*Jurnal Mekanikal*
*Disember 2003, Bil. 16, 107 - 116*

# RHEOLOGICAL PROPERTIES OF PALM OIL AND PALM-MINERAL OIL BLEND

Wan Sani Wan Nik
Faculty of Science and Technology
Kolej Universiti Sains dan Teknologi Malaysia
Mengabang Telipot
21030 Kuala Terengganu
Terengganu

Farid Nasir Ani
Faculty of Mechanical Engineering
Universiti Teknologi Malaysia
81310 UTM Skudai, Johor

and

Masjuki Haji Hassan
Faculty of Engineering
Universiti Malaya
50603 Kuala Lumpur

## ABSTRACT

*This paper deals with the rheological study of refined bleached and deodorized grade palm oil, mineral oil and the effects of blending mineral oil with palm oil. This rheological study precedes the work done to investigate how hydraulic system performance and its dimensionless parameters are affected by palm oil properties. The aim of this initial work is to provide an equation to predict the apparent viscosity of the oils with better accuracy as a function of temperature and shear rates. The apparent viscosity of pure Shell Tellus 100, pure refined bleached and deodorized palm and their blends were measured over a temperature range of 30-100°C and shear rate range of 3.9-131.6s$^{-1}$. It was observed that all oil samples viscosities were affected by shear rate and temperature. Therefore, a modified Andrade's equation was proposed. Viscosity data were fitted to the modified Andrade's equation for constant shear rate range of 3.9-131.6s$^{-1}$. It was found that the modified Andrade's equation fits well with the experimental data where all the coefficient of determinations ($R^2$) were greater than 0.98000.*

## 1.0 INTRODUCTION

The effect of temperature on viscosity has been the interest of researchers in universities and manufacturers of lubricant oils until recent years [1, 2]. The subject seems simple but the contribution is very significant. This is because viscosity is an important energy transfer property and it is also one of the most basic physical properties in the design of hydraulic systems or hydromachines.

However, lack of an accurate model that is valid for all liquid makes it difficult to predict the effect of temperature on viscosity.

This initial study examines a few commonly used mathematical models developed and extended by Vogel-Fulcher, Arrhenius and Andrade [3, 4], as well as develops a model that uses empirical data to predict liquid viscosities over a wide range of temperatures. The study starts with the Vogel-Fulcher model which is an empirical equation applicable to a wide range of temperatures.

Vogel-Fulcher's model is one of the earliest attempts of predicting liquid viscosities and has the least sound theoretical basis. Later theories based on the principals of statistical mechanics have done little to improve the accuracy of the Vogel-Fulcher's liquid viscosity predictions. Since all of the current models are in error by as much as thirty to fifty percent, the viscosities predicted can only be used for prediction purposes. These calculations, however, are still useful as long as the temperatures involved are below the boiling point and the liquid molar volume. In industrial applications, empirical formulas are generally used for more accurate predictive results.

As mentioned previously, among the famous and old viscosity-temperature law is the Vogel-Fulcher relationship [5, 6, 7]:

$$\eta = \eta_o \exp [K/(T-T_\infty)] \tag{1}$$

Equation (1) requires at least three data points. Published viscosities, for one or more viscosities value at different temperatures, have limited value when viscosities are needed at temperatures other than those published ones. To avoid this from occurring, another equation was required to represent the experimental data. For most liquids at temperatures below the normal boiling point, the plot of ln $\eta$ versus 1/T or ln $\eta$ versus ln T is approximately linear [8]. Hence, most regressions are presented in the form as mentioned. A simplified form of Equation (1) can be written according to Arrhenius type relation [9]:

$$\eta = Ae^{\frac{E_a}{RT}} \tag{2}$$

Using the natural logarithmic format and higher-order polynomial in 1/T to give better accuracy, the modified Andrade's equation can be shown as [10]:

$$\ln(\eta) = A + \frac{B}{T} + \frac{C}{T^2} + \frac{D}{T^3} + \frac{E}{T^4} + \text{.........} \tag{3}$$

## 2.0 EXPERIMENTAL METHODS

In this study, the refined bleached and deodorized palm oil grade were obtained from Kempas Edible Oil, Pasir Gudang, Johor. Shell Tellus 100 (hydraulic fluid) was obtained from a local oil supplier in Kuala Terengganu. Blends of 75%, 50% and 25% refined, bleached and deodorized palm oil with hydraulic oil were prepared by weight (% wt). Viscosity measurements were performed with Couette type viscometer at atmospheric pressure. Details of the Brookfield (Stoughton, MA, USA) viscometer model DV -1+ used for the measurement is shown in the appendix.

