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Hydrodynamic Characterization of Palm Oil-Based TMP Ester and Coconut Oil Lubricant Blend for Journal Bearing Application

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Abstract

The growing demand of biodegradable alternative for mineral-based engine oil has intensified research into vegetable oil-based lubricants capable of operating under hydrodynamic conditions without compromising environmental compatibility. However, many formulations rely on chemical additives to improve viscosity stability and load-carrying performance, potentially reducing biodegradability. This study proposes an additive-free lubricant formulated by blending palm-oil-based trimethylolpropane ester (PO-TMP) with refined coconut oil (CO) and evaluates its hydrodynamic performance in journal bearing applications. Blend C75, containing 75 vol% CO and 25 vol% PO-TMP, was prepared and compared with neat CO, PO-TMP, and SAE 40 mineral oil. Hydrodynamic testing was conducted under a radial load of 10 N and rotational speeds from 200 to 2000 rpm using a journal bearing rig equipped with circumferential pressure and temperature sensors, while frictional torque measurements enabled coefficient of friction evaluation. Analytical predictions of minimum film thickness and load-carrying capacity were obtained from the Reynolds equation for short journal bearings. Blending PO-TMP with coconut oil significantly improved viscosity stability without additives, with C75 exhibiting the highest viscosity index (265.8). Despite lower absolute viscosity than SAE 40, C75 generated higher maximum hydrodynamic pressures at all speeds, reduced bearing temperature rise, and maintained the lowest overall friction, achieving an average COF reduction of approximately 25%. The balanced molecular structure of C75 enabled the formation of sufficient film thickness to sustain load-carrying capacity comparable to mineral oil. These findings demonstrate that tailoring complementary vegetable oil structures can enhance viscosity stability, pressure generation, and friction performance while preserving biodegradability, demonstrating C75 as a suitable alternative for mineral oil-based lubricant for journal bearing application.

1 Introduction

Biodegradable engine lubricants derived from vegetable oils are increasingly explored as alternatives to mineral-based lubricants. However, their application is constrained by chemical and physical limitations. Vegetable oils are predominantly composed of triacylglycerols, whose β-hydrogen structure is prone to degradation at elevated temperatures. Additionally, unsaturated fatty acids possess reactive C=C double bonds. These structural characteristics result in limited oxidative stability, poor cold-flow behaviour caused by rapid crystallisation, and restricted viscosity range, which prevents vegetable oils from meeting hydrodynamic lubrication requirements without modification. Journal bearing applications demand optimal viscosity to generate sufficient hydrodynamic pressure for load support. Previous studies reported that additives such as nanoparticles, antioxidants and viscosity improvers have been widely introduced to enhance lubricant performance (Gundarneeya & Vakharia, 2021). However, chemical additive-based modification may compromise biodegradability since a significant portion of lubricants is released into the environment through total-loss applications and spillage (Nowak et al., 2019). To overcome these limitations without relying on chemical additives, blending different vegetable oils has emerged as a strategy to combine complementary properties. Coconut oil exhibits high thermal stability due to its high saturated fatty acid content, but suffers from poor cold-flow characteristics. Conversely, palm oil contains a higher proportion of unsaturated fatty acids, which can improve low-temperature behaviour but reduces degradation resistance. Chemical modification of palm oil through esterification with trimethylolpropane (TMP) has been shown to enhance its thermal stability and tribological performance, making palm oil-based TMP ester (PO-TMP) a promising base stock. Given Malaysia's abundant palm and coconut oil resources, blending PO-TMP with coconut oil offers a feasible biodegradable lubrication solution. The longer fatty acid chains of PO-TMP combined with the higher saturation level of coconut oil are expected to improve stability and hydrodynamic performance. Therefore, this study investigates the potential of PO-TMP and coconut blend as biodegradable lubricants. Their tribological behaviour, physical properties, oil film thickness and load-carrying performance are evaluated and compared with SAE 40 mineral oil as benchmark.

