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Improvers of Pressure-Viscosity Coefficients of Two-Phase Liquid-Solid Lubricants

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Abstract. The prediction of the pressure-viscosity coefficient, α , is one of the most important properties for Elastohydrodynamic lubrication (EHL) condition; thereby, the need for improvers to aid its measurement and performance is necessitated. This article presented two phase liquid – solid lubricants of PTFE and MoS₂ solution in SAE 30 oil at varying compositions. The lubricants tested are SAE #30, SAE #30 plus PTFE and SAE #30 plus MoS₂. High-pressure viscosity measurement was done at pressure up to 1.5 GPa and temperature range at 20°C to 100°C. Viscosity indices are calculated from the measured viscosity at 40 and 100 °C using ASTM D 2270. However, an attempt to predict α for the blended lubricants using the relationship between pressure-viscosity coefficient and Walther's logarithm of kinematic viscosity at atmospheric pressure was used. The pressure-viscosity coefficient of two phase liquid – solid lubricants were successfully predicted and the influence of solid lubricant concentration, and temperature on the lubricants viscosity were determined, and compared with SAE #30 oil. The properties and viscosity of mixtures obtained are optimal lubricant factors which optimize the measurement and performance of the highest EHL pressure-viscosity coefficient of the mixtures, and also enhance the better chance to improve the lubrication of machine element than the SAE #30 conventional engine oil.

Introduction

Failures and friction control and contributes to the daily intense research work in tribology system. Many tribological application involving lubrication film thickness, the value of the pressure-viscosity coefficient is an important factor because it reflects the extent of “thickening” that occurs under high hydrodynamic loads. An incorrect way of determining it will lead to a gross errors and high economic cost. In the conditions of EHL, the lubricant parameter $\alpha\eta$ [1] is a parameter for the prevention of surface failure. The load parameter $\alpha\rho$ [2] is a parameter for traction control at EHL condition. This makes the role of pressure-viscosity coefficient so important for lubricants under EHL conditions. In general, α depends on the lubricant at hand, and on the pressure, temperature, and shear rate in the contact, see Bair [3]. In the advent of high temperature and pressure parameters in the EHL regime, it is necessary to employ oil viscosity index improvers or modifiers. These are PTFE and MoS₂, added to low viscosity oil for effectively thickening them as temperature increase, improving the viscosity characteristics [4]. Predicted values for α are only available for a few oils, and for conditions that differ from the given ones [5-6]. The other alternative is to perform high pressure–viscosity measurements, which is only reserved for researchers who have access to special equipment, and highly skilled persons. In view of this, most researchers' attempts to predict pressure-viscosity is done from the physical properties point of view under the atmospheric pressure whose measurement is comparatively easy [7-9]. Also, understanding the effect of temperature on the viscosity of the oil is very important [10-11] to the

prediction of the pressure–viscosity coefficient. The viscosity of fluid is known to decrease at the rise in temperature. In engines, high temperatures of the lubrication oils are required for combustion of the fuel to be achieved, and mostly very high temperatures [12-14]. Therefore, it is of prime concern and importance to determine the lubricating oils that will be viscous enough to be able to lubricate the moving parts of the engine at high temperatures without causing any severe damage to the engine part. More so, under every mechanical application, the operating temperature of the mechanical system in which the lubricating oil is to be used should be given due consideration. Because in some situations, most of the lubrication oils even start evaporating at high temperature [15-16]. Obviously, there are chances that at high temperatures the lubricating oils might lose its viscosity which will influence the pressure–viscosity coefficient, and might render the lubrication oils ineffective when subjected under use in high temperature conditions. Therefore, proper design of improving the viscosity of lubricating oils is considered in this research, this is for effective prediction of the pressure–viscosity coefficient of oils so that it can sustain the operating temperatures likely to encounter in their applications; otherwise the very purpose of using the lubrication oils will be lost [12]. In this research work, an attempt to predict pressure-viscosity coefficients with viscosity improvers for two-phase (Liquid-Solid) lubricants solution was attempted. PTFE and MoS₂, were the additives specifically used for improving the pressure-viscosity coefficients of a commercially purchased engine oil (SAE #30). PTFE belongs to the fluoropolymer family, it has a very low coefficient of friction and powerful bounds, which provide resistance to fracture and high thermal stability. PTFE is very effective at extremes of high and low temperatures and ideal in hydraulic systems subjected to load and heat. MoS₂ with particle sizes in the range of 1–100 μm is a common dry lubricant. Few alternatives exist that can confer the high lubricity and stability up to 350°C in oxidizing environments. Molybdenum disulfide is often a component of blends and composites where low friction is sought. PTFE and MoS₂ physical properties are shown in Table 1.