8 ml of oil sample was measured by using a graduated cylinder and was then poured into a disposable sample chamber (Figure 1). The loaded disposable sample chamber was placed into a thermo-container by rotating the chamber until it dropped and locked in place. Spindle SC4-18 was attached to the spindle extension with care and then the viscometer was slowly leveled down until the spindle immersed inside the disposable sample chamber.

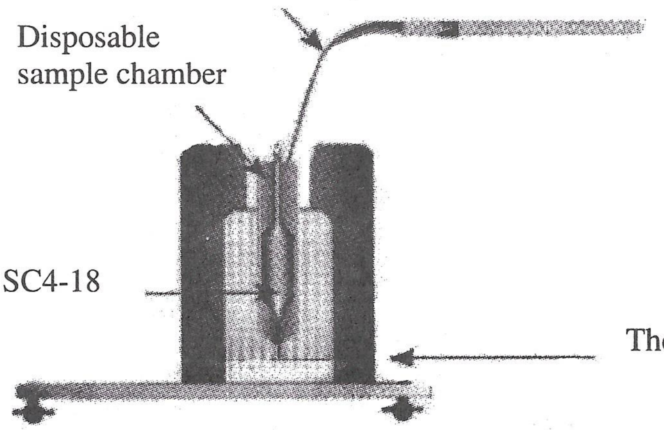


Figure 1 Couette type viscometer [11]

Great care was taken to avoid direct contact between the spindle surface and the inner surface of the disposable chamber. Therefore, they were separated by a thin layer of oil. The viscometer was set to 1.5 minutes for stoppage time after it was allowed 20 minutes to achieve the test temperature controlled by a temperature controller. This step was then repeated for each increment of 10°C from ambient temperature until 100°C.

There were three or four discrete shear rates ranging from 3.95 to 131.64$s^{-1}$ selected for each temperature from ambient temperature to 100°C. The torque (%), spindle speed (rpm) and apparent viscosity (centiPoise) were recorded.

Shear stresses applied to the oil sample were measured by means of rotating the viscometer spindle at certain speeds. Correspondingly, the shear rate was calculated using the following relationship

$$\gamma = \frac{2wr_c^{\,2} r_b^{\,2}}{x^2(r_c^{\,2} - r_b^{\,2})} \tag{4}$$

Equation (4) was derived from the equation of motion and assuming steady state with no slip condition [12]. The values for $r_b$, $r_c$ and $x$ are 0.874cm, 0.953cm and 0.874cm, respectively. Shear stress can be calculated by placing the value of torque (%) into the following relationship

$$\tau = 0.395 \times \text{Torque}(\%) \tag{5}$$

The apparent viscosity can also be obtained by placing the value of the spindle speed (rpm) and torque (%) into the following relationship

$$\eta = \frac{\text{Torque (\%)}}{\text{Spindle speed (rpm)}} \times 30.0 \tag{6}$$

## 3.0 RESULTS AND DISCUSSION

Mathematica (version 4.2) was used to determine the constants of the modified Andrade's equation for all blends. The modified Andrade's equation (Equation (3)) was truncated, where the constant E and the higher-order terms were eliminated into the following form:

$$\ln(\eta) = A + \frac{B}{T} + \frac{C}{T^2} + \frac{D}{T^3} \tag{7}$$

Oil viscosity is a function of temperature. In addition, the parameters A, B, C and D change with shear rate. Therefore, by imposing constant shear rate, the parameters can be determined. In order to determine the equation constants, the following steps were performed using the Mathematica software:

i. Load the non-linear regression package.
ii. Input experimental data, title, x-label, y-label and set the required equation.
iii. Perform non-linear regression and plot experimental data and best fitted curve.
iv. Calculate the mean square error and coefficient of determination.
v. Show the best-fitted equation constant, mean square error and coefficient of determination.

