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Rheology of Environmental Friendly Hydraulic Fluid: Effect of Aging Period, Temperature and Shear

W. B. Wan Nik[1,*], F. N. Ani[2], and H.H. Masjuki[3]

[1]*Engineering Science Department, Faculty of Science and Technology, University College of Science and Technology Malaysia (KUSTEM), 21030 Kuala Terengganu, Terengganu, Malaysia.*
[2]*Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia.*
[3] *Department of Mechanical Engineering, University Malaya (UM), 50603, Kuala Lumpur, Malaysia.*

Abstract

Limitations of petroleum oil in the aspect of non-renewable, not environmental friendly and its non-sustainability in the future have prompted a search for more stable and environmentally friendly alternatives. Bio-oils are potential to be used as industrial fluids. Currently rheological and tribological aspects of bio-oil are being investigated. Rheological properties of bio-oils used as hydraulic fluid were determined at different aging periods, temperatures and shear rates using a concentric cylinder rotational viscometer. Apparent viscosity versus shear rate was successfully fitted to the generalized Ostwald de-Waele, modified power law, Cross, Carreau and Herschel-Bulkley rheological models. The oils were found to exhibit non-Newtonian, shear thinning behavior at all aging periods and temperatures. The flow behavior index, n, varied in the range of 0.6 to 0.9. The consistency index, K, was in the range of 0.0102 to 0.0485 $Pa.s^n$. Both parameters were significantly affected by temperatures and aging periods.

Keywords: Rheology, bio-oil, palm oil, environmental friendly alternative, flow index

1.0 Introduction

Recently, environmental related issues that include biodegradability, toxicity, occupational health and safety, and emissions have created an important issue to be considered especially the use of mineral oils in environmental sensitive areas [1,2]. The European Union (EU) has set an objective of 10% of hydraulic fluid from environmental friendly raw material. This has encouraged number of researchers to involve in the research of vegetable oil as alternative base oils for environmentally benign hydraulic fluids. Mostly, vegetable oils are applied in situation where accidental spillage and leakage would cause serious impact on environment. Such applications include marine, construction and agriculture activities.

In another words, with the increasing environmental consciousness, the use of agricultural oils in non-food applications arises considerable interest. This is also due to their renewable character, biodegradability and aptitude to facile chemical modifications [3]. Furthermore, expanded use of this vegetable-based oil could provide developing countries such as Malaysia with inexpensive and renewable energy from domestic sources.

[*] *Corresponding author: e-mail: [a, *]niksani@kustem.edu.my*

It has been recognized that rheological properties of oil depends on many factors that include temperature, shear rate, concentration, time, pressure, chemical properties, additive and catalyst [4,5]. Most of the researches focusing on the effects of temperature, shear rate, concentration and pressure. However, it is normally found that the effect of temperature is much more apparent on the fluid viscosity.

Allawzi et al. [6] reported that jojoba oil was suitable to be used as a component in lubricating oil formulations for two-cycle gasoline engines. In 2001, Masjuki et al. [7] reported that coconut oil and its blends could be used as alternative biofuel in diesel engines. In addition, vegetable oils have been reported suitable as raw materials for a wide range of industrial products such as lubricants, fuels, skin care products and alkyd resins [8].

Currently, the use of vegetable oil as energy transport media or hydraulic fluid in hydraulic system is being researched at Kolej Universiti Sains dan Teknologi Malaysia (KUSTEM). This work focused on the use of vegetable oil to actuate linear or rotary devices used in industrial automation systems, construction equipment and in simple open loop hydraulic system.

1.1 Governing Equations

The rheology of lubricants has received the attention of various investigators [9,10]. Steffe [11] summarized the models that have been used in representing the flow behavior of non-Newtonian fluids; with the Ostwald de-Waele and Cross being the most useful in solving hydraulic fluid problems. The generalized Ostwald de-Waele, modified power law, Cross, Carreau and Herschel-Bulkley are given by the Equations 1, 2, 3, 4 and 5, respectively. Modified Power Law was specially developed to monitor Newtonian and non-Newtonian behavior of the oil.