Materials and Method

Table 1. Individual properties of the lubricants.

| Liquid Lubricants | Viscosity mm ² /s(=cST) | | FP (°C) | PP (°C) | Density of oil, ρ (kg/m ³) | SG at 15°C | Visc-pres coeff. of oil, α m ² /N | VI |
|-------------------|------------------------------------|--------|-------------|---------|--|----------------|--|-----|
| | 40° C | 100° C | | | | | | |
| SAE # 30 | 93 | 10.8 | 228 | -20 | 850 | 0.890 | 1.6E-8 | 100 |
| Solid Lubricants | | | | | | | | |
| Solid Lubricant | Density g/cm ³ | | MOE, E(GPa) | | | Poison Ratio v | | |
| PTFE | 2.2 | | 0.5 | | | 0.46 | | |
| MoS ₂ | 5.06 | | 329 | | | 0.31 | | |

NB: FP-Flash Point; PP-Pour Point; SG-Specific Gravity; VI-Viscosity Index

The SAE 30 engine oil is used as the base and the standard lubricant for this research. Two commercially viscosity index improvers employed are Polytetrafluoroethylene (PTFE-solid) and Molybdenum disulfide (MoS₂-solid). These products were used as the undiluted improvers in preparing the dispersions used in the viscosity building study to improve the pressure-viscosity coefficient of the modeled lubricants. The experimental lubricants designs were obtained by blending the 5-1% by weight of PTFE-solid or MoS₂-solid into the SAE #30 liquid to form a mixture of liquid-solid solution. Dissolution of PTFE-solid or MoS₂-solid in SAE #30 oil was realized at room temperature with gentle shaking here and there for 30mins to obtain a homogeneous mixture. Basically, three lubricants were obtained which are SAE #30, PTFE-solid in SAE #30 and MoS₂-solid in SAE #30. PTFE and MoS₂ powders used were of particle sizes of 5 μm in SAE #30. Their basic and general individual properties are given in the Table 1. The viscosity of the sample oil was measured by the rotary viscometer. Viscosities were measured at

temperature of 21°C, 40°C, 80°C and 100°C. These measurements were carried out at ± 0.1 of all the selected temperatures which is according to the recommendation of ASTM D2270 [17].

The viscosities and densities at 21°C, 40°C, 80°C and 100°C are tabulated in Table 2 of the physical properties of tested lubricants.

Table 2. Tested Lubricants Physical Properties.

| Type of Lub. | Viscosities and Densities at 5% Solid Additives to T-2 and T-3 | | | | | | | | Specific Gravity |
|--------------|--|--------------------------|---------------|--------------------------|---------------|-----------------------------|---------------|-----------------------------|------------------|
| | 21°C | | 40°C | | 80°C | | 100°C | | SG at 15.6°C |
| | η (Pa.s) | P (kg/m ³) | η (Pa.s) | P (kg/m ³) | η (Pa.s) | ρ (kg/m ³) | η (Pa.s) | ρ (kg/m ³) | |
| T-1 | 0.205 | 890 | 0.089 | 882 | 0.038 | 875 | 0.0108 | 866 | 0.889 |
| T-2 | 0.255 | 892 | 0.093 | 886 | 0.052 | 878 | 0.011 | 869 | 0.884 |
| T-3 | 0.251 | 891 | 0.091 | 884 | 0.051 | 876 | 0.0109 | 867 | 0.886 |

The conditions of the experiments were conducted strictly at the stipulated temperatures, contact pressures and rolling speed provided at the Table 3, unless otherwise stated in the paper.

