Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 7 (15): 2120-2125, 2007
ISSN 1812-5654

Study of Plant Oil and its Ageing Effect on Hydraulic System Efficiency and Rheological Performance

[1]W.B. Wan Nik, [2]K.H. Ku Bulat, [3]H.B. Senin, [4]N.A Ali, [5]M.D. Rahman and [6]F.N. Ani
[1]Department of Maritime Technology,
[2]Department of Chemistry,
[3]Department of Physics,
[4]Department of Engineering, Universiti Malaysia Terengganu, 21030 Terengganu, Malaysia
[5]Kulliyyah of Pharmacy, International Islamic University Malaysia, 25200 Pahang, Malaysia
[6]Department of Thermo Fluid, Universiti Teknologi Malaysia, 81310, Johor Bahru, Malaysia

Abstract: The effects of oil ageing on hydraulic system efficiency and oil rheological performance were studied. The various physical and chemical properties of fresh and aged oils were studied by determining total acid value, iodine value and density. The variation of oil functional group was analyzed by FTIR. The rheological behavior i.e., variation of viscosity with time, temperature and shear rate was studied using Brookfield viscometer. An attempt was made to establish the relationship between variation of viscosity and time of fresh and aged oil. The hydraulic performance has been investigated by determining system volumetric and mechanical efficiencies. The results show that the volumetric efficiency increases with ageing period while mechanical efficiency decreases when the oil ageing time increases.

Key words: Rheology, shear, oil, temperature, performance

INTRODUCTION

Traditionally petroleum oil is used as raw material for lubricating fluid. The petroleum oil is relatively cheap, has a wide viscosity range, compatible with various industrial components and machine and has been widely accepted as lubricating fluid. The advantages and usage of petroleum oil are known since the beginning of 8th century. However, in recent decades, people prefer to use environmental friendly materials. This is due to the drawbacks of petroleum oil which are high toxicity, in finite resource and has low biodegradability. On the other hand, traditionally, the plant oils have been used not only for edible purposes but also for non-food applications such as paint, lubricants, biodiesel, printing ink and hydraulic fluid (Honary, 1996; Erhan and Asadauskas, 1999; Bhattacharyya and Reddy, 1999). Plant oils have quite a number of advantages (Elisabet and Goran, 1997; Andreas, 2001) such as they are non-toxic, renewable, biodegradable, reasonably inexpensive, available in large quantities and easily processed.

Considering the above disadvantages of petroleum based lubricants, many plant based products have been produced and patented (Lal *et al*., 1995; Lawate and Lal, 1998). Consumers are looking for environmental friendly and renewable products or base materials. Recent advances in the chemical additives and formulation techniques plus improved technology in product manufacturing have widened and diversified the field of application of plant oil to non-food applications. Currently, plant oils are being researched as high temperature lubricants (Filley, 2005).

In another scenario, there is active research and development in energy transport media comprising more than 90% plant oil. Thus the final products differ from current petroleum oil. This type of fluid, broadly classified as triglyceride esters, seek to achieve corrosion protection, enhanced thermal and rheological properties in different ways.

Reliable rheological data is crucial for machine design and processing of the oil, especially the plant oil. Temperature, shear and concentration are the variables which considerably affect rheological properties (Haque *et al*., 2001) .The plant oil has long tryglycerides chain. The oil is polar in nature. In one aspect, it is a positive feature. The oil is attracted to the metal surfaces, providing excellent lubricating protection. This attraction is also influence by all other substances present in the oil.

Corresponding Author: W.B Wan Nik, Department of Maritime Technology, Faculty of Maritime Studies and Marine Sciences, Universiti Malaysia Terengganu, Mengabang Telipot, 21030 Kuala Terengganu, Malaysia
Tel: +60-9-668-3342 Fax: +60-9-668-3193

In general, ester molecules are more polar than petroleum based oil and therefore experience stronger interaction with polar molecular species.

In this study, rheological behavior of plant oil blended with Lubrizol 7631 commercial additive was investigated. Here generalized data on the rheological properties of palm oil-additive blend is reported. Effect of oil ageing on hydraulic system efficiency and oil rheological behavior are presented.