2 Methodology

2.1 Lubricant blend and viscosity

The lubricants evaluated in this study are detailed in Table 1. The blended oil was prepared through continuous magnetic stirring at 1000 rpm for 2 h to ensure homogeneity. Next, the density (ASTM D1480-21) and kinematic viscosity (ASTM D2983-22) were measured. The viscosity data were subsequently used to determine the viscosity index (VI) (ASTM D2270), enabling comparison of the temperature–viscosity characteristics of the formulated blend with those of the SAE 40.

Lubricant	Coconut oil (mL)	PO-TMP (mL)	SAE 40 (mL)
C100	100	0	0
C75	75	25	0
C0	0	100	0
SAE 40 (benchmark oil)	0	0	100

Table 1: List of tested oils, including the blend of PO-TMP and coconut oil

2.2 Journal bearing setup and performance evaluation

A journal bearing test rig (Figure 1) was employed to represent crankshaft bearing operation under hydrodynamic lubrication. General journal and bearing specifications are listed in Table 2. Six pressure and temperature sensors were circumferentially positioned at 105°, 135°, 165°, 195°, 225° and 255° to monitor the lubricant film around the bearing clearance, while friction torque was measured using a load cell and recorded through a data acquisition system. Experiments were conducted at rotational speeds of 200, 800, 1400, and 2000 rpm under a constant radial load of 10 N, where this speed range simulated hydrodynamic lubrication behaviour during engine start-up, moderate operation and high-shear regimes. The load-carrying capacity (LCC) was analytically determined from the pressure distribution using the half-Sommerfeld boundary assumption (Eq. 1), while the minimum oil film thickness (OFT) was obtained from the geometrical film thickness relation governed by eccentricity ratio, radial clearance and attitude angle (Eq. 2)

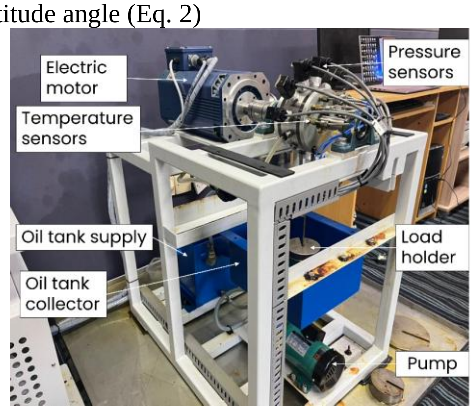

Figure 1: Journal bearing test rig coupled with 10 N radial load.

Parameter	Description
Journal and bearing material	Stainless steel 304
Journal diameter	99 mm
Bearing diameter	100 mm
Bearing length	50 mm
Radial clearance	0.5 mm
Length-to-diameter ratio	0.5

Table 2: General specification of journal and bearing

$$w_r = \frac{\eta_o \omega_b r_b b^3}{4c^2} \frac{\varepsilon}{(1-\varepsilon^2)^2} [16\varepsilon^2 + \pi^2(1-\varepsilon^2)]^{\frac{1}{2}} \quad (1)$$

$$h = c(1 + \varepsilon \cos\phi) \quad (2)$$

where w_r – resultant load, η_o – dynamic viscosity, ω_b – angular speed (rad/s), r_b – bearing radius, b – bearing width, c – radial clearance, ε – eccentricity ratio, h – oil film thickness, ϕ – attitude angle

3 Results and Discussion

3.1 Friction behavior at various shaft speeds

The friction in response to variations in the rotational shaft speed are depicted in Figure 2. It clearly shows that the coefficient of friction (COF) increases with increasing rotational speed, consistent across all tested lubricants, as reported in previous findings (Kasolang et al., 2012; Zulhanafi et al., 2020; Norazman et al., 2024). Hence, the highest COF of all tested lubricants was recorded at 2000 rpm. Moreover, at a fixed load of 10 N, increasing the rotational shaft speed from 200 to 800 rpm led to a 20% increase in the average COF across all tested lubricants, and a more than 600% increase when increased to 2000 rpm. Even though the increase in rotational speed should lead to an increase in the oil film pressure and therefore lower the COF, opposite trend was observed. At higher rotational speeds, changes in viscosity, shear rate, and heat generation of the lubricant occurred. These changes may have affected the ability of the lubricant to maintain a stable and effective film between the contacting surfaces, resulting in higher COF. Blend C75 demonstrated notable COF reduction from both individual vegetable oils at all rotational speeds. At the highest rotational speed, C75 maintained COF of below 0.7 while the rest of the tested lubricants, including SAE 40, ranged with COF of 0.8–1.0.