Table 3. Experimental Conditions.

| Type | Temperature °C | Contact Pressure | Rolling Speed |
|-----------|----------------|------------------|----------------|
| T-1 – T-3 | 20 – 100 | 1 – 2.6 | 0 – 102rev/min |

Thermodynamics Properties of Lubricants

Thermal characterization of lubricants were carried out, considering the most important thermal properties of lubricants which are specific heat, thermal conductivity and thermal diffusivity. These three parameters are essential in assessing heating effects in lubrication, e.g., the cooling properties of the engine oil, the operating temperature of the surfaces, ability of the oil to transfer heat from the engine, etc. These are also very important in bearing design. The measurements were obtained as a function of temperature using standard ASTM methods. The specific gravity was measured at 15.6 °C for all the lubricants and shown in Table 2. The specific heat capacity and thermal conductivity were measured using standard ASTM D 3947 and ASTM D 2717 respectively and have been described in more details in [18]. They have been measured using the transient hotwire method [18]. The measurements were carried out under isothermal condition at an atmospheric pressure and at designated temperatures, 21°C, 40°C, 80°C and 100°C. The heat transfer analysis of the specific heat capacity and thermal conductivity measured were used to predict the thermal diffusivity by calculation. The standard formula used is stated in equation (1) below with the standard units as m²/s. The specific gravity, specific heat capacity, thermal conductivity and thermal diffusivity obtained were illustrated in graphs as shown in the Figures 1 to Figure 3.

$$\chi = \frac{K}{\rho\sigma} \quad (1)$$

where: χ = is the thermal diffusivity [m²/s];

K = is the thermal conductivity [W/m°C];

ρ = is the density [kg/m³];

σ = is the specific heat [J/kg°C].

EHL Pressure-Viscosity Coefficients

The pressure–viscosity coefficient is an indispensable property in the elastohydrodynamic lubrication contacts. These contacts are often found in the engine systems such gears, cams, etc. The commonly used formula is the Barus type that is equivalent to the Hamrock, 1994 [19] and Fein, 1997 [20] shown in equation (2) below:

$$\alpha_{EHL} = \left\{ \int_{\infty}^{\infty} \left[\frac{\mu_0 dP}{\mu} \right] \right\}^{-1} \quad (2)$$

The α_{EHL} pressure–viscosity coefficient can easily be estimated by entering the Figure in Fein’s [20] data handbook with the pressure–viscosity index Z from Table in Fein’s [20] data handbook, in addition with the viscosity μ_0 at atmospheric pressure and at the designated temperature. Fein [20] summarized the work of Roelands’ [21] calculations in Equation (2) which is adequate for predicting α_{EHL} since the precision of most EHL equations are influenced by uncertainty about lubricant film temperature and other factors [20]. In this research, the values of α_{EHL} pressure–viscosity coefficient was determined by Equation (3), involving viscosity μ_0 (pa s) at atmospheric pressure and Roelands’ pressure–viscosity index Z from Equation (4) of Hamrock [19].