$$\eta = K\gamma^{n-1} \tag{1}$$

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

$$\eta = \eta_{\infty,\gamma} + \frac{\eta_{o,\gamma} - \eta_{\infty,\gamma}}{1 + (\alpha_c\gamma)^m} \tag{3}$$

$$\eta = \eta_{\infty,\gamma} + \frac{\eta_{o,\gamma} - \eta_{\infty,\gamma}}{\left[1 + (\lambda_c\gamma)^2\right]^N} \tag{4}$$

$$\eta = K_H\gamma^{n_H - 1} + \eta_{\infty,\gamma} \tag{5}$$

where K, K_H are the consistency index ($Pa.s^n$), m and N are constants (dimensionless), n and n_H are flow behavior index (dimensionless), R is the universal gas constant ($N.m.K^{-1}.mol^{-1}$), γ is the shear rate (s^{-1}), η, η_{hrpm}, η_{ref}, $\eta_{o,\gamma}$, $\eta_{\infty,\gamma}$ are viscosity, viscosity at the highest revolution per minute, focus point of all curve lines (0.010 Pa.s), zero-shear, infinite-shear rate (Pa.s), λ_c, α_c are characteristic relaxation time (s).

2.0 Experimental Methods

A hydraulic test rig has been built in Fluid Mechanics Laboratory, Kolej Universiti Sains dan Teknologi Malaysia with the advice of experts from Mechanical Engineering Faculty, Universiti Teknologi Malaysia and Mechanical Department, Universiti Malaya. The hydraulic test rig used in this study is shown in Figure 1.

Figure 1 Hydraulic test rig used in the study

Palm oil was used as hydraulic fluid in the hydraulic system as described in our previous paper [12]. The oil was supplied by a local refinery. The oil fatty acid was determined using gas-chromatographic method. The oil was blended with Irgalube 343 additive prior being poured into the reservoir. The blend was prepared by diluting appropriate amount of Irgalube 343 into palm oil. A HEIDOLPH Lameris variable speed stirrer with a four-blade paddle agitator was used in order to obtain homogenous blend.

Rheological properties of fresh crop oils and aged hydraulic fluids were measured using Brookfield DVIII viscometer. The dependence of the sample viscosity on temperature was evaluated using Equations 1 to 5 as indicated in Governing Equation Section. In steady shear flow characterizations, increasing and decreasing shear rates were performed at temperatures form 40 ^{o}C to 100 ^{o}C. The coaxial type cylinder viscometer generated 10 discrete shear rates from 3rpm to 100rpm, which is equivalent to 3.9s^{-1} and 131.6s^{-1}. The instrument's accuracy and reproducibility were 1% and 0.2% of full scale, respectively. The thermosel provided constant temperatures for experimentation with an accuracy of ± 0.1^{o}C. All measurements were conducted in Fluid Mechanics Laboratory, KUSTEM.

3.0 Results and Discussion

3.1 Oil Chemistry

Palm oil used belongs to unique group of vegetable oils which has over 40% of oleic acid and close to 35% of palmitic acid. The triglyceride compositions of the oil used are given in Table 1. Almost 60% of fatty acids of the oil used are unsaturated while stearic, palmitic and myristic is saturated.

The iodine value of the fresh palm oil was 59 cg I_2/g. The iodine value is a measure of unsaturation of vegetable oil. The saturated property of the oil imparts a strong resistance to oxidative rancidity. Thus the thermal and oxidative of the oil could be improved if the oil has lower iodine value. In order to confirm the thermal and oxidative stability of the oil the assessment was performed by active oxygen method (AOM) [13].

Table 1: Fatty acid triglyceride composition (%) of palm oil used

Fatty acid	Systematic name	Symbol	% of total weight
Saturated acids			
Palmitic	n-Hexadecanoic	C16:0	34.8
Mono-unsaturated acids			
Oleic	n-Octadec-9-enoic	C18:1	45.5
Poly-unsaturated acids			
Linoleic	n-Octadec-9, 12-dienoic	C18:2	13.8

3.2 Flow Index and Consistency Index for Aged Oils

When new oil is intended to be used as energy carrier or hydraulic fluid, the rheological behavior of the oil need to be investigated and influence of temperature, pressure, shear and contaminant level on the oil viscosity has to be determined [14].

Fluid viscosity is a very important characteristic since the oil has to lubricate moving parts especially for hydraulic pump. Since viscosity gives resistance for fluid to flow, it affects the overall mechanical and volumetric efficiencies of hydraulic systems. The pioneer model for shear dependence of viscosity is the famous Ostwald-de Waele power law model (Equation 1) proposed in 1925 by Ostwald and de Waele. This power law model has been used widely to characterize rheology of common engineering fluids [15].

A power law index or flow index (n) less than unity indicates pseudoplastic behavior; an index greater than unity corresponds to dilatant behavior. Newtonian fluids have a flow behavior index of unity, which indicates that for these fluids the apparent viscosity remains constant for different shear rates.