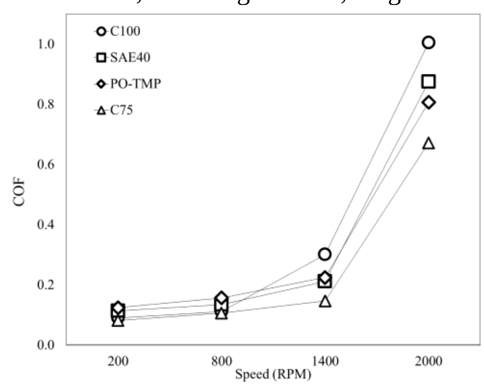

Figure 2: COF of different lubricants at 10 N static load with respect to speed.

It is observed from Figure 3 that across the speed range, at least one of the tested vegetable oil-based lubricants exhibited a lower COF than mineral oil SAE 40, which is attributed to the naturally lower viscosity of vegetable oils compared to mineral oils (Katpatal et al., 2020). The COF behavior of coconut oil reflected its low VI (219.9). Lower COF than SAE 40 was only observed at 200 and 800 rpm, where the relatively lower operating temperature allowed stable hydrodynamic lubrication to be maintained. Among the tested vegetable oil-based lubricants, coconut oil possessed the lowest kinematic viscosity (22.08 mm^2/s at 40°C). This lower viscosity promoted easier flow and reduced shear resistance at low speeds, contributing to lower friction. However, at higher speeds, the viscosity became insufficient to sustain stable surface separation under increasing thermal and shear effects, resulting in a deterioration of friction performance. Coconut oil's COF was also the overall worst when the journal bearing operated at 1400 and 2000 rpm. It is the only tested lubricant to reach a COF of 1.0. PO-TMP has the highest kinematic viscosity (36.7 mm^2/s at 40°C) among the vegetable oil-based lubricants. This high viscosity, however, added extra friction towards the moving surfaces and caused high COF even at low rotational speed. Only at the highest speed of 2000 rpm did PO-TMP show COF improvements compared to mineral oil, since the higher operating temperature provides the lubricant with sufficient viscosity to allow surfaces to move freely. The COF observations from Figures 2 and 3 confirmed that the combination of coconut oil and PO-TMP at 75 vol% and 25 vol%, respectively, effectively improved kinematic viscosity (25.53 mm^2/s at 40°C) and VI (265.8), and consequently reduced COF.

Respective to SAE 40, the COF reduction was averaged at 25%. The synergistic combination of saturated fatty acids from coconut oil with long-chain fatty acids, and the improved thermal stability from PO-TMP, facilitated the maintenance of lubricant film layer on the contacting surfaces.

3.2 Hydrodynamic pressure response under varying speeds

The significant effect on the pressure profile from blend C75 indicates that blending PO-TMP with coconut oil at a 25:75 volumetric ratio enhanced both VI and pressure performance in the journal bearing. Figure 4 reveals that vegetable oil-based lubricants had a higher maximum pressure than mineral oil because they possess a high VI, so they retain more of their viscous resistance even as the bearing heats up at higher speeds (Reddy et al., 2014). SAE 40 showed high sensitivity to temperature changes. This quick reduction in viscosity reduces the lubricant's resistance to the journal's rotational motion, limiting the hydrodynamic pressure it can generate. Lubricants like C75 (VI = 265.8), which maintain a more stable viscosity over changing temperatures, provide greater resistance to shaft motion, allowing the hydrodynamic effect to develop higher maximum pressures.

