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High-pressure behavior and tribological properties of wind turbine gear oil[†]

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Abstract

Different types of synthetic polyalphaolefin (PAO) oils and a mineral oil are considered in this study. High-pressure viscosity test was done and pressure-viscosity coefficient was measured for all sample oils. Results showed the better performance of PAO oils than the mineral oil. Authors also tested some other tribological properties such as low-temperature behavior, bulk property, frictional coefficient, and wear behavior, which are important for wind turbine gear oil. Low-temperature behavior and frictional property of PAO oils exhibited the better results. Study also showed that the prediction of low-temperature fluidity is possible using the sound velocity in the oil. Finally, the presence of polymethakrylate (PMA) absorbent in PAO oil exposed comparatively better results among all PAO oils.

Keywords: Wind turbine gear oil; Polyalphaolefin; Pressure-viscosity coefficient; Low temperature behavior; Molecular behavior

1. Introduction

Gearbox is a fundamental mechanical part of a wind turbine to generate electricity. Lubrication of the gear and bearings in the gearbox are important to improve the performance of a wind turbine. Gresham [1] reported that, at present, the weak spot in the overall design of wind turbine are its gearboxes. Low performance occurs due to poor lubrication in the gearbox and also for improper selection of lubricant. Since it is very difficult to monitor and replace the lubricant in case of wind turbine gear oil, it is very necessary to identify such lubricant, which will perform better and increase the efficiency and life of wind turbine gearbox. Usually, different types of gear oils are using for the lubrication in the gearbox. Mineral-based oils are mainly used as gear oil as they show comparatively low performance. Currently, synthetic lubricants are mostly used due to high viscosity index and low volatility. Polyalphaolefin (PAO) and Polyalkylene glycol (PAG) are newly applied lubricant in wind turbine [2]. Rudnick [3] mentioned that synthetic gear lubricants would play an increasing roll in future lubrication of high-performance gears of new processes, materials, and techniques. In this study authors considered several PAO oils in comparison to a mineral-based wind turbine oil.

High-pressure behavior of wind turbine gear oil is essential for the life of gearbox since it has to high load carrying capacity. On the other hand, the significant parameter for the prevention of damage under EHL condition is $\alpha\eta$, and for traction control is αp, where α is pressure-viscosity coefficient; η is absolute viscosity and p is the average Hertzian pressure. The α is the common parameter which is important property of wind turbine gear oil.

In addition, lubricant has some other important properties such as frictional property, low-temperature fluidity and others to get better performance, as well as increase the efficiency of wind turbine. Considering these phenomena, the authors investigated the range of operating temperature especially found the viscoelastic solid transition temperature T_{VE0} to know the low-temperature behavior. Friction under boundary lubrication was also measured by pendulum test.

2. Sample Oil

Three synthetic types of polyalphaolefin (PAO) oils and a mineral-based oil are considered in this study as lubricants used for gear lubrication. The physical properties of the sample oils are given in Table 1. PAO-B and PAO-C are the blended oils that do not affect viscous behavior of base PAO.

Table 1. Physical properties of sample oils.

Oil name	Density ρ, g/cm^3	Kinematic Viscosity ν, mm^2/s	
	15° C	40° C	100° C
Mineral-A	0.8987	315.2	24.1
PAO-A	0.8607	336.1	38.05
PAO-B	0.8574	333.2	40.76
PAO-C	0.8603	313.1	32.84

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3. Experimental

3.1 High-pressure rheology and property analysis

High-pressure viscosity of tested sample oils was measured up to 0.3 GPa and at -10 to 80° C, using the falling ball viscometer design by Saga University, the same apparatus used by Rahman [4]. Experimental results for PAO-B are plotted in Fig. 1. Pressure-viscosity coefficient α was calculated from the relation using Barus equation [5]. Pressure-viscosity coefficient α for all sample oils is tabulated in Table 2.The variation of α with viscosity is also plotted in Fig. 2, and for mineral oil it can be described by

$$\alpha = C_1 + C_2 \log_{10} \nu \tag{1}$$

where parameters C_1= -0.01 and C_2=8.43. Eq. (1) is valid up to 10^3 mm^2/s of kinematic viscosity. Eq. (2) describes α for higher than 10^3 mm^2/s of kinematic viscosity of the polyalphaolefin oils.

$$\alpha = C_3 + C_4 \log_{10} \nu \tag{2}$$

Table 2. Pressure-viscosity coefficients of sample oils.