MATERIALS AND METHODS

Raw material and equipment: The plant oil used in this study was palm oil. Palm oil was blended with commercial Lubrizol 7631 additive. 0.2% (wt/wt) of Lubrizol 7631 was mixed with palm oil, stirred and heated for about 1 h. Then the blend was poured into a hydraulic reservoir. The hydraulic test rig consists of 25 L hydraulic reservoir, vane pump, pressure relief valve, filter, heat exchanger, transducers and pipings. The 8 cm^3/rev hydraulic pump was rotated at fixed speed of 1200 rpm. The oil temperature was maintained at 55°C with the help of the shell and tube heat exchanger. The oil was sampled from pipe outlet located in the upper part of the hydraulic reservoir.

Rheological measurement: The viscosity of the oil samples was measured using a Brookfiled DVIII viscometer over several shear rates. The apparatus consists of a stationary outer cylinder of radius 0.953 cm and an inner cylinder of radius 0.874 cm which is rotated at discreet speeds of 3, 6, 20, 60 and 100 rpm. The viscometer was calibrated with 4.7 cP Brookfield silicone viscosity standard. Oil samples were taken out from hydraulic test rig at regular intervals. The viscosity of the oils was measured in triplicate at temperatures from 40 to 100°C. The temperature was measured on the surface of the outer cylinder.

The palm oil is assumed to move in concentric circles around the common axis of the viscometer at constant velocity for each fluid element. Due to the centrifugal force at high measuring speeds, the flow may be unstable. The Taylor number has been calculated to be 42. The temperature dependence of the oil was investigated using the Arrhenius-type-relationship Eq. 1. In studying the oil rheological behavior, modified Power law Eq. 2 model was used. The experimental data were fitted to the models (shear rate dependence at 50 and 70°C and temperature dependence at 3, 6, 20, 60 and 100 rpm). Followings are the models used:

$$\eta = \eta_{\infty,T}\ e^{\frac{E_a}{RT}} \quad (1)$$

$$\eta - (\eta_{hrpm} - \eta_{ref}) = K\gamma^{n-1} \quad (2)$$

where, γ, T, R, n, K, E_a are the shear rate (s^{-1}), temperature (K), universal gas constant (N.m K^{-1} mol^{-1}), flow behavior index (dimensionless), consistency index (mPa.s^n) and activation energy (N.m mol^{-1}), respectively. η, η_{hrpm}, η_{ref}, $\eta_{\infty,T}$ are viscosity, viscosity at the highest speed, viscosity of focus point for all curve lines (0.010 Pa.s) and viscosity at infinite-temperature, respectively. All viscosity terms are in Pa.s.

Physical properties of fresh and aged oil: Other physical properties of fresh and aged oil such as total acid value (TAN), specific gravity and iodine value (IV) were determined as per standard methods.

RESULTS AND DISCUSSIONS

Oil thermal analysis: Various physical properties such as acid value, iodine value and specific gravity value of the new oil and the oils having degraded for 200 and 400 h are given in Table 1. From this table, it can be observed that the acid value increases almost exponentially from 0 to 400 h. This is because shearing and heating the oil in the hydraulic system accelerate the oxidative rancidity with the formation of decomposition products such as ketones, aldehydes, free acids, hydroxyl compounds (Meyer *et al*., 1998).

The iodine value also shows some interesting pattern. It decreases with operation time. Since the iodine value measures the number of double bond of plant oil fatty acid, the decrease in iodine value indicates that the unsaturation level of the oil decreases. Directly it shows that the saturation level of the oil increases. The decrease of iodine value from 59.6 to 56.3 cg I_2/g indicates progressive polymerization and reduction of polyunsaturated fatty acids in the aged oil. The high value of saturated component is not favorable in hydraulic system as the saturated fat may block small clearance components such directional and flow control valves. The decrease of iodine value from 0 to 400 h also indicates progressive polymerisation and reduction of polyunsaturated fatty acids in heated oil (Moreno *et al*., 1999).