The rheological parameters determined are summarized in Table 2. By comparing the values of consistency index obtained from modified Power Law (K) and Herschel-Bulkley (K_H) for temperatures, it is found all the values follow this sequence: $(K, K_H)_{100^oC} > (K, K_H)_{80^oC} > (K, K_H)_{60^oC} > (K, K_H)_{40^oC}$ (refer to Table 2). As temperature increased, the K and K_H values increase. Similar observation was reported by previous researchers [4,9] who studied rheological properties of tomato pastes, edible oils and formate-based fluids.

When comparing the values of flow behavior index obtained from modified Power Law (n) and Herschel-Bulkley (n_H), it is found most of the values follow this sequence: $(n, n_H)_{100^oC} > (n, n_H)_{80^oC} > (n, n_H)_{60^oC} > (n, n_H)_{60^oC} > (n, n_H)_{60^oC}$ (refer to Table 2). The sequence indicates that oil sample at 100°C and 40°C exhibit the most Newtonian and non-Newtonian alike behavior, respectively.

The increase in viscosity is due to fact the oil has undergone oxidation degradation during the test period. Even the oil has been fortified with Irgalube 343 additives, the oil could not sustain its property. The loss of antioxidant leads to reduction stability. The reduction in oxidative stability hopefully can be regained by new addition of suitable antioxidants.

Table 2 Flow parameters for oil at 0 and 300 hours

Model, Parameter and Condition			100 hour	300 hour
Modified Power Law	K	40 °C	1.33E-02	2.44E-02
		60 °C	1.38E-02	5.94E-02
		80 °C	1.40E-02	7.05E-02
		100 °C	1.44E-02	8.14E-02
	n	40 °C	9.17E-01	4.50E-01
		60 °C	9.25E-01	5.16E-01
		80 °C	9.37E-01	5.79E-01
		100 °C	9.413E-01	5.81E-01
Herschel-Bulkley	K_H	40 °C	7.57E-03	9.88E-03
		60 °C	1.37E-02	2.27E-02
		80 °C	2.44E-02	4.32E-02
		100 °C	6.31E-02	7.14E-02
	n_H	40 °C	3.39E-01	1.35E-01
		60 °C	4.29E-01	1.36E-01
		80 °C	6.99E-01	3.21E-01
		100 °C	7.29E-01	3441E-01

3.3 Flow Curves and Empirical Constants for Fresh Oils

Reduced viscosity was observed when shear rate was increased from 3.9s^{-1} and 131.6s^{-1} (Figure 1). The reduction of viscosity is much more apparent at low shear rate as shear rate increases. At high enough shear rate viscosity leveling off was observed. Similar observation was reported by Al-Zahrani and Al-Fariss [16] for the viscosity of waxy oils. This shear-thinning behavior is commonly known as pseudo-plastic characteristic with n and $n_H < 1$ (refer to Table 2). This behavior was explained by Al-Zahrani [17] where the shear applied breaks down the internal structure within the fluid very rapidly, reversible and no time dependence.

Figure 2 shows the comparison between experimental and calculated data (based on modified power law, Cross, Carreau and Herschel-Bulkley models). Among four models fitted, Cross model is very well fitted with an average correlation coefficient of 0.99445 for fresh and aged oils and followed by: Carreau model, 0.99238; Herschel-Bulkley model, 0.92153; modified power law model, 0.91321 (at 40, 60 and 80°C). The experimental data are well fitted to the Cross and Carreau models because each model consists of four parameters whereas modified

Power Law and Herschel-Bulkley only consist of two and three parameters to be determined, respectively.

The viscosity of 300 hour sample was significantly higher than that of 0 hour sample (Figure 3). This can be explained by the presence of the more polar polyconjugate sequences in the former, which give rise to a higher cohesive energy and hence an increased viscosity.

