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Exploring the performance of TMP trioleate esters in real-world automotive engines: A tribological analysis

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KEYWORDS

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Ester
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Engine tribotester

ABSTRACT

These days, cutting emissions and increasing fuel efficiency are more pressing issues than ever before. Automakers have long pursued ways to make internal combustion engines more efficient, in addition to electrifying powertrains. Vegetable oil provides substantial research and production cost advantages compared to mineral and synthetic oils, making it a sustainable and economically feasible option. This article examines TMP's tribological performance in a commercial engine vehicle adapted to operate on motor power without combustion energy. The impact of spark plug installation while running is also examined. In contrast, fuel injection adjusts combustion rates during operation, which might impact the lubrication test variable. In this research, a fourball and commercial engine to evaluate the tribological performance of TMP ester, mineral oil (MO) and fully synthetic oil (FSO). The result shows that the TMP ester being the most efficient due to its low viscosity and strong film-forming properties compared to MO and FSO. Besides that, TMP ester has efficiency of 49.33% without spark plug, and 54.5% with the use of spark plug. Spark plugs has improved engine performance by creating a pressurized chamber.

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1.0 INTRODUCTION

The use of traditional mineral oil and additives in lubricant formulations has presented significant problems, including worldwide scarcities resulting from the fast depletion of fossil oil supplies, high toxicity, and non-biodegradability. The use of lubricants derived from mineral oil has the potential to harm the environment because of unintended release, spillage, or inadequate handling or management of the lubricant (Syahrullail et al., 2005; 2011; 2012; 2013). Due to their renewable nature, low eco-toxicity, biodegradability, and improved reliability, there has been a significant interest in biolubricants made from plant oil in this scenario (Sani et al., 2017). Plant-based oils have historically served as lubricants, but in the 20th century, they were quickly surpassed in popularity by mineral oils due to their substantially lower cost. Nevertheless, because to the current surge in plant-based chemistry and the soaring costs of petroleum crude oil, biolubricants are seeing a resurgence in preference. The efficacy of biolubricants, specifically in relation to friction, wear prevention, and lubricity, is still a subject of debate. A key characteristic of a superior lubricant is its strong affinity for metal surfaces. Typically, a plant-derived oil with a long fatty acid chain is necessary to enhance lubrication and provide defence against friction and wear (Wan Nik et al., 2007; Rasep et al., 2021; Sinyavsky, N., & Kostrikova, N., 2023). Most existing research has focused on examining the friction and wear characteristics of vegetable oils either on their own or when combined with specific additives. Yahaya et al. (2021) have conducted a comprehensive analysis of the use of palm oil as a lubricant base stock and the difficulties associated with it. The experimental results indicated that palm oil has lower thermal and oxidative stability and is less efficient under severe loads. Salaji and Jayadas (2021) have recently published a paper on the possible use of nonedible chaulmoogra oil as a lubricant base stock. Despite the lubricant's decreased coefficient of friction, the wear scar diameter exhibited a notable increase. The stated pour point of 15°C requires further improvement.

Plant oils used as lubricating oil have inherent limitations, including reduced low temperature performance and inadequate oxidative stability during operation (Golshokouh et al., 2013a; 2013b; 2014). Modifying the molecular structures of plant oils or combining them with commercial oil, chemical additives, or nanoparticles can enhance the physical and chemical properties of biolubricants, particularly in boundary and hydrodynamic lubrication regimes. (Azman et al., 2018). Chemical modifications of plant oil, such as epoxidation, transesterification, esterification, hydrogenation, and estolide formation, have been conducted to address the limitations of plant oils (Rahman et al., 2023; Afifah et al., 2021; Aiman et al., 2017; Jabal et al., 2014). The choice of acids or alcohols in esterification/transesterification operations directly affects the physicochemical features of the resulting synthetic esters. Synthetic esters often exhibit superior characteristics compared to their comparable botanical oils. Synthetic esters have superior characteristics at low temperatures, including improved flash and fire points, reduced volatility, and enhanced oxidative stability (Cecilia et al., 2020). When the glyceride part of a natural ester, like plant oils, is replaced with a polyhydric alcohol such as neopentylglycol (NPG), trimethylolpropane (TMP), pentaerythritol (PE), or dipentaerythritol (diPE), the thermal and hydrolytic stabilities of the plant oil are significantly enhanced. Polyol ester may be commercially produced in a variety of viscosities and physical qualities by reacting a monobasic acid or monoesters (often methyl) with a polyhydric alcohol in the presence of a catalyst (Shah et al., 2016). Out of these polyol esters, trimethylolpropane ester (TMPE) has gained greater popularity in many applications due to its wider availability and lower cost.

