STUDY ON RHEOLOGICAL AND TRIBOLOGICAL BEHAVIOUR OF RAPESEED OIL

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ABSTRACT

In this paper, modern methods for investigating a characterization of the rapeseed oil are presented. This oil has good characteristics and therefore can be used for manufacturing biodegradable lubricant. It was mathematically determined the dependency between wear scar diameter, sliding speed and load. At the same time, the variation of dynamic viscosity with temperature and shear rate was determined. The dependency between the main characteristics of the rapeseed oil, by using an original evaluation technique, was determined.

KEYWORDS: tribological behaviour, rheological behaviour, rapeseed oil.

1. INTRODUCTION

Rapeseed oil production is the third in the world after production of palm oil and rapeseed oil. Every year, about 30 million hectares of rapeseed are cultivated and about 50 million tones of rapeseed oil are produced. The rapeseed oil consumption is presented in figure 1. In the last years, it can be observed that the consumption of rapeseed oil has increased.

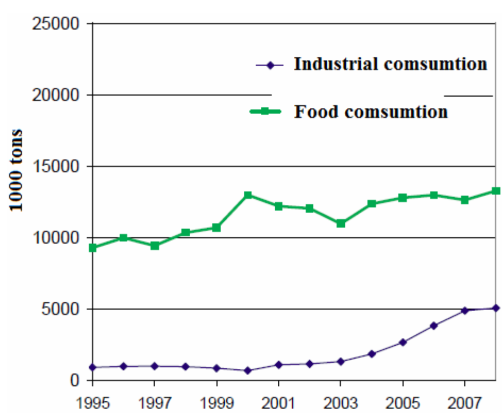

Fig. 1. *Mondial comsumtion of rapeesed oil [1]*

In 2010, the rapeseed oil production in Romania was on the second place after sunflower oil, see table 1. In recent years, the use of environmentally friendly lubricants has become increasingly popular. Environmentally friendly lubricants for total loss applications usually consist of readily biodegradable base oil and proper additives.

Table 1. *The production of vegetable oils in Romania [thousands of tones] [2]*

	2007	2008	2009	2010
Sunflower oil	257	173.2	241.1	197.3
Rapeseed oil	16.3	88.57	74.3	69.1
Soybean oil	48.2	29.7	6.38	2.43

The greater the fraction of the readily biodegradable component in a lubricant is, the more attractive the lubricant becomes for total loss applications. Because of their inherent excellent biodegradability and non-toxicity, vegetable oils are very attractive for this application [3]. Unfortunately, their oxidation stability is poor. Oxidation products can impair lubricant quality and, subsequently, lubrication mechanism performance [4].

The rapeseed (Brassica oleracea) is cultivated as a plant since 16th century, being spread in geographical areas with both warm and cold climate. The rapeseed oil has a low content of saturated fat acids (5-10%), a high content of monounsaturated fat acids and is a reach source of antioxidants components as polyphenol, tocopherols, β-carotene, lutein, phytosterols etc [5], [6], [7].

The physical and chemical properties of the rapeseed oil are: peroxide point = 10 mmol active oxygen/kg, mass fraction of water and volatile substances = 0.15-0.2%, relative density at 20ºC =

0.914-0.920; refraction point = 1.465-1.467; saponification point = 182-193 mg KOH/g oil, iodine point = 105-126 g I_2/100 g [8].

2. EXPERIMENTAL DETAILS

The equipment used for the determination of the variation of viscosity with temperature and shear rate was described in [14]. Solea et al. shown that the tested oil temperature varied between 30ºC and 90ºC from 10 to 10ºC, the tests being carried out for shear rates varying within 3.3 s^{-1} and 80 s^{-1}.

Forwards, a tribological study on rapeseed oil was carried out. For this, by using the four-ball machine, the after wear diameter and friction coefficient were determined.

The testing parameters values are similar to the study of the soybean oil [14]:

- load force – 140 N, 200 N and 260 N;
- speed of the four-ball machine - 800 rot/min and 1200 rot/min;
- sliding speed which corresponds to the nominal speed – 0.307 m/s and 0.461 m/s;
- testing time - 60 minutes.

