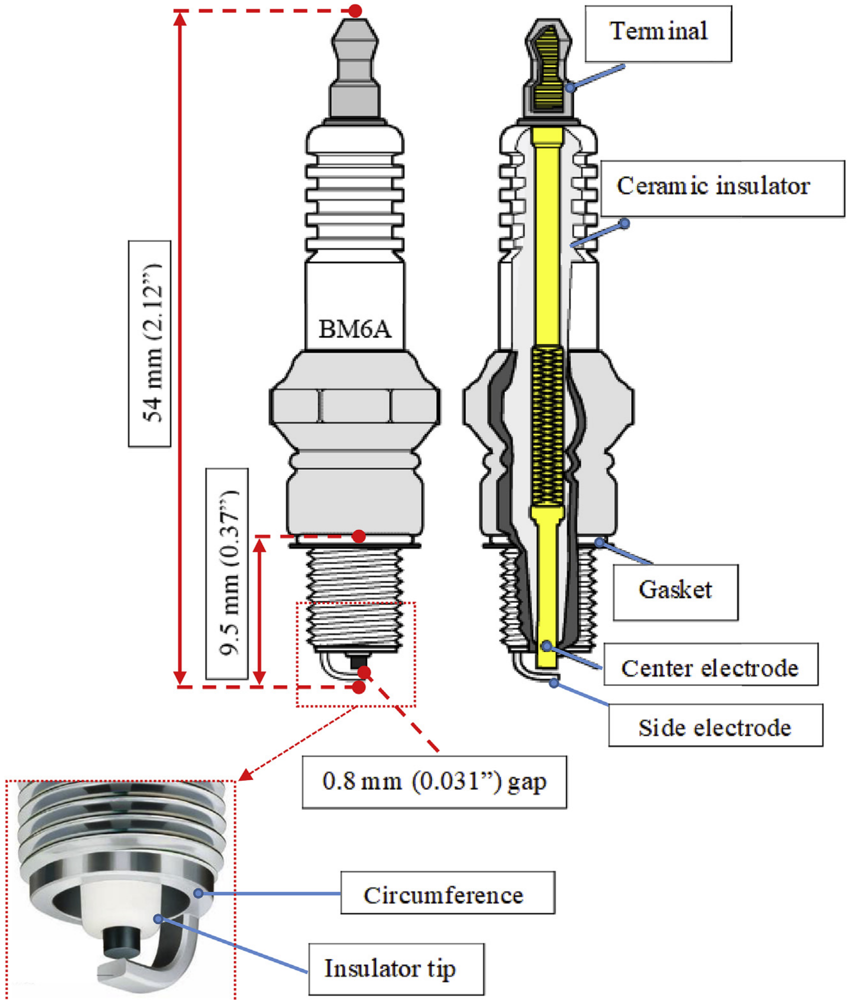


**Fig. 2.** NGK BM6A spark plug.

served only 3 h and 34 min without finishing the fuel when the engine suddenly stopped. If T50 had to finish the balance of 488 ml fuel under the same fuel consumption, it will take 6 h and 58 min. This shows that engine efficiency had been tampered with carbon deposition.

Carbon deposit is observed for all blends. This occurrence is normal when idling as the combustion temperature was lower than 450 °C (842 °F) for self-cleaning to happen. In view of this, the idling speed was selected to inspect the combustion quality of the blends as the carbon deposits are easier and faster to observe.

The highest temperature inside the combustion chamber is at the spark plug electrodes (Kawahara et al., 2017). High temperature combined with high pressure from the combustion cycle makes the fuel and gasoline blend to lose part of its hydrogen and oxygen bonds to become char (Lomakin and Zaikov, 1996). This char is then mixed with the liquid residue which becomes a thick and sticky grease. It will then settle at the spark plug circumference as this is the nearest surface with a lower temperature. After all, this area is also out of the piston movement coverage area which makes it a very suitable area for deposition and sedimentation. As it starts to coat the ring surface, the temperature beneath it will shrink and a continuous development of the deposit on the circumference will finally reach the core e.g. center electrode as well as the side electrode. If the deposition rate is higher than the cleaning rate, the carbon build-up will eventually bridge both electrodes which will become foul (Cui et al., 2018).