The increase in specific gravity from 0.890 to 0.895 indicates that there is heavy element present in the oil. The marginal increase in the specific energy is also might

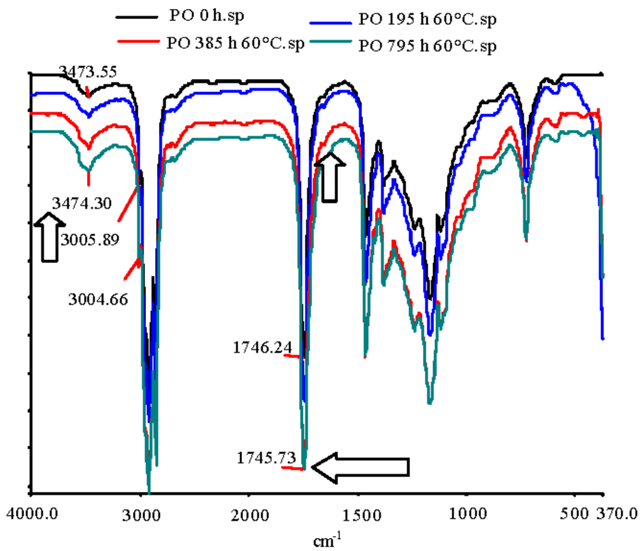

Fig. 1: Functional groups change (0 to 400 h)

Table 1: Physical properties of oil

	0 h	200 h	400 h
Acid value (mg KOH/g)	0.2167	0.4461	0.7425
Iodine value (cg I_2/g)	59.600	59.100	56.300
Specific gravity	0.890	0.891	0.895

be due to the formation of polymeric product. The oil degradation properties are supported by FT-IR studies Fig. 1. The FT-IR spectra of the aged oil showed strong ester carbonyl absorption at around 1745 cm^{-1} and also there is decrease in absorption at around 1615 cm^{-1} for double bond. The significant functional group change occurs at 3473-3474 cm^{-1} which is the formation of new functional group.

The significant peak differences observed were at 3474, 3005 and 1746 cm^{-1}. The oil has strong absorbance at about 1746 cm^{-1} due to stretching vibration of the carbonyl group of the triglycerides esters. Having degraded the oil in the hydraulic system, a new carbonyl absorbance was observed which is due to the formation of aldelhydic or ketonic functionalities and also the peak intensities increase with the time of hydraulic operation. Again, as hydraulic operation increases, the absorbance maximum at around 3005 cm^{-1}, decreases continuously with increasing operation time. This is due to the decreasing concentration of unsaturation in the oil. The shearing action in pipes and pump promotes polymerisation of the oil via conjugation of unconjugated double bonds. Inter and intramolecularly cross-linked polymer-like oil are also formed by virture of cyclisation. Cyclisation proces occurred in the hydraulic system when the system was turned on and off. Pressure in the system was also increased and decreased during volumetric and mechanical determination tests.

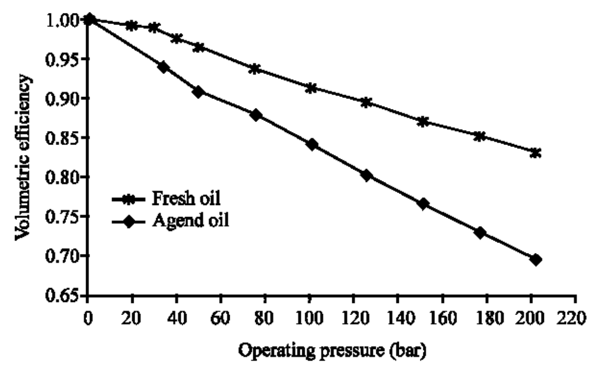

Fig. 2: Volumetric efficiency versus operating pressure

Hydraulic system performance: Figure 2 shows the volumetric efficiency of the system with respect to operating pressure. The volumetric efficiency of the system decreases as large leakage across pump vanes and rotors occurs at elevated pressures. This leakage loss is augmented with the oil compressibility factor. The internal leakage and compressibility effects are well observed at 200 bar pressure.

The ageing of the oil has positive impact on volumetric efficiency. Slight increase in volumetric efficiency was observed when the oil has been aged for 400 h. This is due to less leakage flow which in turn the result of increase oil viscosity.