Table 2 presents the value range of the fat acids concentrations from rapeseed oil and the values of these concentrations chromatographic determined for the rapeseed used for this work.

Table 2. *Fat acids concentrations of rapeseed oil*

Fatty acids	Experimental values %	Theoretical values %
Miristic	**0.05**	<0.2
Palmitic	**4.84**	2.5 – 7.0
Heptadecanoic	**0.14**	<0.5
Heptadecenoic	**0.15**	<0.5
Stearic	**0.14**	0.8 – 3.0
Oleic	**62.73**	51.0 – 70.0
Linoleic	**22.4**	15.0 – 30.0
Linolenic	**7.5**	5.0 – 14.0
Arahidic	**0.5**	0.2 – 1.2
Eicosenoic	**0.2**	<0.5

3. EXPERIMENTAL RESULTS

The statistical analysis of experimental data and correlation between the input and output variables was carried out by Taguchi method. On this direction, DOE (Design of Experiments) statistics tools of a Minitab software was used [9].

In table 3, the friction process variables - sliding speed and load is presented, which were 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.

Tables 4 and 5 present an analysis of the variation of the friction coefficient with average diameter after wear occurrence. The results correspond to the case of lubricating the tribosystem with rapeseed oil.

Table 3. *Experimental results in case of lubricating the tribotester with rapeseed oil*

Nr.	Input parameters		Output parameters	
	Speed [m/s]	Load [N]	D_w	Friction coefficient
1	0.307	140	0.2630	0.0959
2	0.307	200	0.2962	0.0884
3	0.307	260	0.3061	0.079
4	0.461	140	0.2642	0.0858
5	0.461	200	0.2927	0.0781
6	0.461	260	0.3025	0.0712

Table 4. *The variation analysis of D_w parameter*

Source	DF	Seq SS	P%
Speed [m/s]	1	0.0000058	0.319
Load [N]	2	0.0018035	99.267
Error	2	0.0000075	
Total	5	0.0018168	
S = 0.00193950 R-Sq = 99.59%			

Table 5. *The variation analysis of friction coefficient*

Source	DF	Seq SS	P%
Speed [m/s]	1	0.0001325	34.63
Load [N]	2	0.0002482	64.87
Error	2	0.0000019	
Total	5	0.0003826	
S = 0.000982344, R-Sq = 99.50%			

In order to the determine the influence of the input parameters of the process, in case of average diameter of after wear and friction coefficient, the weight value P% is presented in tables 4 and 5. Therefore, the parameter which has a significant weight in defining the average diameter of after wear is load (99.267%). The influence of the sliding speed is very low (0.319%). If we analyze the problem from friction coefficient point of view, load has the most significant influence, meaning 64.87%. Opposite, the friction coefficient (34.63%) has a lower influence on sliding speed.

The linear regression equations, are:

$$D_w = 0.224521 - 0.0127706 \cdot S + 3.39167 \cdot 10^{-4} \cdot L \text{ [mm]} \quad (1)$$

where D_w is after wear diameter;
S – sliding speed;
L – load

$$Cof = 0.132756 - 0.061039 \cdot S - 13.125 \cdot 10^{-5} \cdot L \quad (2)$$

where Cof is friction coefficient.

In figures 2 and 3 the residual probability diagrams are presented. The trust interval is 95%, in case of D_w and *Cof* parameters. This interval is calculated as the difference between measured and theoretical signal. By analyzing these figures, it is obviously that the values of after wear average diameter D_w and friction coefficient *Cof* are within the safe range.