Tables 1-5 show the rheological constants for the oil blends under study. As shown in Table 1, 2 ,3, 4 and 5, the polynomial curve-fitting software was applied to each oil samples at four different shear rates. Mean square error stands for the mean of how much of the data spread unaccounted for by the equation. The temperature range represents the range of temperature, where the modified Andrade's equation was fitted into the experimental data.

The experiment has proven that the behavior of Shell Tellus 100, refined bleached and deodorized palm and their blends exhibit a linear shear stress-shear rate relationship (Newtonian behavior) at high temperature (100°C). This indicates that the shear rate has less effect on viscosity and the viscosity of the oils depends heavily on the change of temperature. However, at low temperature (30°C), the shear rate has a larger effect on changes of viscosity for all the oils being investigated. Shear rate contributes to the changes of viscosity of the oils, but this effect was less pronounced for pure Shell Tellus 100 when compared to pure refined bleached and deodorized palm oil.

Based on Ostwald de-Waele power law model, the flow behavior index for the pure refined bleached deodorized palm oil at 40°C is 0.7820. The corresponding value for the Shell Tellus 100 is 0.9626. This shows that the Shell Tellus is close to Newtonian type. However, the palm oil shows pseudoplastic behavior.

From the results of the regression tabulated in Tables 1-4, the lowest coefficient of determination and the highest mean square error were 0.98014 and 0.00092330, respectively. Meanwhile, for results of the regression tabulated in Table 5, the lowest coefficient of determination and the highest mean square error were 0.99963 and 0.00018103 respectively.

As a rule of thumb, a good fit accounts for at least ninety nine percent of the data variation, where this value corresponds to $R^2 \geq 0.99000$ [13]. Overall, there was only one reading of coefficient of determination which is less than 0.99000, occurring at 3 rpm for 100% RBD palm oil. Therefore, by referring to these coefficients of determination and mean square error values, it can be stated that the experimental data obtained for the refined bleached and deodorized palm oil and their blends with Shell Tellus 100 were very well fitted by the modified Andrade's equation.

## 4.0 CONCLUSION

All oil samples being tested were very well fitted by the modified Andrade's equation. It was not necessary to use higher-order polynomial in 1/T, since almost all of the coefficients determined were greater than 0.99000.

The viscosity curve-fitting model has shown a good fitting to natural oil, mineral oil and their blends oil. This temperature dependence viscosity model provides an outstanding fit with the highest mean square error of 0.00092330 in the range of temperatures investigated at specific shear rate. The present study has made it possible to obtain an accurate viscosity value at different temperatures by placing the equation constants at specific speed into the modified Andrade's equation. Therefore, this temperature dependence viscosity model can be used to determine the viscosity of oil at various temperatures for a particular shear rate with better accuracy for specific applications such as the design of piping system, hydraulic application, rotating machinery lubrication, design of heat transfer equipment and other specific applications.

## ACKNOWLEDGEMENT

The authors would like to thank Mr. Sunny in Engineering Laboratory, KUSTEM who indirectly involved during the test and verifying the data and to Mr. Muhammad for editing the manuscript. We also greatly acknowledge the partial financial support from KUSTEM through grants No. 54045, 55002 and MOSTE IRPA grant 09-02-06-0007-EA-007.


## NOMENCLATURE

| Symbol | Meaning | Unit |
|---|---|---|
| A,B,C,D,E,K | Constants | |
| $E_a$ | Viscous activation energy | (J/mol) |
| R | Gas constant | $(J/K^{-1}mol^{-1})$ |
| $r_b$ | Spindle outer radius | (cm) |
| $r_c$ | Sample chamber inner radius | (cm) |
| T | Temperature | (K) |
| $T_\infty$ | Temperature infinity | (K) |
| $\gamma$ | Shear rate | $(s^{-1})$ |
| $\eta$ | Apparent viscosity | $(g.m^{-1}.s^{-1})$ |
| $\eta_o$ | Apparent viscosity | $(g.m^{-1}.s^{-1})$ |
| $\tau$ | Shear stress | $(g.cm^{-1}.s^{-2})$ |
| $x$ | Radius at which viscosity was measured | (cm) |
| $w$ | Spindle speed | (rpm) |