Figure 3 shows the mechanical efficiency of the system with respect to operating pressure. The efficiency starts low at low pressure. Good efficiency was obtained when operated at pressure higher than 40 bar. The maximum achievable mechanical efficiency is around 80%. The results show that the ageing condition of the oil

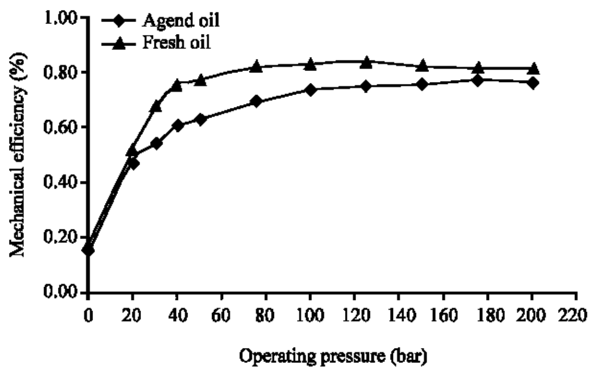

Fig. 3: Mechanical efficiency versus operating pressure

affects the mechanical efficiency of the hydraulic system. System mechanical efficiency drops by 14% when operated at 75 bar, when operated using aged oil compared to fresh oil.

Rheological behavior: Viscous losses in flanges and pipes and shear losses in pumps and valves represent a significant proportion of the efficiency losses in the hydrostatic transmission. Fluid compressibility causes further losses in efficiency in the high pressure pump and valves. Clearly the viscosity and rheological behavior of oil play important role in power transmission of hydraulic system. From Fig. 4, it is found that the viscosity of all oil samples approaches low viscosity as the temperature increases. The increase of temperature tends to increase molecular motion (increase viscosity) and reduce attractive forces between molecules (reduce viscosity). In liquid, the reduced in attractive forces overcome the increase in molecular interchange and therefore viscosity reduces with increasing temperature.

Up to 400 hours operation, the oil was found to be compatible with the elastomeric seals commonly used with petroleum oils. The oil also seems compatible with hoses manufactured from nitrile rubber. The experimental data on the aspect of temperature are further elucidated through the use of model which is Arrhenius-type-relationship. From the model (Eq. 1), the activation energy (E_a) estimated reflects the viscosity-temperature stability of the oil. Hence, oil with the smallest and highest values of E_a indicate the highly and lowly viscosity-temperature stability oil, respectively. Referring to Table 2, results show that most of the zero hour values are smaller than 400 sample for five different speeds tested (3, 6, 20, 60 and 100 rpm). The result indicates that zero hour sample has higher viscosity- temperature stability compared to 400 h sample.

Graphical evaluation on the effect of temperature shows that a continuous increase in temperature would reduce the viscosity variation of oils to a lower value. Therefore, by increasing the temperature it modifies the arrangement of oil molecular structure in a way that the effect of shear rate on the changes of viscosity would not be apparent. However, this effect is reversible as long as the increased of temperature do not create an extreme condition that can promote oxidation or degradation of oil molecular structure.

Instead of temperature, shear rate also plays an important role in the variation of viscosity. In this experiment the shear rate was varied in the range 0.3-80 sec^{-1}. The lower limit varied depending on the sensitivity of the torque measurement. The upper limit varied depending on the transition point from laminar to secondary flow and viscous heating effects at high shear rates. Viscosity value reduces as shear rate increases, which is normally known as pseudo-plastic characteristic. As shear rate increases the reduction of viscosity is significantly observed, especially at the beginning of a very low shear rate as shown in Fig. 5. Similar observation has been reported for the viscosity of waxy oils (Al-Zahrani, 1997). This shear-thinning behavior is having flow behavior index (n) less than 1, refer to Table 3. This behavior is observed as reversible and no time dependence while the shear applied breaks down the internal structure within the fluid very rapidly (Al-Zahrani, 1998). The highest flow behavior index value with n less than 1 indicates highly Newtonian behavior where shear rate has no influence on changes of viscosity. The measurement of viscosity when increasing and decreasing the shear rate was reversible indicating that the polymeric property of the plant oil was not broken.