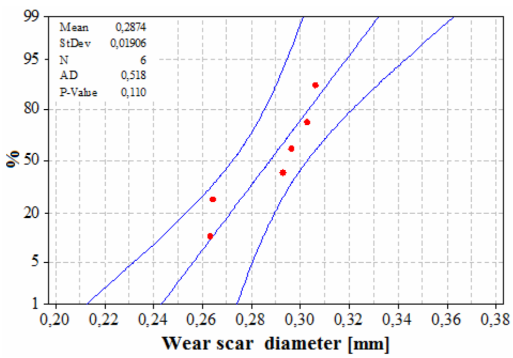

Fig. 2. *Diagram of residual probability (D_w)*

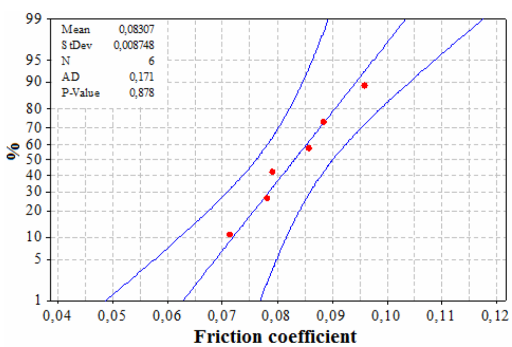

Fig. 3. *Diagram of residual probability (Cof)*

ANOVA variation analysis was used for defining the values of after wear average diameter D_w and friction coefficient *Cof* - equations (1) and (2). Then, a comparative analysis between numerical and experimental values is carried out. In tables 6 and 7 the values of D_w and *Cof* and error values are presented.

Table 6. *After wear average diameter values*

Speed [m/s]	0.307		
Load [N]	**140**	**200**	**260**
$D_{w.\ measured}$ **[mm]**	0.2630	0.2962	0.3061
$D_{w.\ calculated}$ **[mm]**	0.2681	0.28843	0.30878
Error % D_{uz}	**1.93**	**2.62**	**0.87**
Speed [m/s]	**0.461**		
Load [N]	**140**	**200**	**260**
$D_{w.\ measured}$ **[mm]**	0.2642	0.2927	0.3025
$D_{w.\ calculated}$ **[mm]**	0.26612	0.28647	0.30682
Error % D_{uz}	**0.72**	**1.38**	**1.42**

From tables 6 and 7 it can be seen that the values are between 0.26-0,30%. That means the values are within admissible range of tolerance (up to 20%). The average error is 1.49% for after wear average diameter equation and 0.65% for friction coefficient equation.

Table 7. *Friction coefficient values*

Speed [m/s]	0.307		
Load [N]	**140**	**200**	**260**
$D_{w.\ measured}$ **[mm]**	0.0959	0.0884	0.0790
$D_{uz.\ calculated}$ **[mm]**	0.09564	0.087767	0.079892
Error % D_{uz}	**0.26**	**0.71**	**1.12**
Speed [m/s]	**0.461**		
Load [N]	**140**	**200**	**260**
$D_{w.\ measured}$ **[mm]**	0.0858	0.0781	0.0712
$D_{w.\ calculated}$ **[mm]**	0.086242	0.078367	0.070492
Error % D_{uz}	**0.51**	**0.33**	**0.99**

The dependency between the dynamic viscosity and shear rate is shown in figure 4. The testing temperature was: 40ºC, 60ºC and 80ºC. It can be seen that the dynamic viscosity decreases when the shear rate increases.

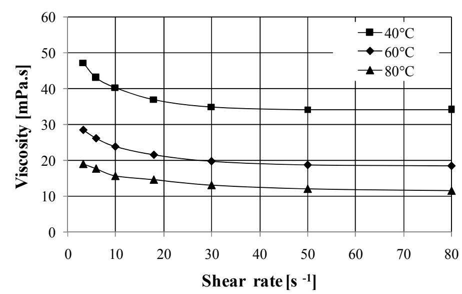

Fig. 4. *Dynamic viscosity vs. shear rate variation*

For rapeseed oil, the tests carried out at 40ºC, for range of shear rate between 3.3 and 30s^{-1}, it can be seen a decreasing of 25.95% of the dynamic viscosity. At the same time, for the range of 30-80s^{-1} the dynamic viscosity decreases no more than 2.4%. When the rapeseed oil was tested at 60ºC, for the first range, the decreasing of the viscosity is 30.89% and for the second range - 5.74%. In the end, for tests at 80ºC, it can be observed a decreasing of the viscosity with 31.44% for the first shear rate range and with 11.45% for the second range.