Oil name	Pressure-viscosity coefficient α, GPa^{-1}					
	-10° C	0° C	20° C	40° C	60° C	80° C
Mineral-A	Wax	Wax	26.1	21.6	16.5	14.3
PAO-A	31.1	23.6	16.6	15.2	12.3	10.3
PAO-B	29.7	22.4	17.3	14.2	12.4	9.0
PAO-C	28.9	23.7	17.4	13.3	12.1	11.6

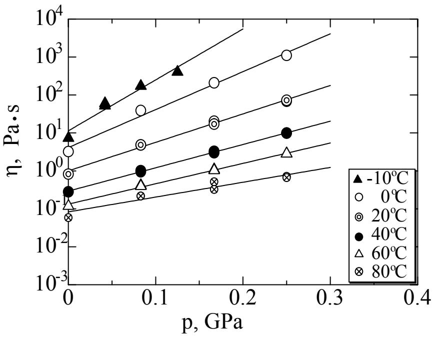

Fig. 1. Pressure-viscosity relation with temperatures for PAO-B oil.

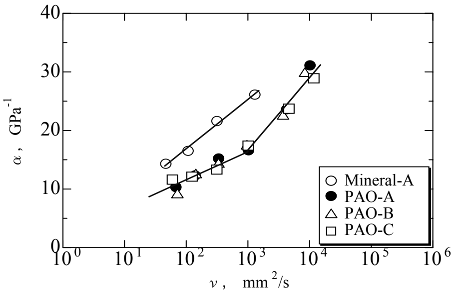

Fig. 2. α - ν relation for the tested sample oils.

Eq. (1) and (2) jointly describe the variation of pressure-viscosity coefficient for polyalphaolefin oils, where C_1=1.97, C_2=4.80, C_3= -20.41, and C_4=12.36.

3.2 Measurement of Viscoelastic Solid Transition Temperature at atmospheric pressure (T_{VE0})

Viscoelastic solid transition temperature at atmospheric pressure T_{VE0} is an important property, representing the low-temperature fluidity of lubricating oil. Experimental setup of T_{VE0} measurement is shown in Fig. 3. An air bubble is closed into a space between test fluid and a cover glass plate; its volume apparently expands as a result of contraction of the fluid by cooling. Thus, the expanded bubble generates tensile stresses along its interface under solidified condition. At the same time, the photoelastic effect appears under a dark polarized field, as shown in Fig. 4. This enables the stress analysis and estimation of mechanical properties of the solidified fluid [6]. Presence of wax has found in Mineral-A oil at –9° C. The temperature, when the photoelastic effect occurs, is known as viscoelastic solid transition temperature at atmospheric pressure T_{VE0}. Experimental results are given in Table 3.

3.3 Measurement of sound velocity to predict T_{VE0}

Sound velocity was measured using the sing-around technique. The sing-around device combines with the ultrasonic transducer and measures the supersonic wave spread time in

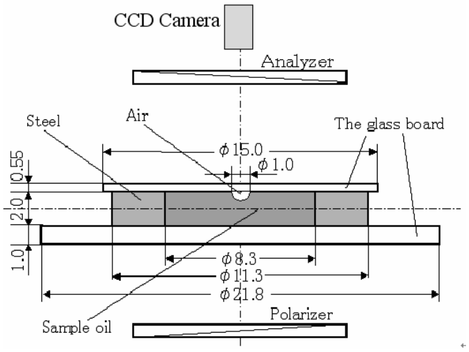

Fig. 3. Experimental set up of T_{VE0} measurement.