$$\alpha_{EHL} = Z \left[5.1 \times 10^{-9} (\ln \mu_0 + 9.67) \right] \quad (3)$$

$$Z = [7.81(H_{40} - H_{100})]^{1.5} (F_{40}) \quad (4)$$

where:

$$H_{40} = \log(\log(\mu_{40}) + 1.200)$$

$$H_{100} = \log(\log(\mu_{100}) + 1.200)$$

$$F_{40} = (0.885 - 0.864H_{40})$$

Viscosity Index

The viscosity index is a random number signifying the result of change of temperature on the kinematic viscosity of oil. A high viscosity index implies a relatively small change of kinematic viscosity with temperature. The viscosity index of oil is calculated from its viscosities at 40 and 100°C. The procedure used for the calculation is given in ASTM Method D 2270-74 for Calculating Viscosity Index from Kinematic Viscosity at 40 and 100°C. The equations used were as follows:
For Oils of 0 to 100 VI

$$U = L - [(VI/100)(L-H)] \quad (5)$$

For Oils of 100 VI and greater

$$U = \text{antilog} [\log H - N \log Y] \quad (6)$$

where

Y = kinematic viscosity of oil in centistokes at 100°C.

L = kinematic viscosity in centistokes at 40°C of an oil of 0 viscosity index and having the same kinematic viscosity at 100°C as the oil whose viscosity index is to be calculated.

H = kinematic viscosity in centistokes at 40°C of an oil of 100 viscosity index, and having the same kinematic viscosity at 100°C as the oil whose viscosity index is to be calculated.

U = kinematic viscosity in centistokes at 40°C to be listed in the body of the table. When the tables are being used in the normal manner, this is also the kinematic viscosity at 40°C of the oil whose viscosity index is being determined.

$$N = \log [0.00715 (VI - 100) + 1] \quad (7)$$

Therefore the:

$$VI = \frac{(\text{anti log } N) - 1}{0.00715} + 100 \quad (8)$$

The kinematic viscosities at 40°C in the table were tabulated to four significant figures. The viscosity index values were carefully calculated by the Equation 8 and the values are tabulated in Table 4.

Table 4. Viscosity Index.

| Type Lubricants | 40°C | 100°C | VI |
|------------------------------|---------|--------|---------|
| T_1 (No additives) | 100.907 | 11.547 | 100.335 |
| T_2 (5% PTFE) | 105.204 | 12.658 | 155.621 |
| T_3 (5% MoS ₂) | 102.941 | 12.558 | 154.510 |

Normal laboratory practices should not be expected to provide significantly better viscosity or viscosity index accuracy than provided in this study.

Results and Discussion

Mineral oils are produced and most commonly used as engine and machine lubricants. However, for most purposes, the viscosity of the oils are not sufficient for it likely desired condition thereby affect the pressure-viscosity coefficient. This prompted this study to improve the parameters including the viscosity, density, thermal conductivity, thermal diffusivity, viscosity index and heat capacity of lubricating oil. Specific attention has been given to the influence of temperature and additives as viscosity improvers to predict pressure-viscosity coefficient of the lubricating oils. The results of the samples tested differed considerably in viscosity, density, thermodynamics properties and viscosity index. Eventually, these parameters influences the prediction of the pressures-viscosity coefficient which are discussed in various sections below.

Thermodynamics Effect

The effect of temperature on the pressure-viscosity coefficient of oils for lubrication is so important, as a result, thermodynamics effect was considered in this analysis. The Figure 1 - Figure 3 shows the specific heat, thermal conductivity and the thermal diffusivity and their variation with temperature respectively. On one hand, it can be seen that the thermal conductivity and diffusivity decline linearly with increase in temperature. On the other hand, the specific heat increases with increase in temperature. Interestingly, the thermal conductivity exhibits a wide variation between lubricants at increase in temperature.