There are four areas of interest for carbon deposition on the spark plug namely, side electrode, spark plug circumference, center electrode and insulator tip (Fig. 2). Generally, the least deposit is observed at T15, followed by T20, T0, T10 and T50. In terms of greasiness, the greasiest is T50 followed by T10. T0 shows a wet deposit on the circumference and a dry carbon deposit on both the electrodes and insulator tip. Both T15 and T20 have hard and dry deposit only on the circumference.

T10 (Fig. 3(b)) and T50 (Fig. 3(e)) had all four areas covered with carbon deposit. T10 has its side and center electrodes as well as at the peak of its insulator tip covered with hard deposit. Its circumference and lower part of the insulator tip was spotted to contain wet deposit. The gap between both electrodes shrank to half to only 0.4 mm. The engine was hesitated to restart and the thick carbon residue blanketing both electrodes was expected to foul the spark plug. T50 spark plug showed the greasy deposition had bridged the center electrode to the side electrode. This situation had short-circuited the spark plug thus eliminating spark production and combustion. It is suspected that the reason for the greasy deposit is due to the low combustion temperature. Unburnt lubricant in liquid form was also observed being emitted at the exhaust port during engine testing with T50 emitting the most liquid residue followed by T0. No liquid residue was observed for T10, T15 and T20.

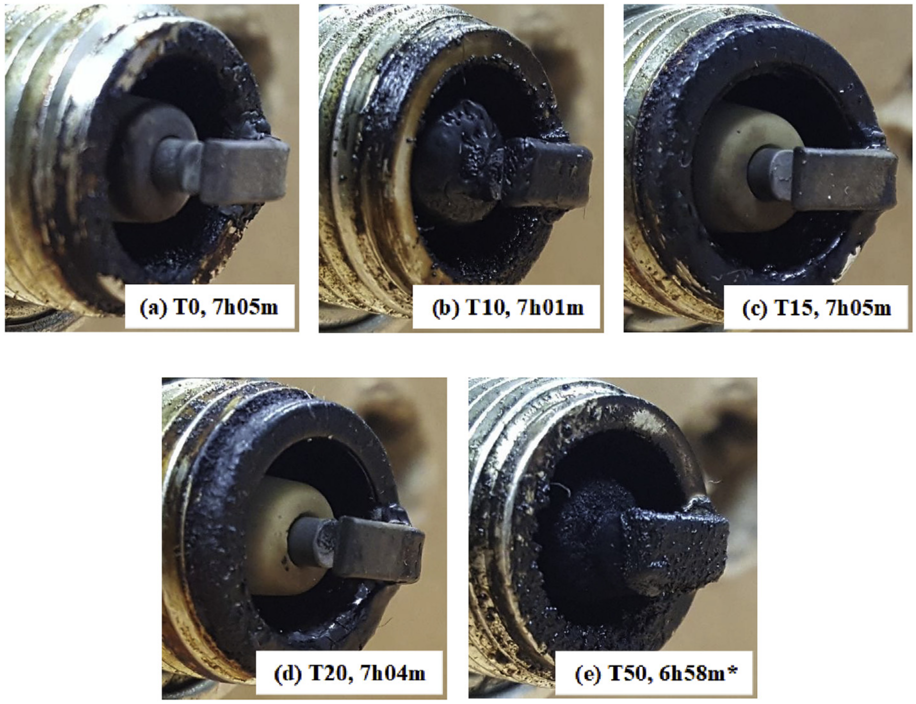


**Fig. 3.** Carbon deposition on spark plug at idling; (a) Fully-mineral T0 – wet deposit on circumference and dry deposit on electrodes, (b) T10 – wet deposit on circumference and dry deposit on electrodes, (c) T15 – dry deposit, (d) T20 – dry deposit, and (e) T50 – fouled, all wet deposits, **calculated*.

Fully mineral-based lubricant T0 (Fig. 3(a)) produced a deposit with unburnt lubricant and gasoline adhered to the circumference. Thin layer of dry carbon deposit was observed on the insulator tip. This shows the beginning of carbon deposition which could eventually spread to the electrodes, causing a drop in the temperatures, causing more deposits to take place. If the rate is to remain constant, then the spark plug will eventually turn foul. The carbon cleaning rate for this blend, however, can be concluded as better than T10 and T50.