The vegetable oil–based lubricants exhibited kinematic viscosities that were, on average, 71% lower than SAE 40. As the temperature increased to 100 °C, the kinematic viscosity of SAE 40 decreased, reducing the kinematic viscosity gap between the two lubricants. At this temperature, vegetable oil–based lubricants were, on average, only 37% less viscous than SAE 40. This also reduced the difference in maximum pressure between C75 and SAE 40 at higher rotational speeds, which were associated with higher mid-plane temperatures. It was also found that the pressure that was developed along the circumference of the journal did not increase with increasing speed. Similar to previous studies, in which an increase in journal speed did not have much effect on the palm mid olein and SAE 40 oil film pressure (Zulhanafi et al., 2020). A different study by Katpatal et al. (2020), however, reported that Jatropha oil mixed with ISO VG 46 increased maximum pressure with increasing speed. Katpatal explained this finding using classical hydrodynamic lubrication, in which increasing journal speed results in more lubricant being entrained through the converging section per unit time, thereby increasing flow resistance and, consequently, raising the hydrodynamic pressure. This explanation assumes a constant eccentricity ratio, in which the journal center remains at a fixed position relative to the bearing center even as speed changes. In the present study, similar to Zulhanafi et al. (2020), the system remained in hydrodynamic lubrication regime by adjusting the eccentricity ratio and film thickness as speed increased. Consequently, the maximum pressure did not increase with speed despite higher lubricant entrainment.

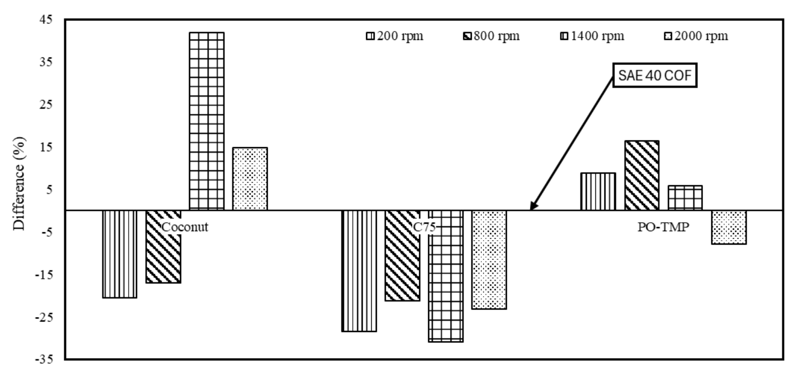

Figure 3: COF comparison with mineral oil in journal bearing at 10 N across speeds

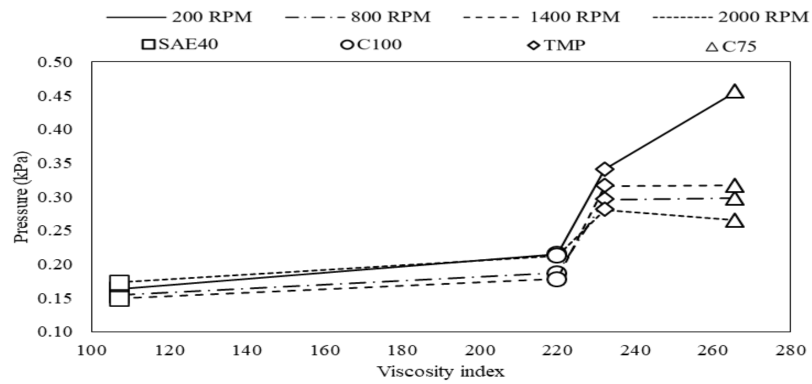

Figure 4: Maximum pressure over viscosity index of different lubricants.

3.3 Effect of lubricant temperature on hydrodynamic performance

C75 exhibited the smallest temperature increment with increasing journal speed, as summarised in Table 3. Controlling temperature rise is critical in hydrodynamic journal bearings because lubricant viscosity is strongly temperature dependent, an increase in operating temperature reduces viscosity and deteriorates bearing performance (Katpatal et al., 2020). Higher temperature has also been associated with increased frictional behaviour (Bouyer and Fillon, 2011). In contrast to SAE40, which showed the highest temperature sensitivity and rapid viscosity reduction, vegetable oil–based lubricants demonstrated superior pressure generation capability due to their higher VI (Reddy et al., 2014). The high VI of C75 (265.8) enabled the lubricant to retain sufficient viscous resistance under elevated thermal conditions, thereby sustaining hydrodynamic pressure development. Since load support in hydrodynamic journal bearings depends entirely on pressure generated through viscous shear and wedge action, the ability to maintain viscosity stability despite the operating temperature increment at higher journal speeds is therefore essential to preserve effective surface separation and minimise friction (Gahir and Matharu, 2023). At 200 rpm, the maximum temperature was recorded at 225°, corresponding to the location of peak pressure. This behaviour is attributed to increased fluid friction within the converging region (Zulhanafi et al., 2020). Similar findings were reported in comparative studies of palm-based lubricants and SAE 40, where palm mid olein exhibited lower temperature rise due to better thermal resistance and viscosity stability (Zulhanafi et al., 2020; Reddy et al., 2014).