Possible engine losses due to inefficient cooling of the piston or bearing and other elements could be controlled by a proper lubricant with the proper ability to carry heat. The heat factor also affects the film thickness formation during sharing. The Figure 1 show the specific heat capacity of 3 lubricating oils of SAE #30 oil as $Sp T1$, 5% weight of PTFE + SAE #30 oil as $Sp T2$ and 5% weight of MoS₂ + SAE #30 oil as $Sp T3$ as a function of the temperature. The lubricating oil of all the groups have a very similar trend of heat capacity, with not so much disparity. But by ranking, the $Sp T2$ group of lubricating oil shows that the specific heat capacity is much preferred to the $Sp T1$ and $Sp T3$. The $Sp T1$ shows the slightly lower than all the sample lubricants. In this case, the higher specific heat capacity guarantee the ability for a lubricating oil to carry heat, thereby, long life of engine parts are assured. $Sp T2$ had significantly shown the highest value in heat capacity as the temperature rises. The heat capacity as an indicator to the effectiveness of lubricating oil to be as cooling agent in the engine (in the case of engine oil). The sample $Sp T1$ exhibited the higher values of heat capacity means it can absorb higher heat from the surrounding during application. This, might help to efficiently - remove heat in the engine. This might be because of the PTFE solids composition in the SAE #30 engine oil, which help in absorbing heat since it also has its own specific heat capacity.

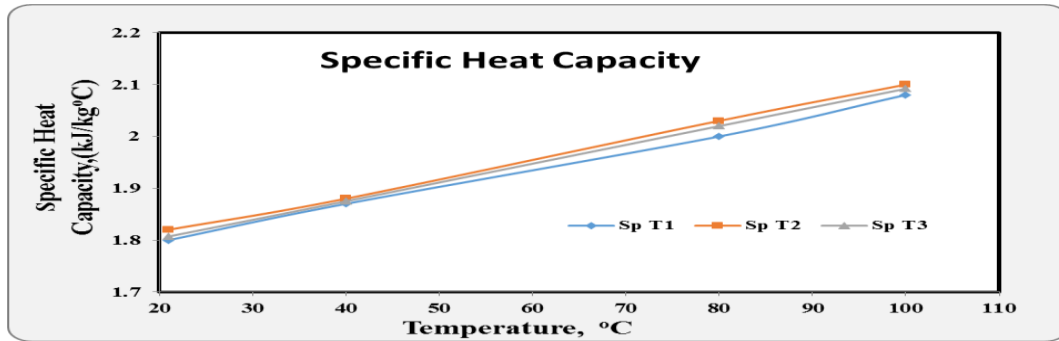


Figure 1. Specific heat capacity for the lubricants as function of Temperature.

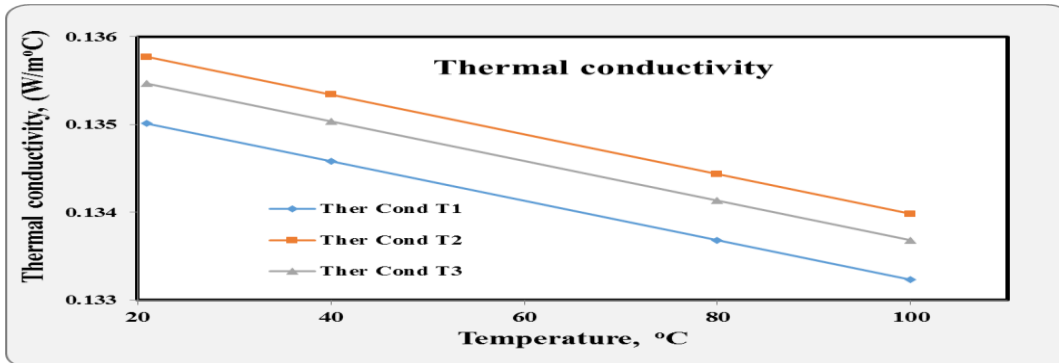


Figure 2. Thermal conductivity for the lubricants as function of Temperature.