For T15 (Fig. 3(c) and T20 (Fig. 3(d)), only the dry carbon deposition was recorded on the spark plug circumference. Both electrodes as well as the insulator tip suffer normal burning and are optically free from deposit. This situation might be due to higher combustion temperature which eliminates the deposition. Sticky grease deposit on the spark plug surface as well as unburnt liquid residue were also not observed at the tailpipe. This means a better cleaning rate was obtained compared to T0 (Fig. 3(a)), T10 (Fig. 3(b)) and T50 (Fig. 3(d)). The combustion temperature was expected to be high enough to burn the fuel and liquid residue leaving only char which adhered to the circumference (Gould et al., 2009).

### 3.2. Exhaust emissions

The two-stroke engine used in this experiment was equipped with carburetor. The air-to-fuel ratio is done based on air suction and volatility of the fuel. Higher air suction creates higher vacuum which sucks in more fuel. The same goes to the volatility of the fuel-lubricant mixture of a two-stroke engine which will evaporate faster for a more volatile fuel.

For each test, a new spark plug was used. The test sequence was 60 min idling followed by 5 min of half and full throttles. The longer idling duration was to allow the deposit to occur and adhere to the spark plug. Five minutes on half and full throttles were carried out within short intervals to avoid higher combustion temperature to damage the carbon deposit on the spark plug. It was long enough to obtain the series of emission recordings within acceptable uncertainties (refer chapter 3.3 Uncertainty Analysis). The average fuel consumption was again recorded to be nearly the same for all candidates (142 ± 1 ml for 60 min idling, 20 ± 1 ml for 5 min half throttle and 34 ± 1 ml during full throttle). The exhaust emissions included in this report are carbon monoxide CO, carbon dioxide $CO_2$, unburnt hydrocarbon HC and opacity. Opacity is a crucial parameter for the two-stroke engine as higher opacity means more visible smoke is being emitted via exhaust manifold, which is not found in a normal four-stroke engine.

#### 3.2.1. Carbon monoxide emission

Fig. 4 shows the concentration of carbon monoxide, the CO emissions from the lubricant-gasoline blends as a function of the engine speed (idle, half and full throttle). The rotation speed for each operation is tabulated in Table 3.

During idling, it was shown that T0 (4.8%vol ±1.3%) produced the lowest CO which was followed closely by T15 and T20 blends with only 0.02 and 0.06% more vol. Considering the uncertainty, these values can be regarded as the same values. On the contrary, T10 and T50 blends emit a higher CO concentration which was recorded at 0.36 and 0.22% vol respectively. At full throttle, T10 and T20 produced the lowest CO followed by T15, T0 and T50 at 4.2, 4.4 and 4.5% vol respectively.

Focus should be directed to half throttling as this is the operating speed. T0 shows the lowest CO emission at half throttling at 3.2% vol followed by T20 (4.1%vol). It is believed that a simpler chemical chain combined with lower flash temperature of T0 enhances the leaning effect and effectively improves combustion, leading to a reduction of CO emissions (Vlahopoulou et al., 2018).

#### 3.2.2. Carbon dioxide emission

Fig. 5 shows the concentration of $CO_2$ emission for all lubricant-gasoline blends relative to engine speed are investigated in this study.

