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RHEOLOGICAL AND TRIBOLOGICAL STUDY ON SOYBEAN OIL

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ABSTRACT

In this work the temperature and share rate influence on soybean oil viscosity was studied. Moreover, a statistical analysis of the experimental data obtained by a tribological study of this oil was carried out. Following this analysis, it was concluded that the dynamic viscosity decreases with the increasing of temperature and share rate. The statistical analysis of the experimental data has contributed to obtaining a mathematical modeling of sliding speed and load influence on after wear diameter and friction coefficient.

KEYWORDS: lubricant, wear, biodegradable, soybean oil, viscosity, shear rate

1. INTRODUCTION

Conservation of materials and energy is becoming a very important issue. The main cause of energy loss in a mechanical system is the friction but this can be reduced by lubrication. Thus, it is very important to improve the lubrication properties. A good combination between oil base and additives is the key to improve this process [1].

For most lubricated applications, the conventional choice is a mineral oil-based lubricant, because of its well-known properties. However, due to their inherent toxicity and non-biodegradable nature, they pose a constant threat to ecology and vast ground water reserves. In this context, environmentally adapted lubricants have become more and more important in industrial applications. The properties of different base fluids vary widely and it is important to understand their effects on the performance of a lubricant in different lubrication regimes [1], [2], [3], [4].

Vegetable oil lubricants are potential substitutes for mineral oil not only because they are renewable raw materials but also because they are biodegradable and non-toxic. Furthermore, they show most properties required for lubricants, such as high index viscosity, low volatility, good lubricity, as well as excellent solvents for fluid additives [1], [2]. However, vegetable oils show poor oxidative and thermal stability, due to the presence of unsaturation.

The soybean oil is manufactured from soy beans, which are origin from China, acclimatized in our country in 1931 and cultivated nowadays in wide areas. The soy beans contain 17 to 20 % oil, which is extracted by cold pressing or extraction with benzene, the solvent being separated from oil by distillation.

As the majority of vegetable oils, inside the soy oil, the glicerydes with fat acids are predominant, having one or more double links, which means it can be included in non-drying oils group [5].

The physical and chemical properties of the soybean oil are: relative density at 15ºC = 0.924…0.930; freezing point = -10...-15ºC, iodine color = 12-45 mg I_2, saponification point = 180...190 mg KOH/g, iodine point = 120...140 g I_2/100g, acidity point = 0.6 mg KOH/g, peroxide point = 10 mmol active oxygen/kg. The soybean oil is an aliment but subjected to a hydrogenation treatment at 40...50°C, it is used for manufacturing soap and grease [6].

2. EXPERIMENTAL DETAILS

The Rheotest 2 equipment was used in order to determine the variation of viscosity with temperature and share rate. The tested oil temperature varied between 30ºC and 90ºC from

10 to 10ºC, the tests being carried out for share rates between 3.3 s^{-1} and 80 s^{-1}.

Furthermore, a tribological study on soybean oil was carried out. In this direction, the after wear diameter and friction coefficient were determined using the four-ball machine. The testing parameters were: loading force – 140 N, 200 N and 260 N; main shaft speed of the four-ball machine - 800 rot/min and 1200 rot/min; sliding speed corresponding to main shaft speed – 0.307 m/s and 0.461 m/s; testing time - 60 minutes. For statistical analysis of the experimental data and for studying the dependency between the input (sliding speed and tribosystem) and output variables (after wear diameter and friction coefficient), the Taguchi method was used. For that, DOE (Design of Experiments) type and general statistics tools of a software product (Minitab Statistical Software) were used [7], [8], [9].

3. EXPERIMENTAL RESULTS

In figure 1 it is shown the dependency between the dynamic viscosity and share rate for testing temperature of 40ºC, 60ºC and 80ºC. The dynamic viscosity decreases with the increasing of share rate for all testing temperature.

