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Frictional behaviour of trimethylolpropane (TMP) oleate at different regimes of lubrication

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ABSTRACT

Trimethylolpropane (TMP) esters possess good frictional properties, portraying good potential as alternative bio-lubricants. However, the most common TMP ester, which is TMP oleate, is found to be widely used only for hydraulics application. Therefore, to explore its potential usage in automotive applications, the present study determines the frictional behaviour of TMP oleate at different operating lubrication regimes. Friction forces for TMP oleate lubricated conjunction, consisting of cast iron pin being rotated against a stainless-steel disk, are measured using a pin-on-disk type tribometer. The applied normal load is 3 kg while the disk rotational speed is varied between 20 rpm and 2000 rpm. Along fluid film and boundary lubrication regimes, the average coefficients of friction for TMP oleate lubricated conjunction are measured to be 0.074 and 0.101, respectively. Along fluid film lubrication regime, with the maximum Hertzian pressure being calculated to be 1.1 GPa, the contact is expected to be

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elastohydrodynamic in nature. Transitions of lubrication regimes, similar to the classical Stribeck curve, are also observed between sliding velocities of 1.8 m.s^{-1} and 2.7 m.s^{-1}. Hence, the measured Stribeck curve demonstrates the potential use of TMP oleate for automotive applications, where a large range of operating lubrication regimes is required.

Keywords: *Trimethylolpropane; Lubrication; Friction; Tribometer.*

Introduction

Fossil fuel-based lubricants have been proven to be extremely effective in prolonging the service life span of machine elements, especially for the transportation sector. However, these lubricants are non-degradable and could pose a serious threat to the environment if not properly handled. Hence, in line with the principles of the Green Tribology concept, it is imperative that biodegradable lubricants (e.g. vegetable oil based) be used whenever possible to avoid environmental contamination.

Synthetic oleochemical esters, such as trimethylolpropane (TMP) esters, are known to be biodegradable and environmentally friendly [1, 2]. These esters are often deemed to be suitable for industrial and automotive applications [3]. However, to date, TMP esters are only found to be commonly used as hydraulic fluids in industrial applications [4, 5]. As an example, Yunus et al. measured the tribological performance of palm oil and palm kernel derived TMP esters to be comparable to commercial hydraulic fluids [6]. Numerous research works have been conducted to further explore the potential of TMP esters to be used for automotive applications. Zahid et al. characterised the tribological behaviour of palm oil derived TMP esters and found that this type of TMP ester has a much better load carrying capacity than polyalphaolefin (PAO), which is one of the commonly used synthetic base oil for automotive lubricants [7]. More recently, Hamdan et al.studied the nano-tribological properties of palm oil derived TMP esters using Lateral Force Microscopy (LFM) [8]. They also observed that palm oil derived TMP esters exhibit good load carrying capacity, which could be beneficial in keeping opposing surfaces in relative motion apart by forming thicker fluid films, possibly encouraging hydrodynamic lubrication regime.

In order to characterise a lubricant for use in automotive applications, especially in passenger cars, it is essential to be able to determine the tribological performance of the lubricant at different lubrication regimes. This is because in a typical passenger car, lubrication systems operate under a wide range of lubrication regimes, as depicted in Figure 1 using the classical Stribeck curve. This requires tribological knowledge on the performance of the lubricant from fluid film to mixed and boundary lubrication regimes.

Such method of characterisation approach based on Stribeck curve are not commonly reported in literature for TMP esters. Therefore, the present study intends to determine the frictional properties of TMP oleate (chemical structure given in Figure 2) at different lubrication regimes. This is in hope that the obtained frictional characteristics of such TMP ester would be able to shed more light into its potential for application in the automotive industry to reduce the reliance on mineral based lubricants.