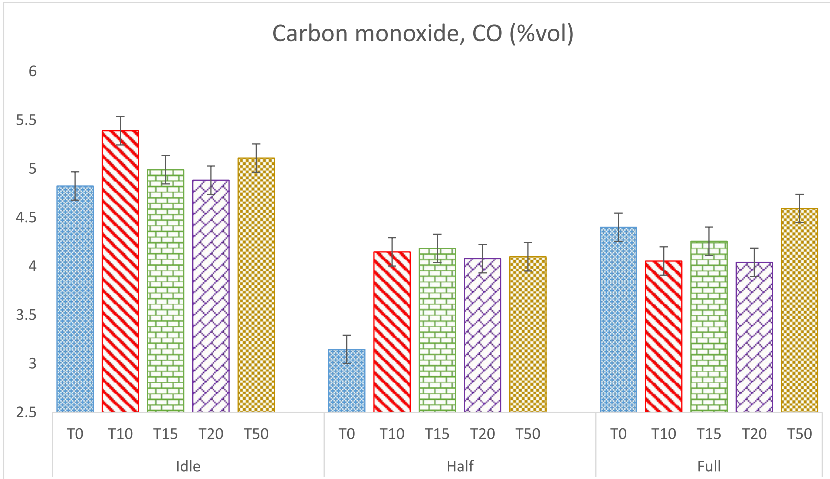


**Fig. 4.** Variation of CO emission as a function of engine speed for all lubricant-gasoline blends.

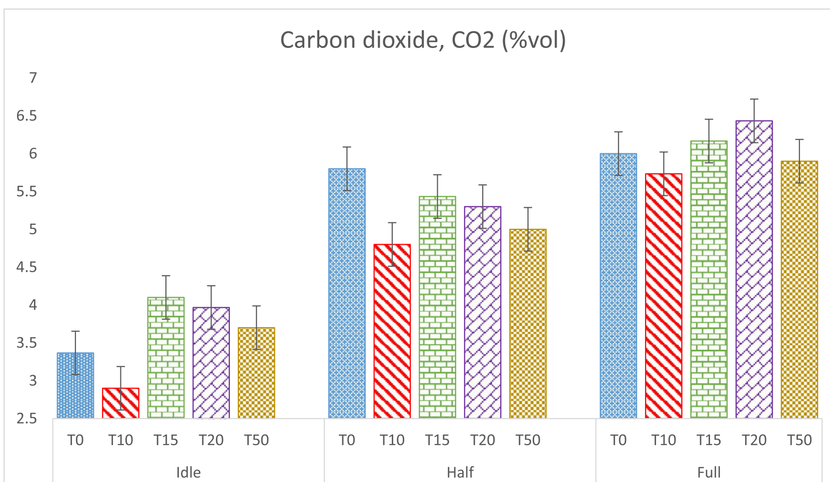


**Fig. 5.** Variation of $CO_2$ emission as a function of engine speed for all lubricant-gasoline blends.

Judging from the lower carbon deposits, it is expected that T15 (Fig. 3 (c)), and T20 (Fig. 3 (d)), will have a better combustion with higher $CO_2$ emission. It is apparent that both T15 and T20 blends produced the highest $CO_2$ compared to T10 and T50. T0 releases the highest $CO_2$ during half throttle operation with 0.4% vol higher $CO_2$ emission compared to T15. T10 and T50 which may be due to insufficient and excessive TMPTO content has led to lower combustion quality as well as lower $CO_2$ emission.

A stark contrast of $CO_2$ concentration to the CO concentration (Fig. 4) can be clearly seen. The higher $CO_2$ concentration is recorded with higher speed for all blends due to higher engine efficiency which leads to better combustion. This observation is consistent with many other researchers (Masum et al., 2015; Yusoff et al., 2017).

### 3.2.3. Hydrocarbon emission

Fig. 6 shows the variations of HC emission for lubricant-gasoline blends as a function of engine operating procedures (idle-, half- and full-throttle). It can be observed that during half-throttle, T0 releases the lowest HC concentration compared with all TMPTO containing blends (T10, T15, T20 and T50). This observation is due to the leaning effect which is associated with the simpler chemical structure of mineral-based oil, which enhances the combustion efficiency of the lubricant-gasoline mixture. However, T15 and T20 follow T0 very closely for all three running modes.

An overshoot of HC concentration is observed for T10 during idle operation which is due to the low combustion quality. This is evident because of the greasy deposit and liquid residue at the exhaust pipe which were observed during carbon deposition test. A low combustion quality leads to lower combustion temperature thus making it unable to burn the residue into soot and volatile emissions. A similar trend was also observed in the literature, whereas high HC emission is observed at lower engine efficiency operation speed (Yusoff et al., 2017).

### 3.2.4. Smoke

Fig. 7 shows the variation of opacity emission for all lubricant-gasoline blends with respect to engine operation procedures. This parameter is unique for a two-stroke engine as its counterpart (four-stroke) emits optically no visible smoke. Smoke that emitted at exhaust manifold by a two-stroke engine originates from the incomplete burning of the lubricant. When compared to a four-stroke engine which does not contain lubricant in its fuel, no visible smoke could be seen emitting from the exhaust pipe.