To enable accurate modeling of pressure-viscosity coefficient in EHL point contacts, it is necessary to consider the variation in the thermal conductivity with the temperature. As shown in Figure 2, the lowest values were found for the *Ther Cond T₁* lubricant, *Ther Cond T₃* lubricant and the highest values for *Ther Cond T₂*. These samples were examined only at the stipulated temperatures (20°C, 40°C, 60°C, 80°C and 100°C) approached their boiling point. The thermal conductivity affects the heat transfer at the lubricating oil film thickness formation. The thermal conductivity of *Ther Cond T₂*, which is 5% weight of PTFE + SAE #30 engine oil lubricants is slightly higher than that of the other samples which are *Ther Cond T₁*(SAE #30 engine oil) lubricant, *Ther Cond T₃* (5% weight of MoS₂ + SAE#30 engine oil) lubricant. The thermal conductivities of these lubricating oils did show significant differences. It is therefore considered as a factor to determine the lubricating oil suitability for engines. At high conductivity, it will enhance the transfer of heat generated during film shearing between the rubbing surfaces when set in operation. Thus, the loss in viscosity due to the higher temperature will be minimal in comparison. The thermal conductivity of *Ther Cond T₂* had significantly higher values at the tested temperature than the other samples, thereby, a very vital factor worth considering to model the pressure-viscosity coefficient of the engine oil. The reason is, there is a significant pressure-viscosity coefficient dependence of the thermal conductivity because of the temperature effect at the EHL point of contacts.

Thermal diffusivity as a function of temperature increased significantly for the samples with lower thermal diffusivity. The thermal diffusivity decreases as the temperature increases. This demonstrates the ability of the lubricant to conduct thermal energy relative to its ability to store thermal energy. The results show similar trends of declination with slightly deviation of values of the thermal diffusivity at the stipulated temperatures of all the models tested. *Ther Diff T1* oil (SAE #30), which has a lower thermal diffusivity value at most of the temperatures, reaches a higher value at 40°C. The *Ther Diff T2* oil (SAE #30 + 5% weight of PTFE), which has significantly two higher values at 21°C and 100°C. The *Ther Diff T3* oil (SAE #30 + 5% weight of MoS₂) has it higher value at 80°C. Even though, the disparity of the values are extremely small yet are so significant for the modeling of the EHL pressure-viscosity coefficient of engine oil in EHL contacts. This is due to the effect of temperature at the rubbing surfaces when subjected to application. In this

experiment, the *Ther Diff T2* oil performance was outstanding because it gained two high values of a good thermal conduction and ability to store energy at both 21°C and 100°C.

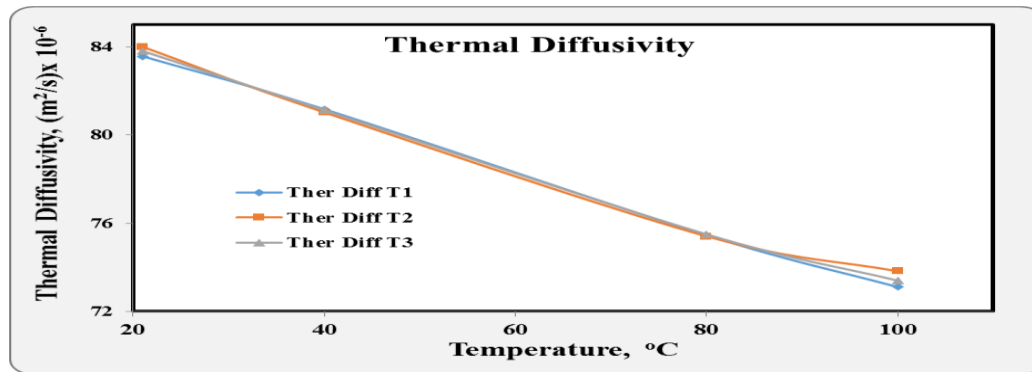


Figure 3. Thermal Diffusivity for the lubricants as function of Temperature.