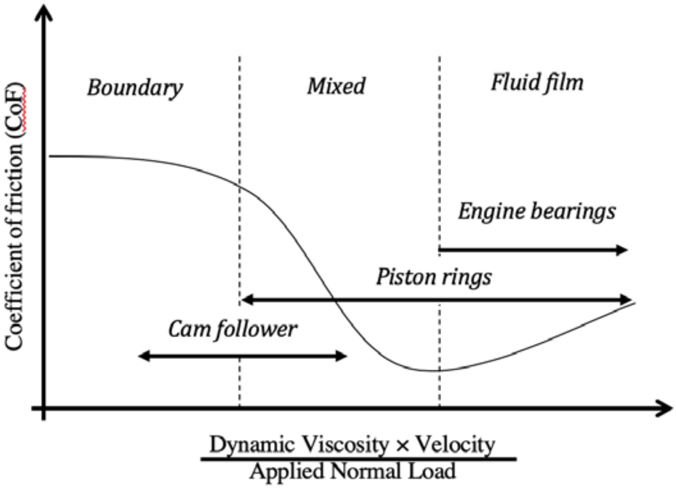


Figure 1: Regimes of lubrication based on Stribeck curve

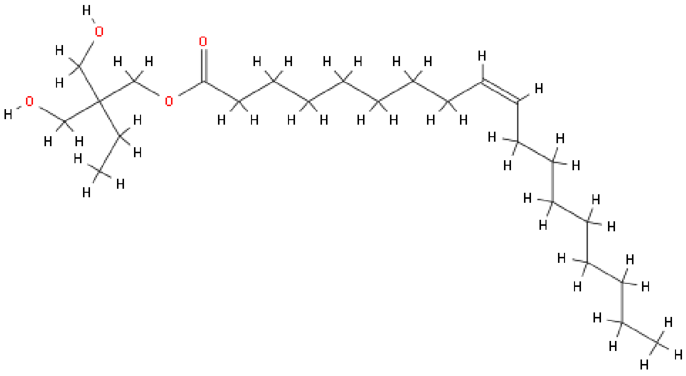


Figure 2: Chemical structure for TMP oleate ($C_{24}H_{46}$) (generated from http://www.chemspider.com)

Experimental Approach

In the present study, a commercially available TMP oleate is obtained. Friction tests for TMP oleate lubricated contact is then conducted using a pin-on-disk type tribometer that is compliant to the standard of ASTM G99. Figure 3 illustrates the schematic diagram of the pin-on-disk tribometer setup used for the present study. As shown in Figure 4, a 32-mm long cast iron pin with a spherical end cap of 10 mm diameter is rotated against a stainless-steel disk for 20 sets of speed values between 20 rpm and 2000 rpm. The selected wear track for this friction test is 20 mm, giving sliding velocities in the range of 0.044 m/s and 4.4 m/s. The applied normal load used for the current study is 3 kg.

For each of the speed tested, the friction test is conducted for three and a half minutes, during which the measured friction force is also ensured to reach steady state before proceeding to the next test condition. This procedure is similar to the method proposed by Kovalchenko et al. [9] in determining lubrication regime transition for lubricated contacts. It is also to note that TMP oleate is continuously supplied through a pump to the pin/disk conjunction to ensure a fully flooded contact as suggested by Hamdan et al. [10]. At the beginning and end of the friction tests, kinematic viscosity of the studied TMP oleate is measured at different operating temperatures. This is to determine whether there is any form of significant rheological property change in the tested lubricant after the friction test, which by then could already have accumulated up to a total of 2,583 m in sliding distance.