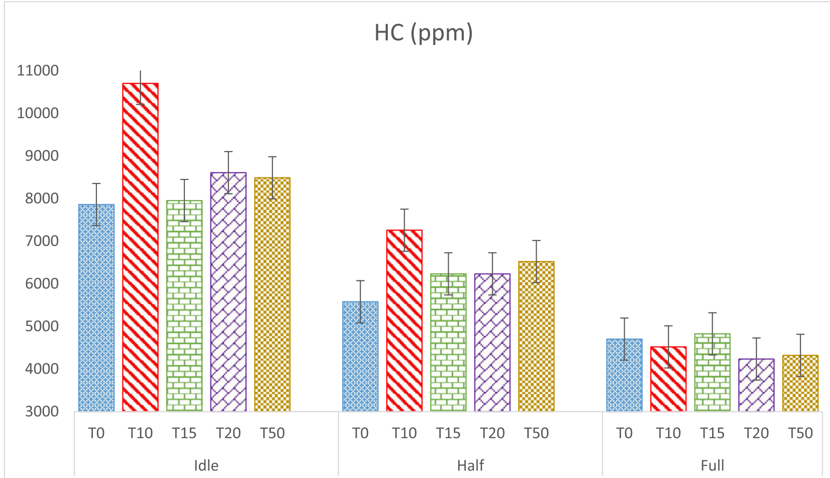


**Fig. 6.** Variation of HC emission as a function of engine speed for all lubricant-gasoline blends.

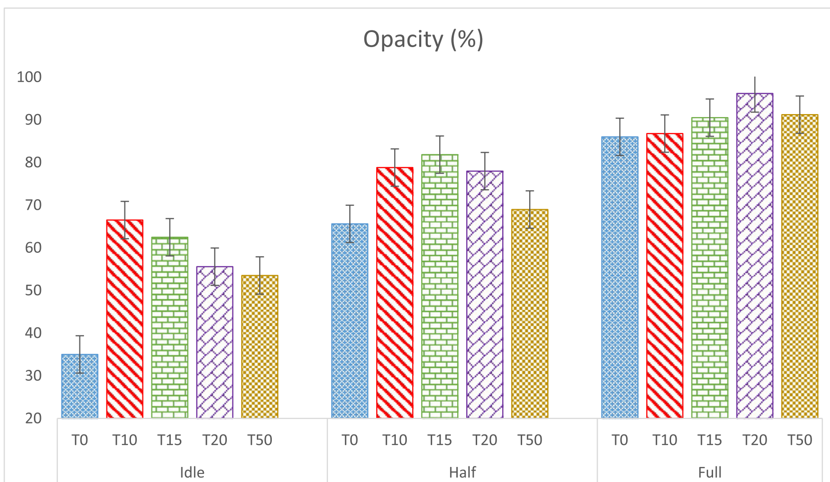


**Fig. 7.** Variation of opacity emissions as a function of engine speed for all lubricant-gasoline blends.

To measure the concentration of smoke, opacity is utilized as a measured parameter. It is apparent that the higher rotation speed will result in higher opacity. 96% opacity is recorded by T20 at full throttling followed by T50 (91%), T15 (90%), T10 (87%), and T0 (86%). Even though the smoke emission for full throttle operation is almost the same for all blends, it is evident that T0 emits the lowest smoke concentration for half throttling and idling. However, T0 together with T50 emits their carbon footprints in the form of liquid residue, resulting in lower soot and opacity compared to T10, T15 and T20.

As the composition of the smoke mainly contains unburnt carbon or soot, it is sensible to state that TMPTO has a denser carbon composition compared to its mineral counterpart which had incidentally enriched the fuel blends with higher carbon leading to an increase in smoke emission. With this statement, the opacity of T10 should be lower than T15 and T20 which is in a good agreement for half and full throttle. However, for idling its value recorded the highest among the three blends. This again, is due to the low combustion quality which is evident in the unburnt hydrocarbon being emitted by T10 during idling (refer Fig. 6). The overshoot of HC recorded for T10 during idling was abnormal due to incomplete burning of fuel. This situation also resulted to a wet deposit which was found on the T10 spark plug.