Effect of Additives

In order to determine the effect of the additives, the model oils were formulated with base oil and additives concentrations from 1 percent to 5 percent. The densities and the viscosities were measured experimentally. The Figure 4 and Figure 5 shows the significant differences recorded at various percentages. From both graphs, there is a strong correlation between them at the increase of additive content in the base SAE #30 oil. The blended lubricating oils exhibited significant increase in density and viscosity at temperatures of -21°C. This is as the result of the individual additives density and viscosity adding up to the blended base oil lubricant density and viscosity. The thickening effect of the oils, which promotes the increase of the molecular weight. Therefore, at the increase of the additives in the base oil, the lubricity of the lubricating oil becomes much better. Based on this experiment, the density and viscosity are the functions of the quantity of additives added to the base oil. The higher the quantity of the additives added, the higher the density and viscosity of the model oil. The most pronounced thickening effect has been found with the PTFE additives. Much less thickening effect was found using MoS₂. The thickening effect increased with increasing molecular weight. Further increase of the quantity of the additives beyond the experimental design for this research is unknown, but future research could determine the behavior and how it will affect the pressure-viscosity coefficient of engine oils.

The two kinds of additives used were all very promising but the PTFE shows a much better performance than the MoS₂. PTFE happens to have a higher molecular weight than that of the MoS₂, thereby having higher density and viscosity. The effect of these concentrations impacted on both the density and viscosity of the oils. In the Table 2, the various concentrations were tested at the stipulated temperatures and the results shown. The variations in densities and viscosities of different oil samples with temperature shows that densities and viscosities are inversely proportional to temperature. As the heat applied to oil is increased, the lubricating potential falls until the oil completely loses its viscosity. This will then expose the engine to the risk of over heat and eventually damage. Therefore, the densities and viscosities of the model oils were all known to be functions of temperature, a well known phenomenon. The decrease of the PTFE additives to the engine oil were slightly lower than the MoS₂ additives and base oil without additives. The viscosity index of the model oil were also tabulated in the Table 5, it shows the viscosity index were improved by the additives. The results shows about 35% increase of viscosity index of the blended oils to the base oil without additives. The most pronounced additives for improving the viscosity index has been found with the PTFE, even though MoS₂ was slightly lower than the PTFE with the higher molecular weight. The effect of polymer concentration on viscosity index VI was because of the molecular weight of the polymer additive.

Understanding of the behavior of the pressure-viscosity coefficient in EHL conditions will need the investigation results of the other potential parameters such as the density, viscosity, viscosity index and the thermodynamics properties of the lubricating oil.

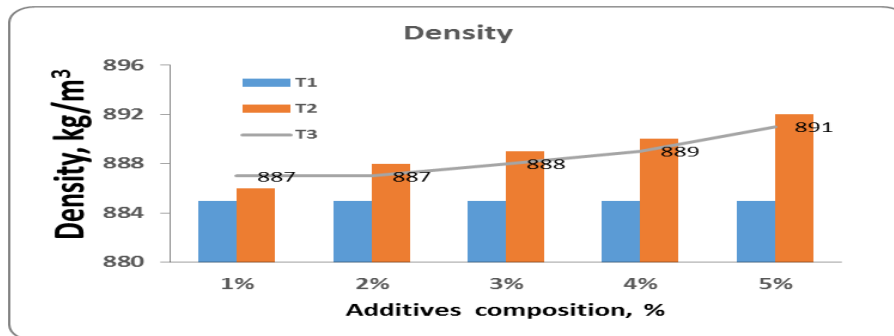


Figure 4. Density as a function of additives.

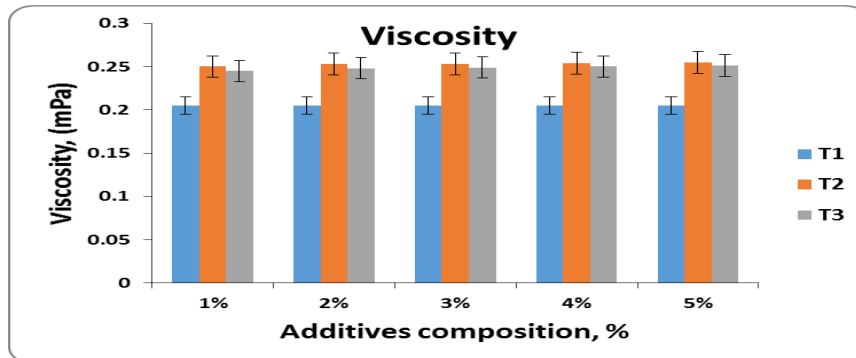


Figure 5. Viscosity as a function of additives.