Initial speed (rpm)	Final speed (rpm)	Temperature increment (°C)			
		C100	C75	PO-TMP	SAE 40
200	800	5.696	4.622	4.721	7.435
800	1400	4.486	2.703	3.788	8.104
1400	2000	5.327	5.299	7.408	8.109

Table 3: The temperature increment yielded by different lubricants as journal rotates at rising speed.

3.4 Effect of viscosity and rotational speed on oil film thickness

Figure 5 exhibited that increasing journal speed resulted in the formation of a thicker lubricant film due to higher entrainment velocity, which promotes greater surface separation. It should be noted that the analytical OFT values were obtained based on the assumption where lubricant viscosity is treated as constant for each evaluated operating condition. Therefore, the calculated OFT represents the lubricant's capability to generate load-supporting pressure at a representative operating viscosity, rather than capturing the continuous viscosity changes occurring during the full experimental bearing cycle.

Additionally, the results clearly demonstrate that lubricant viscosity plays a critical role in determining OFT behaviour, as described by the Reynolds equation. It has been discussed in the previous section that elevated lubricant temperature reduces the viscosity, thereby weakening the hydrodynamic pressure developed within the converging lubricant wedge. Higher-viscosity lubricants provide greater resistance to shear deformation, enabling more effective pressure build-up and improved surface separation. This behaviour is consistent with findings reported by Norazman et al. (2024), who observed enhanced load support with higher-viscosity palm-based lubricants. Conversely, reduced viscosity weakens the continuity and stability of the lubricant wedge, increasing the susceptibility to film thinning and mixed lubrication conditions, particularly under dynamically varying load distributions (Gui et al., 2011). Among the evaluated vegetable-oil-based lubricants, the sequence of minimum oil OFT followed the order: coconut oil < blend C75 < PO-TMP, which closely reflects their viscosity characteristics. Coconut oil exhibited the lowest viscosity due to its dominance of medium-chain saturated fatty acids (C8–C12), leading to weaker intermolecular cohesion and reduced resistance to flow. In contrast, PO-TMP demonstrated higher viscosity, attributed to its longer hydrocarbon chain structures and stronger molecular interactions. These characteristics enhance internal shear resistance and promote greater hydrodynamic pressure generation, enabling PO-TMP to sustain a thicker lubricant film under identical operating conditions. The intermediate minimum OFT response observed for blend C75 constitutes a key outcome of the present study. This trend indicates that the blend provides sufficient viscous resistance to sustain an adequate hydrodynamic film while avoiding excessive shear-induced drag associated with high viscosity lubricants. The balanced molecular structure of C75, combining long-chain fatty acid components from PO-TMP with the glycerol-based characteristics of coconut oil, contributes to improved viscosity–temperature stability. From a hydrodynamic lubrication perspective, the observed OFT reflects an optimised capacity to generate load-supporting pressure within the lubricant wedge, resulting in stable surface separation. Consequently, the performance of C75 suggests the existence of an optimal viscosity in which sufficient OFT can be maintained to minimise the risk of film thinning, particularly under dynamically changing operating conditions. The blending strategy employed in C75 highlights the potential of tailoring fatty-acid molecular structure and viscosity behaviour to enhance lubrication performance without relying on viscosity-enhancing additives.