### 3.3. Uncertainty Analysis

The experimental uncertainties are related to various factors such as the selection and calibration of the instruments, observation and data collection techniques, as well as experimental planning and design. The uncertainties for the carbon deposition and exhaust emission parameters are presented in Appendix A. The overall uncertainty was 4.06% which is within an acceptable range. It was determined using the following equation:

$$= \sqrt{\sum (Uncertainty\ of\ each\ parameter)^2}$$

Overall experimental uncertainty = square root of [(uncertainty of $CO)^2$ + (uncertainty of $CO_2)^2$ + (uncertainty of $HC)^2$ + (uncertainty of $Opacity)^2$] = square root of [$(1.30)^2 + (3.17)^2 + (1.29)^2 + (1.76)^2$] = 4.06%

### 3.4. Decision matrix analysis

To conclude both the combustion quality and emissions of all blends, a decision matrix analysis has been developed which can be referred in Table 4 and Table 5. It is clear that:

1. Mineral-based lubricant (T0) dominates the volatile emissions with 23 points. T0 is superior in CO emissions, HC concentrations and opacity during idling and half throttling. However, it is ranked third out of five blends in carbon deposition with both wet and dry deposits were observed on the spark plug area. T0 also emitted liquid residue which was observed at the tailpipe.
2. T20 is the best among bio-based lubricant blend (29 points) which shows a low CO and $CO_2$ emissions during idling and half-throttling. Only dry carbon deposit was observed. No liquid residue at the exhaust manifold was recorded. It dominates the carbon deposition chart with only 6 marks.
3. T15 and T50 scores 38 and 40 points with their strength at CO emissions during half throttling. T15 shows only dry carbon deposit while T50 has greasy deposits. T50 was recorded to emit liquid residue at the exhaust manifold. T15 scores 8 points in carbon deposition while T50 scores the worst with 30 points.
4. T10 delivers the worst result in emissions analysis with 50 points. Wet and dry deposits were observed on the spark plug. T10 also emitted unburnt liquid emission. For carbon deposition T10 scores 21 points which placed it in number four position out of the five blends.

## 4. Summary

In this study, one mineral lubricant (T0) and four TMPTO blends (T10, T15, T20 and T50) were blended with gasoline at 5:100 v/v and tested on two-stroke spark ignition engine in order to determine the carbon deposition and exhaust emission. All blends were tested at three different operation parameters namely idle, half and full throttles with zero engine load. The following conclusions are drawn and are important to be considered:

1. TMPTO blends inherit flash temperature at par with standard mineral lubricant. They also exhibit comparable viscosities and even lower acid value compared to mineral lubricant.
2. Optimal ratio of TMPTO-to-mineral mixture leads to both species to burn completely during combustion. This can be observed for T15 and T20 which leave both electrodes free from carbon deposit.
3. Mineral-based lubricant T0 shows both greasy deposit on circumference and dry carbon deposit on the spark plug electrodes. This is an initial sign of carbon fouling.
4. Mineral lubricant T0 burns cleaner during half throttle operation. This is evident with the lowest CO and highest $CO_2$ emitted during this operation. However, its low combustion quality leads to carbon deposition. Liquid residue observed at the exhaust manifold will eventually leak out and pollutes the soil and ground water.

**Table 4**
Decision matrix for volatile emissions.

| Blend | Condition | T0 | T10 | T15 | T20 | T50 |
|---|---|---|---|---|---|---|
| CO emissions rank | Idle | 1 | 5 | 3 | 2 | 4 |
| | Half | 1 | 4 | 5 | 2 | 3 |
| | Full | 4 | 2 | 3 | 1 | 5 |
| $CO_2$ emissions rank | Idle | 4 | 5 | 1 | 2 | 3 |
| | Half | 1 | 5 | 2 | 3 | 4 |
| | Full | 3 | 5 | 2 | 1 | 4 |
| HC emissions rank | Idle | 1 | 5 | 2 | 4 | 3 |
| | Half | 1 | 5 | 3 | 2 | 4 |
| | Full | 4 | 3 | 5 | 1 | 2 |
| Opacity concentration rank | Idle | 1 | 5 | 4 | 3 | 2 |
| | Half | 1 | 4 | 5 | 3 | 2 |
| | Full | 1 | 2 | 3 | 5 | 4 |
| **Score (lower is better)** | | **23** | **50** | **38** | **29** | **40** |