Over the last several decades, technological progress in engineering has allowed a significant decrease of about 40% in carbon dioxide (CO_2) emissions in the industrial sector. In 2021, all of the efficient small vehicles got combined fuel efficiency ratings of 30 mpg or more, with the best two getting more than 50 mpg in both city and highway driving. Typically, the most fuel-efficient automobiles on the road as of 2022 are small and subcompact cars, direct injection technology, variable valve timing, variable compression ratio, cylinder deactivation, powertrain electrification, and other solutions that enhance efficiency (Burris et al., 2023). According to Wang et al., (2021), friction causes a loss of around 10 to 20% of energy in an internal combustion engine. The given phenomenon may be further separated, approximately in a ratio of 9 to 1, into two types of losses: viscous losses caused by the flow of lubricant, and frictional losses caused by contact with boundaries, mainly in the piston ring/cylinder bore, crank train, and valvetrain systems. To minimize dissipative losses, one might choose lubricants with lower viscosity and smaller displacement volumes (Lee and Zhmud, 2021). Frictional losses can be minimized by apply antifriction coatings to essential components and include certain additives in the engine oil. According to Lin et al., (2016), using piston rings with the TiSiCN coating created by SwRI® may decrease friction between the piston and bore, resulting in a 0.5% increase in fuel efficiency and a significant decrease in wear of the ring and liner.

The purpose of this article is to examine the tribological performance of TMP ester in a real-world commercial engine vehicle that has been modified to run on motor power independently without the use of combustion energy. This study also investigates the effect of spark plug installation during running. This contrasts with fuel injection, which introduces fluctuations in combustion rates during operation, which can affect the lubrication test variable.

2.0 EXPERIMENTAL PROCEDURE

2.1 Lubricant Sample

A total of three different kinds of lubricating oils were put through their paces in this experiment, where the main lubricant was TMP Trioleate ester that received from “Oleon” company and been compared to the commercial lubricant that is fully synthetic engine oil (Shell helix 5w-40), and mineral oil (Shell helix 15w-40). The detail product of TMP Ester is shown as in table 1. Figure 1 shows the three-sample lubricant and Table 2 shows the rheological properties of the sample that been used in this research.

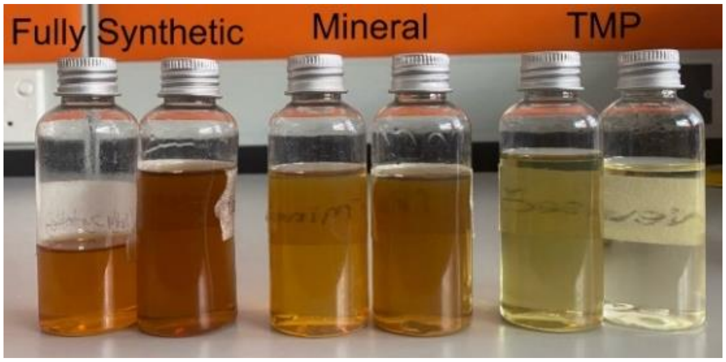

Figure 1: Sample Lubricant for this research.

Table 1: TMP trioleate ester product identifier.

Product form	: Substance (UVCB)
Trade name	: RADIALUBE 7364
IUPAC name	: Fatty acids, C18-unsatd., diesters and triesters with trimethylolpropane
EC No	: 701-042-9
CAS NO	: 1335202-94-2
REACH Registration No	: 01-2119496071-40

Table 2: The rheological properties of all sample lubricant.