## REFERENCES


1. Igwe, I.O., 2004, "The Effects of Temperature on the Viscosity of Vegetable Oils in Solution", *Industrial Crops and Products*, Vol. 19, pp.185-190.
2. Kerschbaum, S. and Rinke, G., 2004, "Measurement of the Temperature Dependent Viscosity of Biodiesel Fuels", *Fuel*, Vol. 83, pp. 287-291.
3. Cameron, A., 1981, "Basic Lubrication Theory", Ellis Horwood Ltd., Chichester, 3rd ed.
4. Buckley, C.P. and Jones, D. C., 1995, "Glass-Rubber Constitutive Model for Amorphous Polymers Near the Glass Transition", *Polymer*, Vol. 36, pp. 3301-3312.
5. Mahiuddin, S. and Ismail, K, 1996, "Temperature and Concentration Dependence of the Viscocity of Aqueous Sodium Nitrate and Sodium Thiosulphate Electrolytic Systems", *Fluid Phase Equilibria*, Vol. 123, pp. 231-243.

6. Rohman, N., Wahab, A., Dass, N. N. and Mahiuddin, S., 2001, "Viscosity, Electrical Conductivity, Shear Relaxation Time and Raman Spectra of Aqueous and Methanolic Sodium Thiocyanate Solutions", *Fluid Phase Equilibria*, Vol. 178, pp. 277-297.
7. Sopade, P.A., Halley, P., Bhandari, B., D'Arcy, B., Doebler, C. and Caffin, N., 2003, "Application of the Williams–Landel–Ferry Model to the Viscosity–Temperature Relationship of Australian Honeys", *Journal of Food Engineering*, Vol.56, pp. 67-75.
8. Noureddini, H., Teoh, B.C. and Clements L.D., 1992, "Viscosities of Vegetable Oils and Fatty Acids", *Journal of American Oil Chemists'* Society, JAOCS, Vol. 69, pp.1189 –1191.
9. Vlad, H. and Oprea, S., 2001, "Evaluation of Rheological Behaviour of Some Thermoplastic Polyurethane Solutions", *European Polymer Journal*, Vol. 37, pp. 2461–2464.
10. Gerpen, J.H.V. and Tat, M.E., 1999, "The Kinematic Viscosity of Biodiesel and Its Blends with Diesel Fuel", *Journal of American Oil Chemists' Society, JAOCS*. Vol. 76, pp. 1511–1513.
11. Brookfield Engineering Laboratories, Inc., 2000, "*Brookfield Digital Viscometer Operating Instructions*", Middleboro, MA (USA).
12. Bird, R.B., Stewart, W.E. and Lightfoot, E.N., 1960, "*Transport Phenomena*", John Wiley & Sons, Inc.
13. Palm, W.J., 2001, "*Introduction to Matlab 6 for Engineers*", McGraw-Hill Higher Education.

Table 1 Predicted parameters and statistics for 100% RBD palm oil

| Shear rate | Constants for modified Andrade's equation | | | | $R^2$ | MSE | Temp. Range (°C) |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | | | |
| 3.9 | 1.7150000E+00 | -1.3128700E+03 | 1.3551165E+06 | -2.1360291E+08 | 9.8014E-01 | 9.2330E-04 | 30 - 100 |
| 7.9 | -4.7809400E+01 | 5.2959600E+04 | -1.8475848E+07 | 2.1806846E+09 | 9.9163E-01 | 4.4151E-04 | 30 - 100 |
| 65.8 | 3.4403900E+01 | -3.2989300E+04 | 1.0486322E+07 | -9.9443427E+08 | 9.9952E-01 | 1.7373E-04 | 30 - 100 |
| 131.6 | -7.4996800E-01 | 1.3221400E+03 | -7.2792000E+05 | 2.3240576E+08 | 1.0000E+00 | 5.1692E-07 | 50 - 100 |