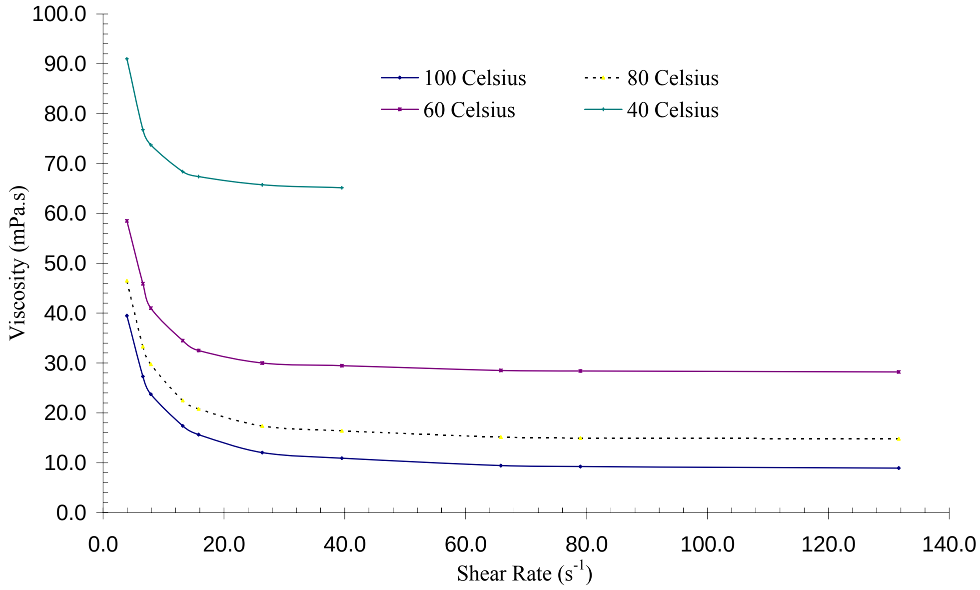

Figure 1 The flow diagram of fresh oil

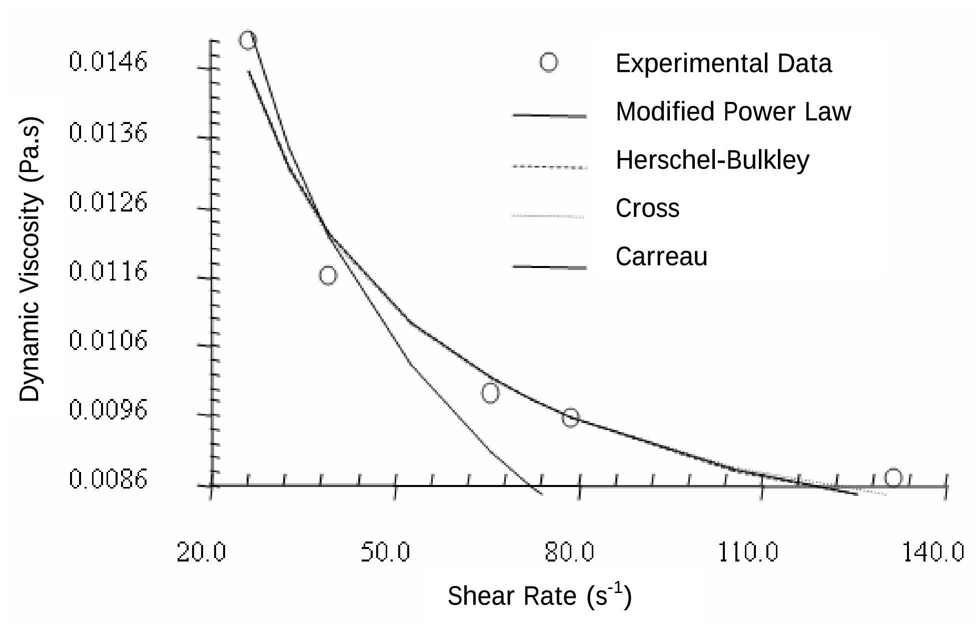

Figure 2 Comparison on suitability of rheological models for the aged oil

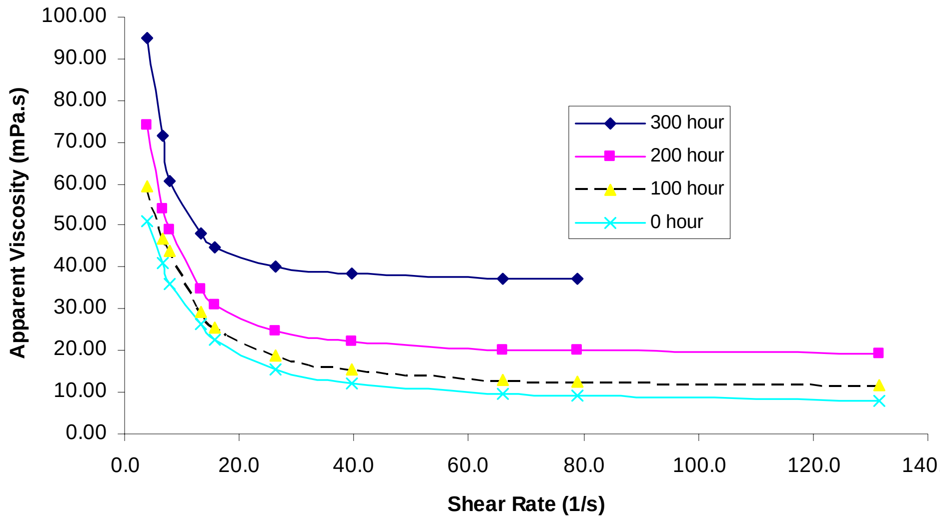

Figure 3. The effect of aged period and shear rate on the oil viscosity

4.0 Conclusion

All oil samples collected presented a non-Newtonian behavior in the range of aging period, shear rates and temperature considered. The viscosity of 300 hour sample was significantly higher than that of 0 hour sample. Correlation coefficients for all oil samples are greater than 0.9. Flow behavior index smaller than unity indicates that the fluid exhibits pseudoplastic behavior. The results show that the pseudoplasticity of the oil increases with test rig operation time. The flow behavior index decreases from 0.94 to 0.45 when the oil was sheared and degraded for 300 hours. The production of primary oxidation product is indicated by increasing consistency index, zero shear and infinite shear rate viscosities.

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References

[1] Jayadas, N.H. and Nair, K. P. (2005). Coconut Oil as Base Oil for Industrial Lubricants—Evaluation and Modification of Thermal, Oxidative and Low Temperature Properties. In Press, Corrected Proof.
[2] Bartz, W. J. (1998). Lubricants and the Environment. Tribology International, **31**(1-3):35-47.
[3] Hintze-Bruning, H., (1993). Utilization of Vegetable Oils in Coating. Ind. Crops Prod. 1, 89-99.
[4] Goodrum, J.W., Daniel, P., Geller, P., and Thomas, T.A. (2003).Rheological Characterization of Animal Fats and Their Mixtures with #2 Fuel Oil. *Biomass and Bioenergy*, **24**: 249-256.
[5] Wan Nik, W.B. (2005). Thermal and Rheological Properties of Palm Based Oil as Hydraulic Fluid. Universiti Teknologi Malaysia, Mechanical Engineering Phd Thesis.
[6] Allawzi, M., Abu-Arabi, M., Al-zoubi, K. and Tamimi,A. (1998). Physicochemical Characteristics and Thermal Stability of Jordanian Jojoba Oil. *JAOCS*, *75*, 57-62.