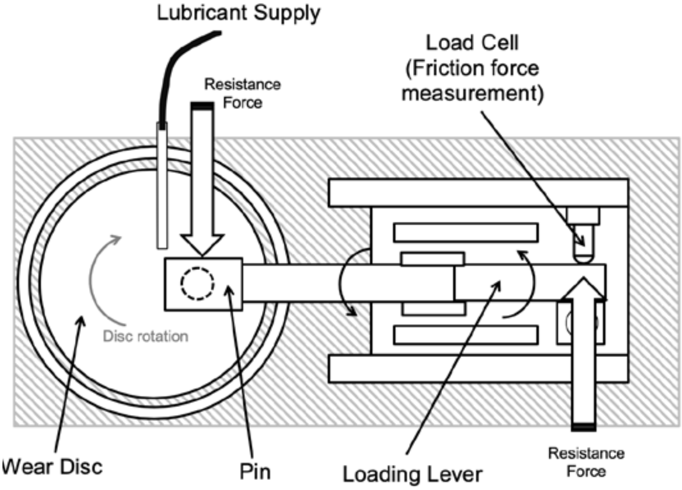


Figure 3: Pin-on-disk type tribometer setup

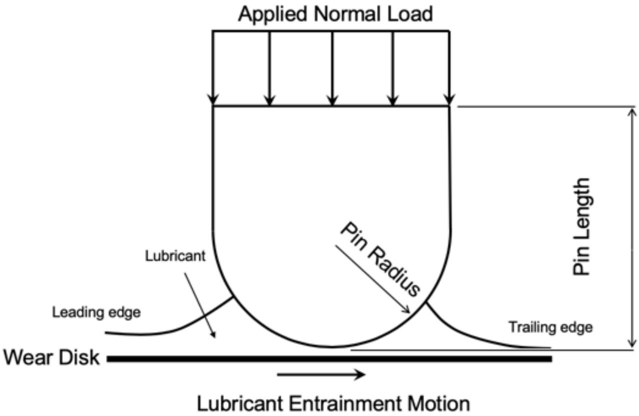
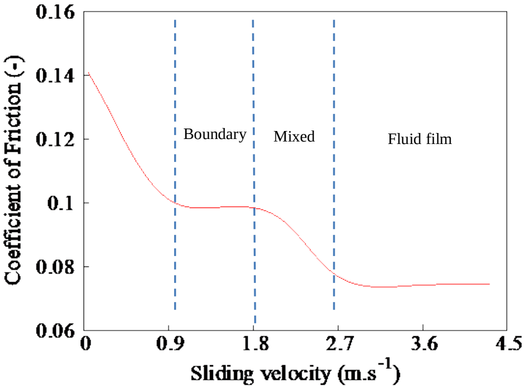


Figure 4: Pin/disk tribological conjunction investigated

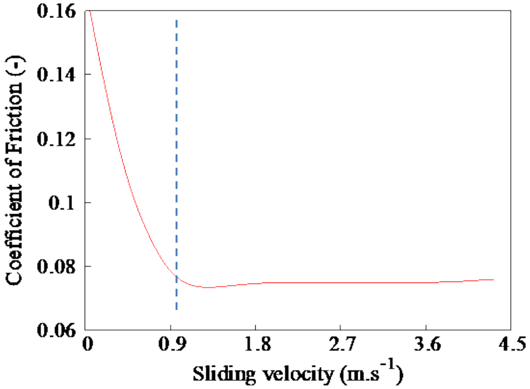
Results and Discussions

The emphasis of the present study is to determine the frictional behaviour of TMP oleate at different lubrication regimes. Figure 5(a) illustrates the coefficient of friction (CoF) measured using the pin-on-disk type tribometer for TMP oleate at an arbitrary applied normal load of 3 kg. The CoF is measured to be approximately 0.138 at 0.044 ms^{-1} and then reduce to 0.101 at 0.9 ms^{-1}. This shows that at 3 kg load, boundary film formed by TMP oleate fails to hold at sliding velocities below 0.9 ms^{-1}, which leads to possibly direct surface-to-surface interaction. With increasing sliding velocity up to 0.9 ms^{-1}, the reduction of CoF is observed. This is believed to be due to more TMP oleate molecules being entrained into the contact conjunction, leading to the build-up of a more stable boundary film. From 0.9 ms^{-1} to 1.8 ms^{-1}, the CoF value remains fairly constant at an average of 0.101, suggesting boundary lubrication regime [11]. Between 1.8 ms^{-1} and 2.7 ms^{-1}, the investigated TMP oleate lubricated conjunction is shown to go through mixed lubrication regime, where the contact experiences a drop in CoF from 0.101 to approximately 0.074.