Table 2 Predicted parameters and statistics for 75% RBD palm oil-25% Shell Tellus 100

| Shear Rate | Constants for modified Andrade's equation | | | | $R^2$ | MSE | Temp. Range (°C) |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | | | |
| 3.9 | -5.7308400E+00 | 7.7820000E+03 | -2.6713924E+06 | 3.7539203E+08 | 9.9813E-01 | 2.7713E-04 | 30 - 100 |
| 7.9 | -3.8299100E+01 | 4.2068900E+04 | -1.4824249E+07 | 1.8123726E+09 | 9.9984E-01 | 3.0645E-05 | 30 - 100 |
| 65.8 | -6.1964300E+00 | 6.5233300E+03 | -2.3854204E+06 | 4.1258707E+08 | 9.9979E-01 | 6.4617E-05 | 40 - 100 |
| 131.6 | -6.5804000E+00 | 6.7063900E+03 | -2.4279210E+06 | 4.2019155E+08 | 9.9999E-01 | 2.5518E-06 | 50 - 100 |

Table 3 Predicted parameters and statistics for 50% RBD palm oil-50% Shell Tellus 100

| Shear rate | Constants for modified Andrade's equation | | | | $R^2$ | MSE | Temp. Range (°C) |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | | | |
| 3.9 | 6.0097600E+00 | -5.9604700E+03 | 1.9677699E+06 | -9.2438740E+07 | 9.9946E-01 | 2.3629E-04 | 30.9 - 100 |
| 7.9 | -2.6839300E+01 | 2.7362600E+04 | -9.3078070E+06 | 1.1775410E+09 | 9.9997E-01 | 1.3794E-05 | 30.9 - 100 |
| 65.8 | 3.0042200E+00 | -3.2763600E+03 | 9.9878400E+05 | 3.6965484E+07 | 9.9999E-01 | 5.3506E-06 | 40 - 100 |
| 131.6 | -4.3214000E+01 | 4.5333800E+04 | -1.6056342E+07 | 2.0326998E+09 | 1.0000E+00 | 3.5587E-07 | 60 - 100 |

Table 4 Predicted parameters and statistics for 25% RBD palm oil-75% Shell Tellus 100

| Shear rate | Constants for modified Andrade's equation | | | | $R^2$ | MSE | Temp. Range (°C) |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | | | |
| 3.9 | -1.0652300E+02 | 1.0654900E+05 | -3.5297612E+07 | 4.0078471E+09 | 9.9946E-01 | 2.3180E-04 | 30.2 - 100 |
| 7.9 | -7.4884800E+01 | 7.7940200E+04 | -2.6887482E+07 | 3.2052295E+09 | 9.9979E-01 | 9.4723E-05 | 30.2 - 100 |
| 65.8 | -3.2411200E+01 | 3.3856800E+04 | -1.2004074E+07 | 1.5633198E+09 | 9.9997E-01 | 8.4451E-06 | 50 - 100 |
| 131.6 | -7.7146600E+01 | 8.0812200E+04 | -2.8463014E+07 | 3.4893666E+09 | 1.0000E+00 | 1.5002E-08 | 60 - 100 |

Table 5 Predicted parameters and statistics for 100% Shell Tellus 100

| Shear rate | Constants for modified Andrade's equation | | | | $R^2$ | MSE | Temp. Range (°C) |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | | | |
| 3.9 | -7.4495000E+01 | 7.6183500E+04 | -2.5775338E+07 | 3.0303613E+09 | 9.9963E-01 | 1.8103E-04 | 31.6 - 100 |
| 7.9 | -6.0453300E+01 | 6.5512100E+04 | -2.3493202E+07 | 2.9281249E+09 | 9.9987E-01 | 6.9534E-05 | 31.6 - 100 |
| 65.8 | -1.5854900E+00 | 1.5772300E+03 | -8.2964900E+05 | 2.9247091E+08 | 9.9999E-01 | 3.8165E-06 | 50 - 100 |

# APPENDIX

Brookfield LVDV –I+ viscometer with important accessories