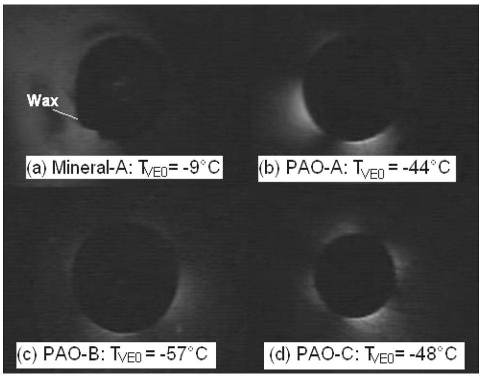

Fig. 4. Photoelastic effect appears under a dark polarized field.

the liquid sample. The basic principle of this device is that the ultrasonic wave pulse launches from the transmission oscillator, propagates in the sample, and is finally received by the reception oscillator. The sound velocity in the sample oil is calculated from the propagation time in the sample oil and the distance between the two ultrasonic transducers in the oil container. Mia et al. [7] used the same apparatus for the prediction of pressure-viscosity coefficient of lubricating oils based on sound velocity.

Calculating adiabatic compressibility or adiabatic bulk modulus from sound velocity measurement is a well-established practice. It can be determined from the Wood equation $U=(K/\rho)^{1/2}$; where U is the sound velocity (m/s), K is adiabatic bulk modulus (Pa) and ρ is the measured density (kg/m^3).

4. Results and Discussion

High-pressure viscosity as well as the pressure-viscosity coefficient of mineral-A oil at 0° C and below, could not be measures due to the wax content. It also shown clearly when lowering the temperature in T_{VE0} measurement. High pressure can be easily applied to the polyalphaolefin oils and the pressure-viscosity coefficient can be easily measured and described depending its viscosity, which is directly related to the applied pressure. Experimental results of sound velocity, adiabatic bulk modulus, and viscoelastic solid transition temperature are given in Table 3. The adiabatic bulk modulus and the viscoelastic solid transition temperature both depend on the samples bulk property. The relation between T_{VE0} and K are shown in Fig. 5. Low adiabatic bulk modulus indicates better low-temperature fluidity. PAO oils show lower K as well as the lower T_{VE0} than the mineral-based oils. PAO oils also exhibit better low-temperature fluidity as wind turbine lubrication the temperature range should be -30 to 100° C [1]. Among the PAOs, T_{VE0} for PAO-B is lowest (-57° C), with the lowest K. Investigating this phenomena, the authors observed the molecular weight distribution from the Gel Permeation Chromatography (GPC) analysis in Fig. 6. Analysis showed the different behavior of the three PAO oils. The peak top at M_w=742 for PAO-A indicates straight polyalphaolefin. Whereas for PAO-B, two peaks were found: M_w=528 for polyalphaolefin and M_w=1869 for polymethakrylate (PMA). PAO-B is a lower-viscosity grade base blended oil than PAO-A and PMA. In case of PAO-C, peak occurred at M_w=683 for base polyalphaolefin and another peak at M_w=267 for any synthetic oil. Presence of PMA in PAO-B caused the lowest T_{VE0}.

Then authors observed the frictional and wear behavior of sample oils through conventional 4-ball wear test and pendulum test. The photographic views of wear scars for a fixed ball in 4-ball wear test are shown in Fig. 7. Experiments were conducted at load 1.39 kN with 60 rpm upper rotating ball speed, corresponding to a sliding speed of 0.035 m/s for 1 h at room temperature. Low wear scar diameter has found for all sample oils, which is about 0.5 mm. PAO-B has showed the lowest wear scar. Boundary friction coefficient was again measured using the pendulum test. Comparisons of the experimental friction coefficients are shown in Fig. 8. PAO-B showed lowest friction coefficient. Muller et al. [8] found the effect of PMA in the boundary lubricating properties. They showed PMA produced a pronounced increase in film thickness at low speeds, indicative of boundary film, and also have a lower boundary friction. Hence the presence of PMA in PAO-B resulted in better wear and frictional behavior.