Table 2: Different oil samples fitted with arrhenius-type- relationship model and e_a values

	E_a	
Speed (rpm)	0 h	400 h
100.0	22957	23522
60.0	23769	23901
20.0	18687	19441
6.0	7578	8987
3.0	4753	4997

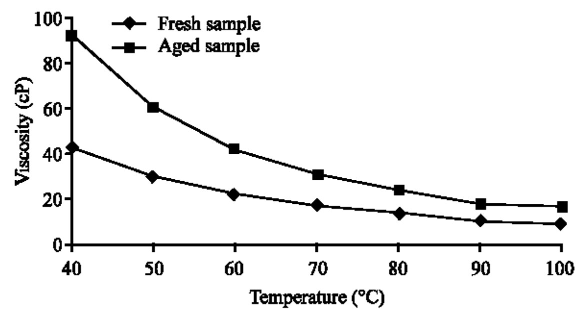

Fig. 4: Viscosity versus temperature

Table 3: Flow behavior index, n, according to modified power law

T (°C)	0 h	200 h	400 h
50	0.887	0.455	0.450
70	0.982	0.631	0.596

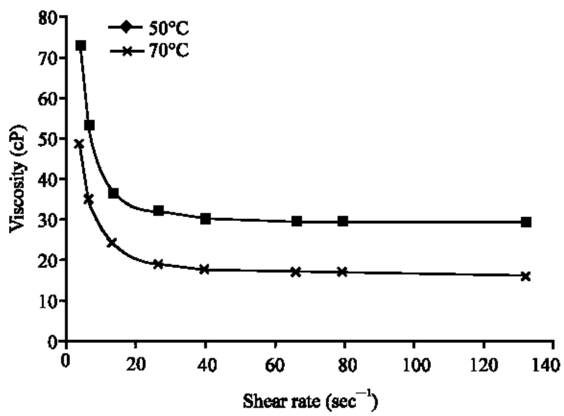

Fig. 5: Viscosity versus shear rate

Previously, experimental work with palm oil methyl ester in both accelerated tribiological tests and in full-scale hydraulic system has shown that the problems of low viscosity, erosion and the adverse effect that the fluid has on the fatigue lives of rolling element bearings make the successful operation of equipment difficult. There is, however, growing evidence that success is possible, even at the present level of technology. It is proved by the plant oil in this 400 h test. It is found the viscosity of zero hour sample is less affected by shear rate when compared to 200 and 400 h sample. This is supported by the fact that most of the flow behavior indices of zero hour sample are greater than 200 and 400 h sample.

The changes in viscosity of the oil samples are shown in Fig. 4 and 5. The slower rate of rising viscosity in the initial stage may be due to the inhibition action of the commercial additives such as aromatic phenolic type compound (Frankel, 1996; Hopia*et al*., 1996) present in the oil. As this antioxidant retards the oxidative thermal degradation to some extend, so the rate is slow during initial ageing. It has been supposed that during the early stage of ageing of the oil, the triglyceride ester molecules undergo different kinds of reactions such as the isomerisation of unconjugated systems into conjugated systems and decomposition into lower molecular weight products such as hydroxyl, carbonyl, carbonyl compounds and esters which have a greater tendency to recombine to form new products. This retardation period is followed by the rapid interaction of the decomposition products to form new ones including the bulk viscosity. Thus during the ageing period at 55°C in the presence of contaminants and air, there is thermal polymerization through Diels-Alder reaction, oxidation polymerization, ester exchange reaction, cyclisation etc., which increased the viscosity of the aged oil. The formation of polar groups such as carbonyl, hydroxyl, ester, etc. is supported by FTIR studies.

In order to study the effect of temperature on the Newtonian level, the oil was examined at two different temperatures (Fig. 5). The result shows that the oils approach a more Newtonian behavior at higher temperature, i.e., the viscosity variation with shear rate decreased with increasing temperature.

By referring to shear rate dependence model Eq. 2, again it is found that most of the flow behavior indices of zero hour sample are greater than 200 and 400 h samples (Table 3). This indicates that zero hour sample exhibits more Newtonian alike behavior.