EHL Pressure – Viscosity Coefficient

The prediction of the pressure-viscosity coefficient, α , requires the function of temperature as a significant factor, therefore, it was measured at these four temperatures (21°C, 40°C, 80°C and 100°C). For all the oil lubricants, α decreases, whenever the temperature increases. For example the temperature of the piston or bearing is very relevant to the operating system. At low film thicknesses at operating conditions, it is attributed to low EHL viscosity-pressure coefficient which is also influenced by the temperature. In Figure 6, the lubricating oil with PTFE additives, have all very high pressure-viscosity coefficients at the measured temperatures. MoS₂ additives had the second highest pressure-viscosity coefficient of all oils tested. The *Pr-vis T1* indicates oil without additives, while *Pr-vis T2* (PTFE) and *Pr-vis T3* (MoS₂) with additives. This shows the fact that, the additives were capable of improving the pressure-viscosity coefficient. The reason could be because of the two properties of the lubricating substances blended together for optimal behaviour as compared to just the properties of the single lubricating oil, the SAE #30. Based on this research work, the pressure-viscosity coefficient of engine oils could be predicted with the help of the right additives and right composition into the engine oil.

The model oils tested, EHL pressure – viscosity coefficients of all was noted to be a function of temperature. The results of the experiment shows the optimum model oil was the *Pr-vis T2*, which had the highest pressure – viscosity coefficients at varied temperatures.

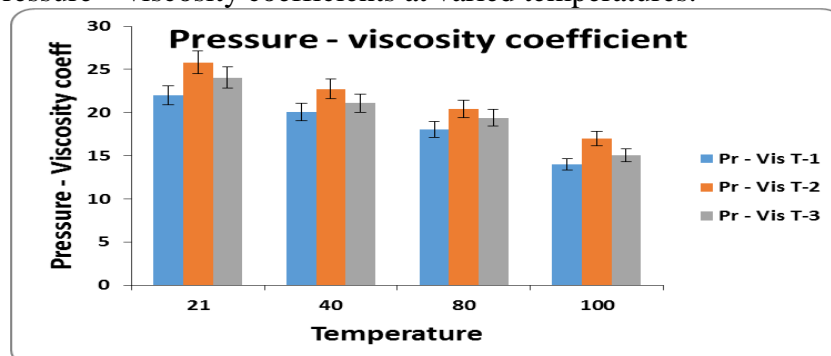


Figure 6. EHL Pressure – Viscosity Coefficients as a function of temperature.

Conclusion

The study shows that, temperature and additives have high influence on modelling the EHL pressure-viscosity coefficient of engine oils. This is because density, viscosity and thermodynamics property of solid lubricants when blended with engine oils optimize its properties, and is able to absorb heat at high temperatures. The additive molecular weights influence the densities, viscosities and the thermodynamics properties of lubricating oil sample tested. The temperature effect on additives was a good parameter for predicting the pressure-viscosity coefficient of lubricating engine oil at EHL contacts. The results show that PTFE additive is the most appropriate additive for modeling EHL pressure-viscosity coefficient for lubricants for engines; closely followed by MoS₂ additives. However, the results reveal that the base SAE # 30 oil, performed poorly against the blended lubricants due to their low densities, viscosities and thermodynamic properties at high temperatures. This could also result to fuming of the oils at higher temperatures which will destroy the properties of the lubricating oil quickly but with the solid lubricant's element in the SAE #30, heat absorption is efficient. Therefore, the correct proportion of the solid lubricating additives blended with the SAE #30 engine oil is a promising method of predicting the EHL pressure-viscosity coefficient of EHL contacts, which was fairly well supported by both experiment and empirical calculation.

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