Table 3. Experimental Results of sample oils.

Oil name	U_{40} [m/s]	K_{40} [GPa]	T_{VE0} [° C]
Mineral-A	1433	1.813	-9
PAO-A	1405	1.667	-44
PAO-B	1413	1.608	-57
PAO-C	1405	1.667	-48

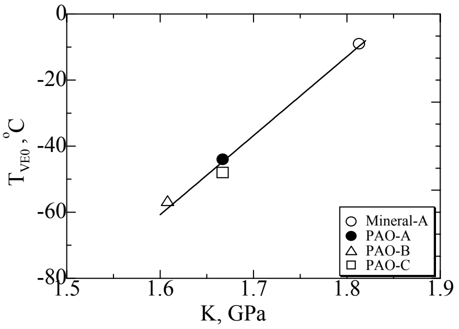

Fig. 5. Relation between T_{VE0} and K of tested sample oils.

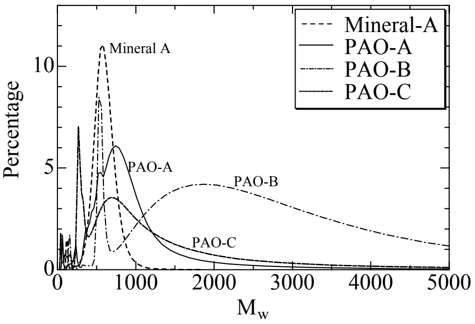

Fig. 6. Molecular distributions of sample oils from GPC test.

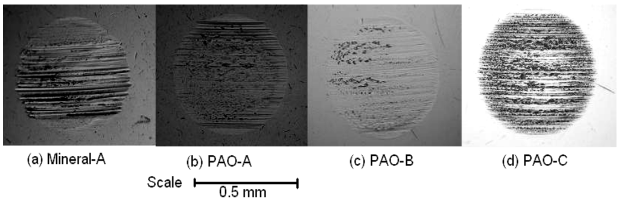
(a) Mineral-A (b) PAO-A (c) PAO-B (d) PAO-C

Fig. 7. Photographic view of wear scar of tested sample oils.

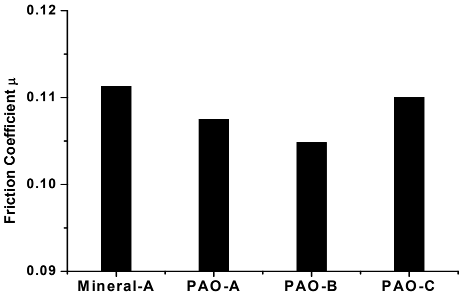

Fig. 8. Comparisons of friction coefficient within sample oils.

5. Conclusions

Polyalphaolefin oils have good properties for the wind turbine gearbox. These oils have wide temperature range (i.e. very good low temperature fluidity and high viscosity index compare to the mineral oil). PAO oils also sustain high pressure with excellent pressure-viscosity coefficient, which is essential for wind turbine gears and bearings. Low friction coefficient and low wear scar also indicate that they make a good lubricant for the wind turbine gears. The presence of polymethakrylate (PMA) absorbent in PAO oil showed comparatively better results than others.

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Nomenclature

α : Pressure-viscosity coefficient
η : Absolute viscosity
ρ : Density
ν : Kinematic viscosity
p : Pressure
T_{VE0} : Viscoelastic solid transition temperature at atmospheric pressure
U : Sound velocity
K : Adiabatic bulk modulus
U_{40} : Sound velocity at 40° C
K_{40} : Adiabatic bulk modulus at 40° C
M_w : Molecular Weight

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