Parameter	TMP Ester	MO	FSO	Standard
Specific density at 25°C (g/cm3)	0.926	0.875	0.854	ASTM D1298-85(90)
Dinemic viscosity at 40°C (mPa.s)	40.63	20.021	22.868	ASTM D7042
Kinematic viscosity at 40°C (mm^2/s)	45.0	105.4	79.1	ASTM D445-94
Kinematic viscosity at 100°C (mm^2/s)	16.54	14.5	13.1	ASTM D445-94
Viscosity index (VI)	383	141	167	ASTM D2270

2.2 Experiment Set-Up

2.2.1 Fourball Test

The fourball tribotester is a device used to measure the coefficient of friction (COF) and anti-wear (AW) capabilities of lubricating oil and additives. The normal load, rotating speed, and temperature of the machine were all established in compliance with ASTM guidelines. Figure 2 shows the schematic diagram of fourball test.

Table 3 lists the specifications of the tester that was designated as a recognized institution in the fundamental analysis of lubricant properties (Ing et al., 2012):

Table 3: Experimental conditions.

Parameters	Details
Standard	ASTM D4172
Speed (rpm)	400, 600, 800, 1000 and 1200
Duration (min)	60
Quantity (ml)	10
Temperature (°C)	75

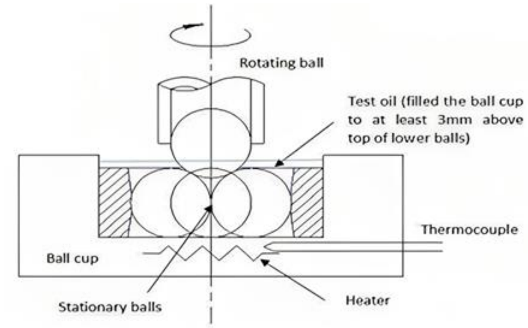

Figure 2: Schematic of the fourball arrangement.

2.2.2 Engine Tribotest

During the engine's operating phase, this test rig is set up to discover many factors, including the friction and wear characteristics inherent in the contact between the piston ring and the cylinder liner. Because the inverter can only detect and display important metrics like the engine's speed, current, voltage, and power output driven by the three-phase electrical motor, it will not show the value of that parameter on its screen. Therefore, to get the target value including the friction characteristics, one must resort to the basic formula controlling the power output of a three-phase electrical motor. Figure 3 shows the experiment set up for the commercial engine tribotest and Table 4 shows the parameters for experiment testing.

Table 4: Experiment parameters.

Parameters	**Detail**
Speed (RPM)	400, 600, 800, 1000, 1200
No of cylinder	4
Duration (hr)	6
Transmission	4-Speed automatic transmission
Condition	With spark plug and without spark plug
Lubricant	TMP, Mineral oil and fully synthetic oil

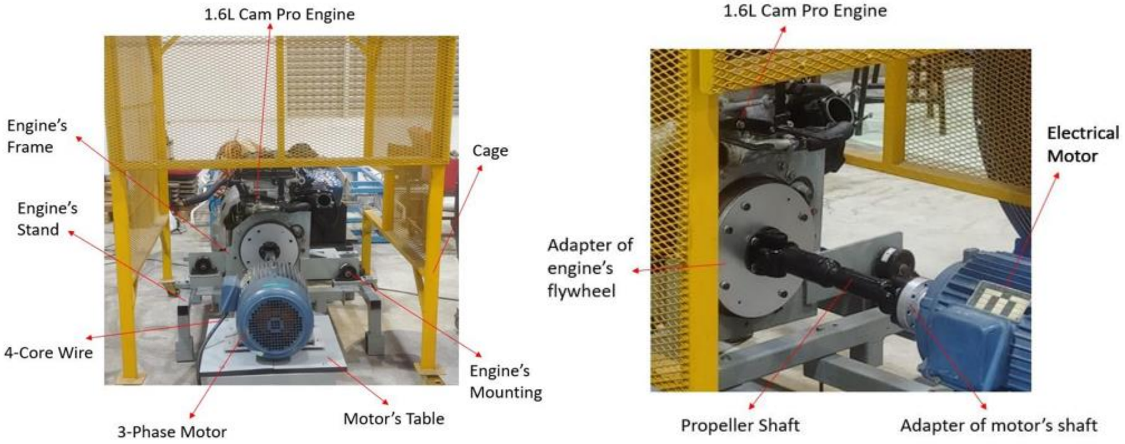

Figure 3: Experiment set up for engine tribotest.