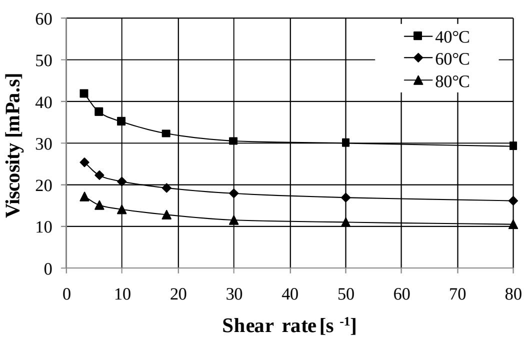

Fig. 1. Dynamic viscosity / share rate variation

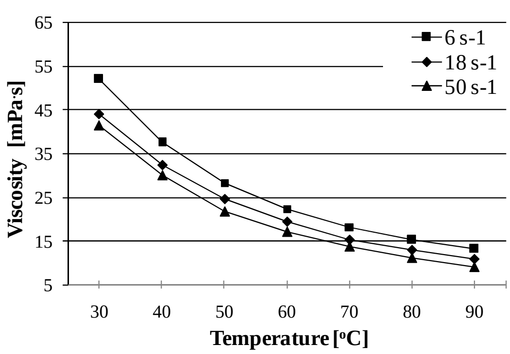

Fig. 2. Dynamic viscosity / temperature variation

A drop of share rate can be seen in the small share rates domain (3.3 – 18 s^{-1}).

When increasing the share rate the viscosity decreasing is small.

For soybean oil tested at 40ºC, within the range of share rate between 3.3 and 30 s^{-1}, it can be observed a decreasing of 26.71% of the dynamic viscosity while within the range of 30-80 s^{-1} the decreasing of the dynamic viscosity is only 4.5%. For soybean oil tested at 60ºC, within the first range of share rate the decreasing of the viscosity is 29.91% by for the second range the viscosity decreased with 9.4%. In the end, for soybean oil tested at 80ºC, it can be observed a decreasing of the viscosity by 32.62% for the first share rate range and by 8.5% for the second range.

In figure 2, the variation of the viscosity with respect to temperature for share rates between 6 s^{-1}, 18 s^{-1} and 50 s^{-1} is presented. The dynamic viscosity decreases while the temperature increases, this behavior being observed by, [10], [11] when studying this effect using other vegetable oils.

Within a temperature range between 30ºC – 60ºC an important decreasing of the dynamic viscosity can be observed when comparing with the results obtained when the temperature varies between 60ºC – 90ºC. In case of soybean oil tested at 6s^{-1} share rate, for a temperature between 30ºC – 60ºC the decreasing of the viscosity is 57%, while the viscosity decreasing for a temperature between 60ºC – 90ºC is 40%.

For the entire temperature range, for a share rate of 6 s^{-1}, the dynamic viscosity variation is 74.25%, while for share rates 18 s^{-1} and 50 s^{-1} the variation was 75.25%, respectively 77.88%.

The increasing of share rate leads to an important decreasing of the dynamic viscosity with respect to temperature. In order to support the results of viscosity variation with respect to temperature, Andrade (1) and Azian (2) equations were used, [12], [13], [14].

$$\ln \eta = \ln A + \frac{B}{T} \qquad (1)$$

$$\ln \eta = A + \frac{B}{T} + \frac{C}{T^2} \qquad (2)$$

where T is the absolute temperature and A, B and C are the material constants. Tables 1 and 2 present the values of the parameters in the equations of Andrade and Azian and the corresponding correlation coefficients.