From 2.7 ms^{-1} sliding velocity onwards, the measured average CoF of 0.074 indicates fluid film lubrication regime [11]. To determine the type of fluid film lubrication regime along this region, the maximum Hertzian pressure is first calculated. At 3 kg load, the maximum Hertzian pressure calculated is approximately 1.1 GPa (assuming Poisson’s ratio and modulus of elasticity for cast iron to be 0.21 and 110 GPa and for stainless-steel to be 0.27 and 210 GPa, respectively). With such range of contact pressure and also measured CoF value, it could be surmised that the observed fluid film lubrication regime is of elastohydrodynamic in nature [11]. The observed transitions of lubrication regimes are similar to the classical Stribeck curve. However, when compared with the commonly used synthetic base oil in engine lubricants, polyalphaolein (PAO), it is measured in Figure 5(b) that PAO only exhibits fluid film lubrication regime at sliding velocities above 1 ms^{-1}. For velocities below 1 ms^{-1}, it is observed that the fluid film began to rupture, failing to exert any form of boundary lubrication, leading to significant surface asperity interactions that generates higher friction. This is expected as additive packages are often required for such base oil to achieve the desired boundary lubrication properties.



(a) TMP Oleate



(b) Polyalphaolein (PAO)

Figure 5: Measured coefficient of friction (CoF) for TMP oleate for 3 kg applied normal load at varying sliding velocities

Once the friction tests are completed for all sliding velocity conditions, the kinematic viscosity of the investigated TMP oleate is measured from 298 K to 373 K. The change of kinematic viscosity for TMP oleate with temperature after the friction test is illustrated in Figure 6. These viscosity values are also compared with in the values before the friction tests are conducted. It is shown that no significant viscosity change (<10% change) is observed even after the tests, which already accumulated up to 2,583 m sliding distance usage.

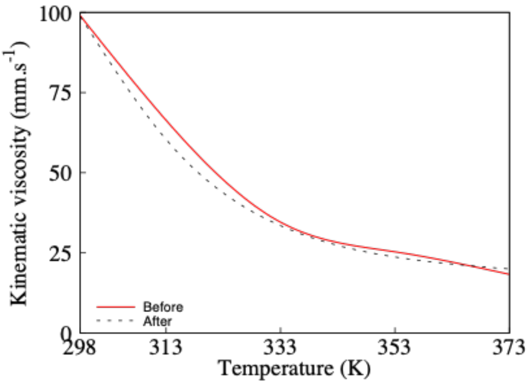


Figure 6: Measured kinematic viscosity of TMP oleate at different temperatures (Before and after friction test)

Finally, the wear scar diameter on the cast iron pin is optically measured and given in Figure 7. The amounted wear volume on the pin after the friction tests for TMP oleate lubricated conjunction is determined to be approximately 11.75×10^{-3} mm^3. On the contrary, as a result of a non-existent boundary lubrication film formation, the wear volume on the pin lubricated with PAO is measured to be 213.71×10^{-3} mm^3. Such wear behaviour comparison indicates that TMP oleate does have great potential as an alternative to existing mineral oil-based lubricants.

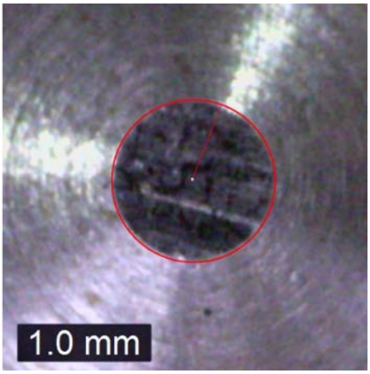


Figure 7: Measured wear scar diameter on cast iron pin after friction test

Conclusions

In the present study, frictional behaviour of TMP oleate at different lubrication regimes has been measured using a pin-on-disk type tribometer. The results reported in this study demonstrates the tribological behaviour of TMP oleate when used as a lubricant under a cast iron/stainless steel conjunction at different operating lubrication regimes. It is observed that Stribeck-like CoF trend is measured for applied normal load of 3 kg. The average CoF values along fluid film lubrication and boundary lubrication regime are 0.074 and 0.101, respectively. The lubrication regime transition, which is also known as mixed lubrication regime, is measured to occur between sliding velocities of 1.8 $m.s^{-1}$ and 2.7 $m.s^{-1}$. The capability of TMP oleate in operating along a large range of lubrication regimes alongside with its positive wear characteristics demonstrates the potential of this TMP ester to be used as an alternative to mineral oil-based lubricants for automotive applications.

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