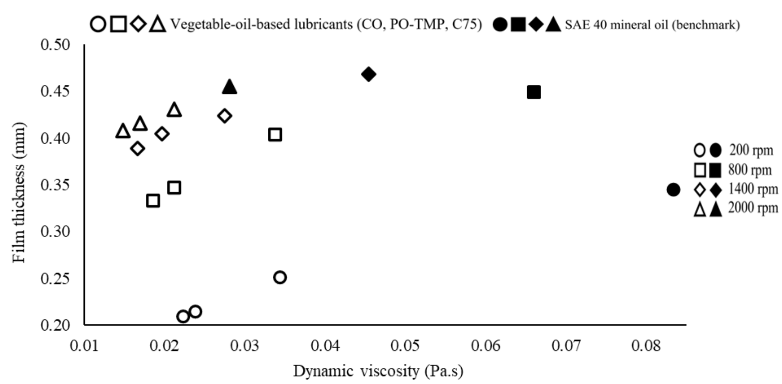

Figure 5: Minimum oil film thickness vs viscosity at varying journal speeds

3.5 Influence of hydrodynamic pressure on load-carrying capacity

Figure 6 shows that LCC increased with rising local lubricant pressure, consistent with classical analytical solutions of journal bearing performance (Raimondi and Boyd, 1958; Rasep et al., 2021). This relationship confirms that the capability of a lubricant to sustain hydrodynamic pressure is a governing factor in load support. In hydrodynamic journal bearings, parameters including lubricant viscosity, rotational speed and eccentricity ratio collectively determine pressure generation and therefore influence LCC (Norazman et al., 2024). The present experimental observations therefore support hydrodynamic lubrication theory by demonstrating that locally measured pressure development corresponds with analytically predicted load capacity. A notable feature in Figure 6 is the relatively stable and higher LCC exhibited by the C75 blend over a wider pressure range compared with SAE 40. This indicates improved pressure sustainability and effective load support behaviour. Despite being formulated as an additive-free vegetable oil blend, C75 achieved LCC performance comparable to mineral oil. Similar trends have been reported where modified vegetable oils displayed enhanced pressure generation and load capacity due to favourable viscosity and oxidative stability characteristics (Norazman et al., 2024). Such improvements are often associated with stronger molecular polarity, promoting more stable lubricant film formation and reducing the likelihood of surface interaction. Overall, the findings suggest that blending coconut oil with PO-TMP enhances hydrodynamic pressure development and contributes to more stable LCC behaviour, highlighting the potential of optimized biodegradable lubricants as practical alternatives for journal bearing applications.

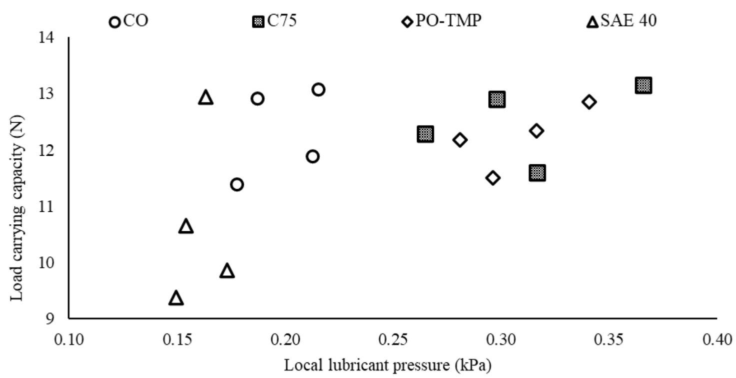

Figure 6: Load-carrying capacity as a function of measured local lubricant pressure

4 Conclusion

This study demonstrated that blending palm oil-based TMP ester with coconut oil can enhance hydrodynamic lubrication performance without chemical additives. The C75 blend showed increased viscosity and a high viscosity index (265.8), providing improved viscosity–temperature stability and enabling consistent hydrodynamic pressure development. Consequently, C75 reduced the coefficient of friction by 25% relative to mineral oil and exhibited the lowest bearing temperature rise during operation. Analytical evaluation further confirmed that the blend maintained sufficient minimum oil film thickness and achieved load-carrying capacity comparable to SAE 40 mineral oil. These findings indicate that complementary vegetable-oil blending offers a practical approach for environmentally compatible journal bearing lubricants.

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