**Table 5**
Decision matrix for carbon deposition.

| Carbon deposit | Condition | T0 | T10 | T15 | T20 | T50 |
|---|---|---|---|---|---|---|
| Side electrode | Char | x | 1 | x | x | 2 |
| | Dry | 1 | 4 | 3 | 2 | 5 |
| Center electrode | Char | x | 1 | x | x | 2 |
| | Dry | 3 | 4 | 1 | 2 | 5 |
| Insulator tip | Char | x | 1 | x | x | 2 |
| | Dry | 3 | 4 | 2 | 1 | 5 |
| Side electrode ring | Char | 1 | 2 | x | x | 3 |
| | Dry | 3 | 4 | 2 | 1 | 5 |
| **Score (lower is better)** | | **11** | **21** | **8** | **6** | **30** |

## Acknowledgements

The authors would like to acknowledge the University of Malaya, Malaysia for financial support through the Grand Challenge grant project titled "Tribological Characteristic of Bio-based Lubricant" [GC001E-14AET], Universiti Teknikal Malaysia Melaka and Ministry of Higher Education, Malaysia [RAGS/1/2014/SG06/FKM/B00067].

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.02.224.

## References

Adam, T., Farfaletti, A., Montero, L., Martini, G., Manfredi, U., Larsen, B., et al., 2010. Chemical characterization of emissions from modern two-stroke mopeds complying with legislative regulation in europe (EURO-2). Environ. Sci. Technol. 44 (1), 505–512. https://doi.org/10.1021/es9021969.

Cui, W.S., Liu, W.Z., Tian, J., Chen, X.Y., 2018. Study on the plasma generation characteristics of an induction-triggered coaxial pulsed plasma thruster. Plasma Sci. Technol. 20 (2).

Gould, D., Gardiner, D.P., LaViolette, M., Allan, W.D., 2009. Further development of a smoke sensor for diesel engines. J. Eng. Gas Turbin. Power-Transac. Asme 131 (2).

Hanafi, M.H.B., Nakamura, H., Hasegawa, S., Tezuka, T., Maruta, K., 2018. Effects of n-butanol addition on sooting tendency and formation of C-1 -C-2 primary intermediates of n-heptane/air mixture in a micro flow reactor with a controlled temperature profile. Combust. Sci. Technol. 190 (12), 2066–2081. https://doi.org/10.1080/00102202.2018.1488694.

Hanafi, M.H.M., Mahmood, W.M.F.W., Bin Abdollah, M.F., Rafeq, S.A., Nor, N.F.M., Zulfattah, Z.M., , et al.Ibrahim, A., 2013. Comparison of soot particle movement based on crank angle. Int. Tribol. Conferen. Malaysia 68, 245–250. https://doi.org/10.1016/j.proeng.2013.12.175, 2013.

Hooper, P.R., 2018. Investigation into a stepped-piston engine solution for automotive range-extender vehicles and hybrid electric vehicles to meet future green transportation objectives. Proc. Inst. Mech. Eng. - Part D J. Automob. Eng. 232 (3), 305–317. https://doi.org/10.1177/0954407017698304.

Kawahara, N., Hashimoto, S., Tomita, E., 2017. Spark discharge ignition process in a spark-ignition engine using a time series of spectra measurements. Proc. Combust. Inst. 36 (3), 3451–3458.

Kaya, G., Ozdalyan, B., 2017. Combustion analysis of a two stroke reverse-uniflow gasoline engine. Isi Bilimi Ve Teknigi Dergisi-J. Therm. Sci. Tech. 37 (1), 53–59.

Kelly, C.A., Ayoko, G.A., Brown, R.J., Swaroop, C.R., 2005. Underwater emissions from a two-stroke outboard engine: a comparison between an EAL and an equivalent mineral lubricant. Mater. Des. 26 (7), 609–617. https://doi.org/10.1016/j.matdes.2004.08.013.

Lawal, M.N., Abolarin, M.S., Nasir, A., Musa, A.N., 2017. Differential air/fresh charge demand, supply and utilisation in two-stroke spark ignition engines. Int. J. Automot. Mech. Eng. 14 (4), 4769–4784. https://doi.org/10.15282/ijame.14.4.2017.13.0374.

Lomakin, S.M., Zaikov, G.E., 1996. Pyrolysis and carbonization of cross-linked poly(methyl methacrylate). Int. J. Polym. Mater. 33 (3–4), 133–140.