Figure 5 show the shear thinning behavior of the oil. The thin lubricating films can cause cavitation and subsequent erosion of the hydraulic components. Some problems may arise from the combined effects of this low viscosity, high vapour pressure and the high bulk modulus of the plant oil. In order to use the shear-thin oil, for satisfactory performances, the clearances must be kept small and the stiffnesses of the associated shafts and housings must be matched to ensure that bearing alignment is maintained under all load conditions. The low viscosity oil also can create problem of heat dissipation and thermal distortion.

CONCLUSION

The effects of oil ageing on hydraulic system efficiency and oil rheological performance were studied. The results show that the volumetric efficiency increases with ageing period while mechanical efficiency decreases when the oil ageing time increases. In short, all the oils tested behave towards pseudoplastic category.

ACKNOWLEDGMENTS

We greatly acknowledge the financial support from Ministry of Science, Technology and Environment, Malaysia and KUSTEM (Grant No. 55002). Assistance from Mr. Azhar, Mr. Mahmood, Mr. Zaki, Mr. Jamal, Mr. Tarmizi, Mr. Razman, Mrs. Asbah and Mr. Rozimi during the experiment is also acknowledged.

REFERENCES

Al-Zahrani, S.M. and T.F. Al-Fariss, 1998. A General Model for the Viscosity of Waxy Oils. Chem. Eng. Processing, 37: 422-437.

Al-Zahrani, M., 1997. A Generalized Rheological Model for Shear Thinning Fluids. J. Petroleum Sci. Eng., 17: 211-215.

Andreas, W., 2001. Lubricants Based on Renewable Resources an Environmentally Compatible Alternative to Mineral Oil Products. Chemosphere, 43: 89-98.

Bhattacharyya, S. and C.S. Reddy, 1999. Vegetable Oils as Fuels for Internal Combustion Engines: A Review. J. Agric. Eng. Res., 57: 157-166.

Elisabet, K. and D. Göran, 1997. Environmentally Adapted Hydraulic Oils. Wear, 207: 41-45.

Erhan, S.Z. and S. Asadauskas, 2000. Lubricant Basestocks from Vegetable Oils. Industrial Crops and Products, 11: 277-282.

Haque, A., R.K. Richardson and E.R. Morris, 2001. Effect of Fermentation Temperature on the Rheology of Set and Stirred Yogurt. Food Hydrocolloids, 15: 593-602.

Honary, L.A., 1996. An Investigation of the Use of Soybean Oil in Hydraulic Systems. Fuel and Energy Abstracts, 37: 443-445.

Hopia, A., S.W. Huang and E. Frankel, 1996. Phenolic Diterpenes from Rosemary as Antioxidants in Linoleic Acid, Methyl Linoeate and Corn Oil Triglycerides. Food Chem., 57: 57-59.

Filley, J., 2005. New Lubricants from Vegetable Oil: Cyclic Acetals of Methyl 9, 10. Bioresou. Technol., 96: 551-555.

Frankel, E.N., 1996. Antioxidants in Lipid Foods and Their Impact on Food Quality. Food Chem., 57: 51-55.

Lal, K., M.D. Dennis and G.D. Jeffry, 1995. Pour Point Depressant for High Mono-unsaturated Vegetable Oils/Biodegradable Base and Fluid Mixtures. US Patent No. 5413725.

Lawate, S.S. and K. Lal, 1998, High Oleic Polyol Esters, Compositions and Lubricants, Functional Fluids and Greases Containing the Same. US Patent No. 5773391.

Meyer, A.S., M. Heinonen and E.N. Frankel, 1998. Antioxidant Interactions of Catechin, Cyanidin, Caffeic Acid, Quercetin and Ellagic Acid on Human LDL Oxidation. Food Chem., 61: 71-75.

Moreno, M., F.J. López, J.V. Adelantado and F.V. Reig, 1999. Determination of Unsaturation Grade and Trans Isomers Generated during Thermal Oxidation of Edible Oils and Fats by FTIR. J. Mol. Structure, 482-483: 551-556.