Table 1. Parameters in Andrade equation

Share rate [s^{-1}]	6	18	50
A	-4.3957	-4.7513	-5.4080
B	2512.42	2577.41	2755.99
Correlation coefficients	0.99649	0.99834	0.99863

Table 2. Parameters in Azian equation

Share rate $[s^{-1}]$	6	18	50
A	7.7774	3.42165	2.5756
B	-5565.6	-2846.2	-2541.89
C	$1.34 \cdot 10^6$	$0.9 \cdot 10^6$	$0.88 \cdot 10^6$
Correlation coefficients	0.99997	0.99983	0.99988

By comparing the correlation coefficients values, resulted after determining the parameters of Andrade and Azian equations, it can be seen that the values of the correlation coefficients are closer to 1 when Azian equation is used. Azian equation makes a very good approximation of the experimental data and for this reason it can be used to determine the oil viscosity variation with respect to temperature.

Table 3 presents the experimental plan structure, the independent variables of friction process (sliding speed and load). These variables are used as input parameters. There are also mentioned the output parameters of the tribosystem (the average diameter of after wear and friction coefficient) and the output and input parameters range variation.

Table 3. Tribotester with soybean oil

No.	Input parameters		Output parameters	
	Speed [m/s]	Load [N]	D_w	Friction coefficient
1	0.307	140	0.2873	0.0810
2	0.307	200	0.3345	0.0654
3	0.307	260	0.3556	0.0710
4	0.461	140	0.2678	0.0679
5	0.461	200	0.2975	0.0642

The analysis of the variation between the average after wear diameter and friction coefficient in case of lubricating the tribosystem with soybean oil is presented in table 4 and 5. For determining the influence of the input parameters of tribosystem and relevant interactions, when analyzing the average diameter of after wear and friction coefficient, the weight value *P%* is analyzed in tables 4 and 5.

Table 4. The variation analysis of D_w parameter

Source	DF	Seq SS	P%
Speed [m/s]	1	0.0017854	34.86
Load [N]	2	0.0031422	61.35
Error	2	0.0001938	
Total	5	0.0051213	
S = 0.00984251, R-Sq = 96.22%			

Table 5. Analysis of friction coefficient

Source	DF	Seq SS	P%
Speed [m/s]	1	0.0000749	35.81
Load [N]	2	0.0000989	47.28
Error	2	0.0000354	
Total	5	0.0002092	
S = 0.00420852, R-Sq = 83.07%			

Therefore, the parameter which has a significant weight in defining the average diameter of after wear is load (61.35%).
The sliding speed has a lower influence (34.86%). Concerning the friction coefficient, the most significant influence is represented by load, meaning 47.28%.

The sliding speed has a lower influence on the friction coefficient (35.81%). The equations resulted from a linear regression, for wear diameter and friction coefficient are:

$$D_{uz,soia} = 0,303659 - 0,224026 \cdot v + + 4,54583 \cdot 10^{-4} \cdot F \; [mm] \quad (3)$$

$$Cof_{soia} = 0,0980541 - 0,0458874 \cdot v - - 5,75 \cdot 10^{-5} \cdot F \quad (4)$$

Figures 3 and 4 present the residual probability diagrams with a trust range of 95%, for output parameters D_{uz} and *Cof*, as a difference between the measured answer signal and the theoretical one of each test.

From graphical representation, it can be seen that the values of after wear average diameter D_{uz} and friction coefficient *Cof* are within the specified trust range.