2.3 Friction Loss Calculation

Friction may have an impact on the power output and power input of a system in mechanics. The power output, also known as useable power, refers to the portion of energy that is used to do work, while the power input represents the whole energy generated by the source. Friction may result in the dissipation of a portion of the input energy as heat, hence diminishing the efficiency of the system. Within the realm of machinery, the total power produced at the shaft, which is then transferred to the load, is diminished by mechanical losses including friction and windage losses. In order to enhance efficiency, it is crucial to reduce friction by using lubrication and implementing design enhancements.

The power loss analysis can be represented as

$$P_{input} = \frac{E_{total}}{t} \tag{1}$$

$$P_{output} < P_{input} \tag{2}$$

$$P_{loss} = P_{input-}P_{output} \tag{3}$$

$$E_{loss} = E_{total} - W = Friction\,force \times distance \tag{4}$$

Where,
P_{output}= Power output
P_{input}= Power input
E_{total}= Total energy
E_{loss} = Energy loss
t= Time
W= Work done

In order to factor in the influence of friction on the efficiency of a machine, it is necessary to take into account the energy losses caused by friction. The losses may be calculated using the previously given formula:

$$\text{Efficiency} = \frac{P_{output} - E_{loss}}{P_{input}} \times 100\% \tag{5}$$

3.0 RESULTS AND DISCUSSION

3.1 Friction Coefficient Based on Fourball-Test

The provided image is a bar graph illustrating the coefficient of friction (for three different types of oils that is, Mineral Oil (MO), Fully Synthetic Oil (FSO), and TMP ester Oil across various rotational speeds (see Figure 5). The graph depicts the coefficient of friction for Mineral Oil, Fully Synthetic Oil, and TMP Ester at speeds ranging from 400 to 1200 RPM. It provides insights that are consistent with the Stribeck curve. At first, all oils have elevated friction coefficients while moving at low speeds (400 RPM), which suggests the presence of boundary lubrication. When the speed reaches 600 RPM, there is a noticeable reduction in friction. This reduction is most prominent in TMP Ester, which maintains a consistently low and stable friction even at higher speeds (800, 1000, and 1200 RPM). This indicates a shift towards a combination of lubrication types, maybe including hydrodynamic lubrication. Conversely, Mineral Oil and Fully Synthetic Oil exhibit only a moderate decrease in friction, with tiny increments at higher velocities, suggesting an incomplete shift beyond mixed lubrication. These patterns, though not entirely in line with the Stribeck curve, indicate that TMP Ester has the potential to provide a more efficient protective layer as the speed increases.

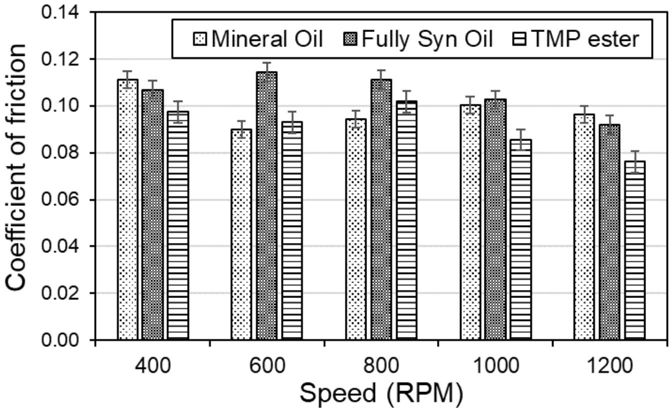

Figure 5: Coefficient of friction of all sample.

MO exhibits a relatively consistent coefficient of friction across different speeds, ranging from approximately 0.10 to 0.12 µm. With a viscosity of 20.021 mPa.s, this oil provides moderate resistance to flow, contributing to its stable friction performance. The consistency suggests that MO is a reliable lubricant for applications where maintaining a steady coefficient of friction is crucial. The moderate viscosity helps in forming a stable lubricating film, which ensures uniform friction characteristics across varying speeds (Zulhanafi and Syahrullail, 2019). FSO also demonstrates consistent friction characteristics, with slight variations around 0.10 to 0.11 µm. This oil has a slightly higher viscosity of 22.868 mPa.s, which offers a bit more resistance to flow compared to MO. The higher viscosity can enhance the lubricant film's thickness, providing better protection and potentially reducing wear. This increased viscosity helps maintain stable friction levels across different speeds, making FSO suitable for applications requiring consistent friction behaviour under varying operational conditions (Yahaya et al., 2023). TMP ester generally shows a lower coefficient of friction compared to both MO and FSO, with values ranging from approximately 0.09 to 0.10 µm. TMP ester has the lowest viscosity of the three, at 12.35 mPa.s. The lower viscosity means TMP ester flows more easily, which can reduce internal fluid friction and lead to a lower coefficient of friction (Samidin et al., 2021). This lower friction is particularly beneficial in applications where minimizing friction is crucial for enhancing performance and extending the lifespan of mechanical components. The reduced internal resistance due to lower viscosity helps TMP ester excel in high-performance and high-efficiency applications.