Lopez, J.J., Molina, S., Garcia, A., Valero-Marco, J., Justet, F., 2017. Analysis of the potential of a new automotive two-stroke gasoline engine able to operate in spark ignition and controlled autoignition combustion modes. Appl. Therm. Eng. 126, 834–847. https://doi.org/10.1016/j.applthermaleng.2017.07.213.
Masum, S.M., Masjuki, H.H., Kalam, M.A., Palash, S.M., Habibullah, M., 2015. Effect of alcohol-gasoline blends optimization on fuel properties, performance and emissions of a SI engine. J. Clean. Prod. 86, 230–237.
NGK, 2018a. SPARK PLUG BASICS. NGK Spark Plugs (U.S.A). Retrieved 08 March 2018, from. http://www.ngksparkplugs.com/about-ngk/tech-talk/spark-plug-basics.
NGK, 2018b. What Is a Fouled Spark Plug? NGK Spark Plugs (U.S.A.), Inc. Retrieved 07 March 2018, from. http://www.ngksparkplugs.com/about-ngk/faqs/spark-plug-faqs/what-is-a-fouled-spark-plug.
Prati, M.V., Costagliola, M.A., 2009. Emissions of fine particles and organic compounds from mopeds. Environ. Eng. Sci. 26 (1), 111–121. https://doi.org/10.1089/ees.2007.0206.
Singh, Y., Farooq, A., Raza, A., Mahmood, M.A., Jain, S., 2017a. Sustainability of a non-edible vegetable oil based bio-lubricant for automotive applications: a review. Process Saf. Environ. Protect. 111, 701–713. https://doi.org/10.1016/j.psep.2017.08.041.
Singh, Y., Singla, A., Singh, A.K., 2017b. Tribological characteristics of Mongongo-oil-based biodiesel blended lubricant. Energy Sources, Part A Recovery, Util. Environ. Eff. 39 (3), 332–338.
Singh, Y., Singla, A., Upadhyay, A., Singh, A.K., 2017c. Sustainability of Moringa-oil-based biodiesel blended lubricant. Energy Sources, Part A Recovery, Util. Environ. Eff. 39 (3), 313–319.
Spezzano, P., Picini, P., Cataldi, D., Messale, F., Manni, C., 2008. Particle- and gas-phase emissions of polycyclic aromatic hydrocarbons from two-stroke, 50-cm(3) mopeds. Atmos. Environ. 42 (18), 4332–4344. https://doi.org/10.1016/j.atmosenv.2008.01.008.
Sturms, R., White, D., Vickerman, K.L., Hattery, T., Sundararajan, S., Nikolau, B.J., Garg, S., 2017. Lubricant properties of omega-1 hydroxy branched fatty acid-containing natural and synthetic lipids. Tribol. Lett. 65 (3).
Syahir, A.Z., Zulkifli, N.W.M., Masjuki, H.H., Kalam, M.A., Alabdulkarem, A., Gulzar, M., , et al.Harith, M.H., 2017. A review on bio-based lubricants and their applications. J. Clean. Prod. 168, 997–1016.
Talib, N., Rahim, E.A., 2018. Experimental evaluation of physicochemical properties and tapping torque of hexagonal boron nitride in modified jatropha oils-based as sustainable metalworking fluids. J. Clean. Prod. 171, 743–755.
Vlahopoulou, G., Petretto, G.L., Garroni, S., Piga, C., Mannu, A., 2018. Variation of density and flash point in acid degummed waste cooking oil. J. Food Process. Preserv. 42 (3).
Yusoff, M.N.A.M., Zulkifli, N.W.M., Masjuki, H.H., Harith, M.H., Syahir, A.Z., Kalam, M.A., , et al.Khuong, L.S., 2017. Performance and emission characteristics of a spark ignition engine fuelled with butanol isomer-gasoline blends. Transport. Res. Transport Environ. 57, 23–38.
Zakaria, M.Z., Saaduna, M.N.A., Idris, N., Haminudin, N.F., Abdollah, M.F., Ahmad, E.Z., 2015. Effect of ph towards hydrogen gas output of a small and portable Alkaline electrolyser. J. Teknologi. 76 (5), 49–52.
Zulkifli, N.W.M., Azman, S.S.N., Kalam, M.A., Masjuki, H.H., Yunus, R., Gulzar, M., 2016. Lubricity of bio-based lubricant derived from different chemically modified fatty acid methyl ester. Tribol. Int. 93, 555–562.