In figure 5, the temperature dependant variation of the viscosity for shear rates within 6 s^{-1}, 18 s^{-1} and 50s^{-1} is presented.

Goodrum et al. [10] and Kosmert et al. [11] mentioned that the dynamic viscosity decreases while the temperature increases, in case of other vegetable oils. The dynamic viscosity is significantly decreasing when temperature range is 30ºC-60ºC. This is comparing with the dynamic viscosity when testing at 60ºC-90ºC. At 6s^{-1} share rate and temperature 30ºC-60ºC the viscosity decreases with 61.92%.

Also, for temperature of 60ºC-90ºC, the viscosity decreases with 46.03%.

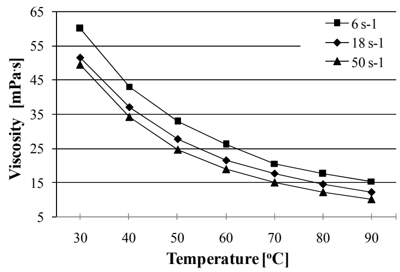

Fig. 5. *Dynamic viscosity vs. temperature variation*

Therefore, for a share rate of 6 s^{-1}, the dynamic viscosity variation is 74.42%, while for values of 18 s^{-1} and 50 s^{-1} the variation is 76.21%, respectively 79.45%. The decreasing of the dynamic viscosity with respect to temperature is determined by the increasing of share rate.

When calculating the viscosity variation depending on temperature, Andrade (3) and Azian (4) equations were used by [12], [13].

$$ln\,\eta = ln\,A + \frac{B}{T} \tag{3}$$

$$ln\,\eta = A + \frac{B}{T} + \frac{C}{T^2} \tag{4}$$

where T is the absolute temperature and constants A, B and C depends on material.

Tables 8 and 9 presents the values of the parameters in the equations (3) and (4) and the correlation coefficients related to these parameters.

Table 8. *The parameters in Andrade equation*

Share rate [s^{-1}]	6	18	50
A	-4.2438	-4.7638	-5.72103
B	2510.023	2623.579	2898.6
Correlation coefficients	0.99614	0.99758	0.99709

Table 9. *The parameters in Azian equation*

Share rate [s^{-1}]	6	18	50
A	8.0736	5.7519	7.0561
B	-5663.794	-4354.662	-5580.3
C	$1.352 \cdot 10^6$	$1.154 \cdot 10^6$	$1.41 \cdot 10^6$
Correlation coefficients	0.99971	0.99996	0.99997

Considering that correlation coefficients values are closer to 1 when using Azian equation, there is not necessary to identify a polynomial function of higher order because the correlation coefficients are high enough with values between 0.99971 and 0.99997. Azian equation makes a very good approximation of the experimental data and therefore, it can be used for the oil viscosity variation determination.

4. CONCLUSIONS

In accordance to Taguchi method, parameter load (64.87%) has the greater influence on the friction coefficient and, at the same time, the sliding speed has the smallest influence (34.63%). If consider the after wear diameter, the load influence is 99.27% and at the same time the sliding speed has a very low influence, which may neglected (0.32%).

There is a decreasing of the dynamic viscosity which depends on shear rate increasing at any testing temperature. The domain can be divided into 3 intervals: i) the first (0-10 s^{-1}), while the viscosity increases up to 10 s^{-1}, which will determine the viscosity to drop suddenly; ii) the second (10-30 s^{-1}), after value 10 s^{-1} is reached, the decreasing of the viscosity is significant and iii) the third interval (over 30 s^{-1}), when the viscosity is almost constant for any share rate value.

There can be carried out a better prediction of viscosity-temperature dependency, if using Azian equation. This is because the use of this equation leads to the best correlation coefficients.

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