When compared to the viscosity of MO (20.021 mPa.s) and FSO (22.868 mPa.s), the viscosity of TMP ester is 12.35 mPa.s, which is much lower than both of these other oils. It is possible for oils with a lower viscosity to flow more smoothly and to generate a lubricating coating that is thinner and more uniform. This results in a reduced coefficient of friction because it lessens the amount of friction that occurs inside the lubricant itself and minimizes the amount of resistance that motion encounters (Aiman et al., 2024). Due to the fact that TMP ester is an ester-based lubricant, it often has a molecular structure that is more compatible with minimizing friction. Because of the polar character of their molecules, esters are recognized for their exceptional lubricity (Hussain et al., 2021). This feature boosts their capacity to stick to metal surfaces and provides a stable lubrication coating. Esters are also noted for their durability. This robust adhesion contributes to the maintenance of a continuous and efficient lubricating layer, hence lowering the amount of metal-to-metal contact and friction that occurs. The thermal stability and oxidative resistance of esters are typically superior than those of mineral oils under most circumstances (Mehta et al., 2016). Because of this feature, TMP ester is able to keep its lubricating capabilities even when subjected to a wider variety of temperatures and operating conditions. Because of this, TMP ester is able to maintain a low coefficient of friction even when subjected to circumstances that are both variable and high-speed. A thick and durable lubricating layer may be formed by using TMP ester because of its molecular structure (Zulkifli et al., 2014). The strength of the film plays a vital role in minimizing wear and friction by avoiding direct contact with surfaces that are in motion. Ester molecules' high polarity makes them ideal lubricants because they create a strong link with the surfaces they coat, making the resulting coating more stable and less frictional. Besides that, according to Chang et al., (2015), TMP also has a high content of olein acid (C18:1), where numerous of study shows that higher concentration of oleic acid able to reduce the friction (Yahaya., et al., 2023; Zulhanafi et al., 2019).

3.2 Engine Tribotest Without Spark Plug

The results of the engine tribotest that was set up for examination of TMP, FSO, and MO without the use of spark plugs are shown in Figure 6. In order to properly evaluate the effect that various oils have on power losses in engines, it is essential to have a solid understanding of how each kind of oil behaves while the engine is operating at different speeds. Having this understanding is essential for maximizing the effectiveness and performance of the engine.

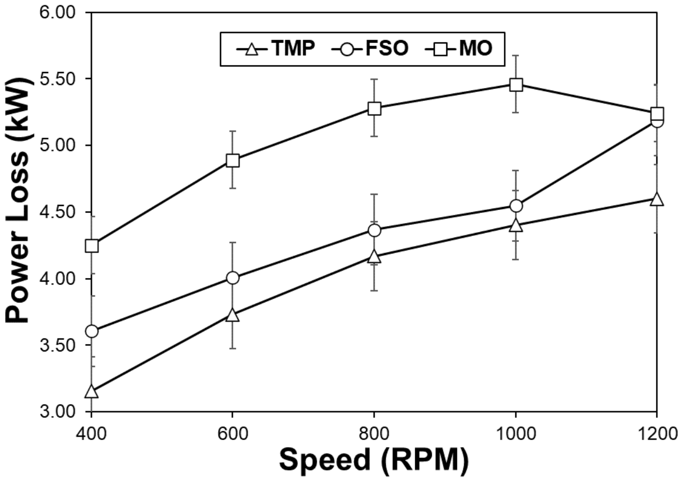

Figure 6: Power loss of sample lubricant without spark plug.