[7] Masjuki, H.H., Kalam, M.A., Maleque, M.A., Kubo, A. and Nonaka, T. (2001). Performance, Emissions and Wear Characteristics of an Indirect Injection Diesel Engine Using Coconut Oil Blended Fuel. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 215(3), 393-404 (2001).

[8] Eromosele, C.O., Paschal, N.H. (2002).Characterization and Viscosity Parameters of Seed Oils from Wild Plants. *Bioresource Technology*, **86**: 203-205.

[9] Fernandes, V.J. and Santos, I.M. (2004). Thermoanalytical and Rheological Characterization of Automotive Mineral Lubricants After Thermal Degradation. *Fuel,***3**(7-18): 2393-2399.

[10] Bair, S., Khonsari, M. and Winer, W. O. (1998). High-pressure Rheology of Lubricants and Limitations of the Reynolds Equation. *Tribology International.* **31**(10): 573-586.

[11] Steffe, J.F. (1992). *Rheological Methods in Food Process Engineering*. East Lansing: Freeman Press, p.37.

[12] Wan Nik, W.B., Ani, F.N. Masjuki, H.H. (2003). Hydraulic System Test Rig and Evaluation of Crop Based Oil as Hydraulic Fluid. *Recent Progress in Transport Phenomena*, *Proc. The 14th International Symposium on Transport Phenomena*.

[13] Hui, J. (1996). *Coconut Oil, Bailey's Industrial Oil and Fat Products*. New York: Wiley-Interscience Publications, Wiley. p. 97-123.

[14] Kokini, J.L. (1992). *Rheological Properties of Foods. In Handbook of Food Engineering*, eds. D.R. Held-man and D.B. Lund, Marcel Dekker, New York.

[15] Guo, D. and Jiang, L. (1998). Rheological Behaviour of a New Kind of Fuel—residual Oil, Coal and Water Triplex Synfuel. *Fuel*, **77**: 1697-1700.

[16] Al-Zahrani, S.M. and Al-Fariss, T.F. (1998). A General Model for the Viscosity of Waxy Oils. *Chemical Engineering and Processing*, 37, 422-437.

[17] Al-Zahrani, S.M. A Generalized Rheological Model for Shear Thinning Fluids. *Journal of Petroleum Science and Engineering*, **17**: 211-215 (1997).