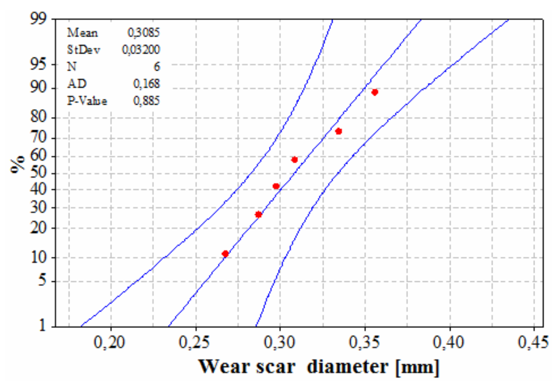

Fig. 3. Residual probability diagram for D_{uz}

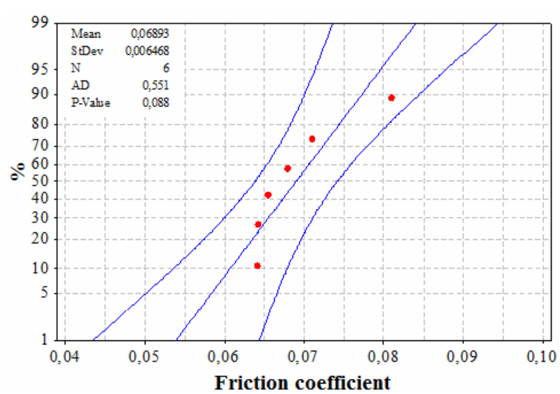

Fig. 4. Residual probability diagram for *Cof*

By using linear regression equations (3) and (4) deduced using ANOVA variation analysis, which define the values of after wear average diameter D_{uz} and friction coefficient *Cof*, a comparative analysis with measured values was carried out. Therefore, tables 6 and 7 present the values of D_{uz} and *Cof* and error values between the experimental and analytical methods.

Table 6. Values of after wear average diameter

Speed [m/s]	0.307		
Load [N]	**140**	**200**	**260**
$D_{uz.\ measured}$ [mm]	0.2873	0.3345	0.3556
$D_{uz.\ calculated}$ [mm]	0.2985	0.3258	0.3530
Error % D_{uz}	**3.89**	**2.67**	**0.72**
Speed [m/s]	**0.461**		
Load [N]	**140**	**200**	**260**
$D_{uz.\ measured}$ [mm]	0.2678	0.2975	0.3086
$D_{uz.\ calculated}$ [mm]	0.2640	0.2913	0.3185
Error % D_{uz}	**1.41**	**2.12**	**3.2**

Table 7. Values of friction coefficient

Speed [m/s]	0.307		
Load [N]	**140**	**200**	**260**
$D_{uz.\ measured}$ [mm]	0.081	0.0654	0.071
$D_{uz\ calculated}$ [mm]	0.0759	0.0724	0.0690
Error % D_{uz}	**6.27**	**10.81**	**2.79**
Speed [m/s]	**0.461**		
Load [N]	**140**	**200**	**260**
$D_{uz.\ measured}$ [mm]	0.0679	0.0642	0.0641
$D_{uz\ calculated}$ [mm]	0.0688	0.0654	0.0619
Error % D_{uz}	**1.39**	**1.86**	**3.35**

By analyzing the prediction error values (tables 8 and 9) it can be seen that the values are between 0.72% and 10.81%, which means they are within the admissible tolerance of statistical analysis (max. 20%).

The predicted average error is 2.33% for after wear average diameter equation and 4.41% for friction coefficient equation.

4. CONCLUSIONS

The rheological study presented in this paper highlights that the dynamic viscosity decreases when the temperature increases, phenomenon observed at all share rates used for testing the soybean oil. The dynamic viscosity decreases when shear rate increases at all three testing temperature values. Within the small shear rate values domain, the viscosity has an important decreasing while within the range of high shear rate values domain the viscosity decreasing is insignificant.

Thus, in case of soybean oil tested at 40ºC, having a shear rate between 3.3 and 30s^{-1}, the decreasing of dynamic viscosity is 26.71%. When the shear rate is between 30 and 80s^{-1} the decreasing of dynamic viscosity is 4.5%.

The viscosity variation with respect to temperature analysis was studied using Andrade and Azian equations. The higher values of correlation coefficients was obtained by using Azian equation. Therefore, Azian equation leads to a better prediction of the experimental data. In order to study the relations between the input and output parameters, DOE (Design of Experiments) type and general statistics tools of a software product (Minitab Statistical Software) were used.

According to Taguchi analysis, load (47.28%) is the parameter which mostly influences the friction coefficient and the smallest influence is given by the sliding speed (35.81%). Considering the after wear diameter, the load influence is 61.35%, while the sliding speed has a smaller influence (34.86%).

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