Power losses in MO have a positive correlation the result of fourball test. The observed pattern suggests that Mineral Oil's efficacy diminishes as RPMs increase, possibly due to its viscosity properties. The power loss is calculated around 50-80% from 400-1200rpm. As the rotational speed of the engine rises, the internal forces that cause the oil to slide against itself also increase, resulting in a decrease in viscosity and a reduction in its ability to effectively lubricate. As a result, there is a rise in friction and mechanical losses. MO is acceptable for low to moderate engine speeds, but its performance drastically decreases at higher speeds, making it less desirable for high RPM applications. On the other hand, FSO exhibits a complex behaviour in which power losses first escalate with engine speed and thereafter diminish as speed further increases. The power loss is calculated around 50-78% from 400-1200rpm. The initially observed rise in viscosity may be attributed to the oil's ability to adjust to the growing shear pressures. As the engine speed increases, the sophisticated additive packages and consistent molecular structure of Fully Synthetic Oil become effective, improving lubrication and decreasing friction. Consequently, there is a reduction in power losses while travelling at greater speeds. Hence, Fully Synthetic Oil is ideal for engines that function at various speeds, providing efficiency and performance advantages at higher RPMs after an initial adaptation phase.

TMP ester has a tendency in which power losses tend to rise as engine speed increases, however this increase is less noticeable than in the case with Mineral Oil when no spark plug is used. The power losses are calculated around 50-75% from 400-1200rpm. These findings indicate that TMP ester exhibits superior lubricating properties and more efficiently minimizes friction under elevated shear conditions compared to Mineral Oil. The composition of TMP Oil, which often incorporates specialized base stocks and modern additives, offers exceptional thermal stability and resistance to thinning under severe shear, resulting in consistent performance across different engine speeds (Hussain et al., 2021). Therefore, TMP ester is beneficial for situations in which engines function at high RPMs but yet require dependable lubrication to reduce power losses.

In the absence of a spark plug, the type of oil plays a more critical role in determining power losses. Mineral oil, in particular, shows the most significant increase in power losses as engine speed increases. This can be attributed to mineral oil’s relatively lower ability to maintain consistent lubrication under high shear and temperature conditions, leading to increased friction and mechanical wear. Without the efficient pressurise by a spark plug, the engine's reliance on the oil's lubricating properties becomes more pronounced. Fully synthetic oil and TMP ester, with their advanced formulations and superior thermal stability, perform better than mineral oil, but they still exhibit increased power losses without the presence of a spark plug.

3.3 Engine Tribotest With Spark Plug

Figure 7 shows the result of the engine tribotest set up for with spark plug test of TMP, FSO and MO, where the data for MO demonstrates an inverse relationship between power losses and engine speed, indicating that power losses decrease as engine speed rises. The observed pattern indicates that as the RPM increases, MO has an enhanced ability to decrease friction and mechanical losses in the engine. The greater efficiency may be attributed to the viscosity properties of the oil and its ability to maintain a stable lubricating coating even at higher shear rates often seen in engines operating at higher speeds (Garcia et al., 2023). Therefore, MO is a good resource for situations when engines primarily function at higher RPMs. Besides that, the reduced of power losses is calculated around 4.85% at 1200 rpm compared to the without spark plug condition. FSO similarly exhibits a decrease in power losses as engine speed increases, however the rate of decrease differs from that of MO. FSO are specifically engineered to provide exceptional performance in various temperatures and operating situations. The significant decrease in the rate of power loss may be attributed to the sophisticated additive packages and the consistent molecular composition of synthetic oils, which improve lubrication and minimize internal friction more efficiently than MO (Pichler et al., 2023). FSO also has reduced the power loses around 5.42% at 1200rpm compared to the condition of without spark plug. FSO is an optimal selection for high performance engines that function at diverse speeds and circumstances.

The power losses of TMP ester decrease significantly as the engine speed rises. The significant decrease in RPM indicates that TMP ester has exceptional performance in maintaining little friction and effective lubrication, even at very high rotational speeds. Specialized base stocks and additives are often used in the formulation of TMP ester to enhance their heat stability and shear resistance, resulting in outstanding performance (Zulkifli et al., 2014). These properties ensure that the oil remains effective in reducing power losses even as the operational demands increase. The substantial decrease in power losses with TMP ester highlights its potential for use in high-speed, high-stress engine environments where maintaining efficiency and performance is critical. The TMP ester, however, shows a lower value in reducing power losses, that is around 2.35% only at 1200rpm compared to MO and FSO.

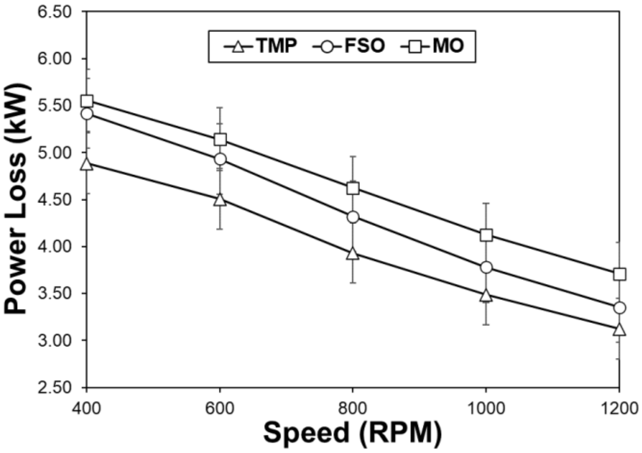

Figure 7: Power loss of sample lubricant with spark plug

The presence of a spark plug in an engine significantly influences power losses across various types of oils, highlighting the importance of ignition efficiency in overall engine performance (see Figure 8). When a spark plug is utilized, power losses tend to decrease across all types of oils as engine speed increases. The spark plug facilitates the ideal ignition of the fuel-air combination, resulting in enhanced combustion efficiency. However, in this scenario, the process of combustion is disregarded. Nevertheless, the existence of a spark plug has resulted in the creation of a pressurised chamber inside the engine, since the spark plug hole cover is sealed. This pressure reduces the strain on the engine, allowing it to operate more smoothly and effectively. Consequently, the lubricating properties of the oil are better utilized, minimizing friction and mechanical losses. This trend is consistent across mineral oil, fully synthetic oil, and TMP ester, indicating that the pressured condition facilitated by the spark plug enhances the overall lubrication and reduces power losses. Therefore, engines equipped with spark plugs benefit from increased efficiency and performance, especially at higher rotation (rpm), where maintaining effective combustion is crucial.

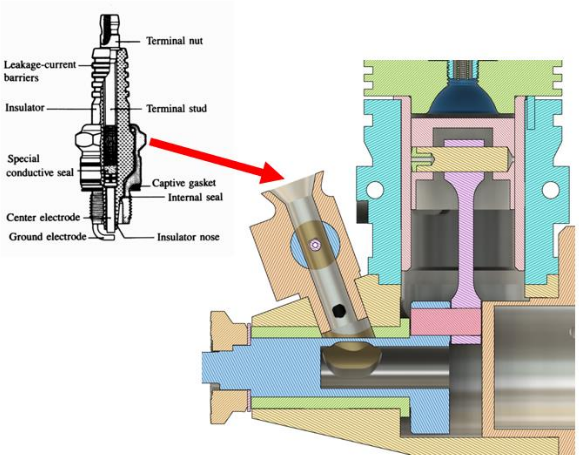

Figure 8: The spark position in commercial car engine.

CONCLUSIONS

To summaries, oils' ability to reduce friction is greatly affected by their viscosity and molecular properties. Mineral oil causes more friction due to its moderate viscosity and less efficient molecular structure. The high viscosity of fully synthetic oil makes it an excellent lubricant, although it isn't as efficient for reducing friction as TMP ester. As compared to other friction reducers, TMP ester stands significantly above other options because to its exceptional heat stability, low viscosity, and powerful film-forming characteristics. This research emphasizes the need of choosing the right oil according to individual performance needs, especially when reducing friction is of utmost importance.

Adding a spark plug to an engine greatly reduces power loss and improves performance with any oil. Spark plugs reduce engine strain by creating a pressurized chamber that allows the fuel-air combination to ignite more efficiently. The lubricating qualities of the oil may be effectively used at these pressurized conditions, leading to less friction and mechanical losses. All three types of oil exhibit the same pattern under pressure, proving that it improves lubrication and decreases power losses: mineral, fully synthetic, and TMP. Since efficient combustion is so important at higher RPMs, engines that use spark plugs run more efficiently and perform better generally.

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